Bentonite Mechanical Evolution

WORK PACKAGE 2
DELIVERABLE D2.2

Review of data and models on the mechanical properties of bentonite available at the start of Beacon

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Reporting period: 01/06/17 – 30/11/18

Date of issue of this report: **30/11/17**

Start date of project: **01/07/17**

Duration: 48 Months

This project receives funding from the Euratom research and training programme 2014-2018 under grant agreement No 745 942

Dissemination Level (choose)		
PU	Public	X

DISTRIBUTION LIST

Name	Number of copies	Comments
Athanasios Petridis (EC) Christophe Davies (EC) Beacon partners		

REPORT HISTORY

Version	Date	Changes	Editor(s)	Reviewer(s)
1.0	30/11/17	Report for submission to EC. Report updated to address comments from: S Norris F Bernachy-Barbe MV Villar Galicia JC Mayor A Dueck and M Åkesson	Kate Thatcher (Quintessa Ltd)	Sarah Watson (Quintessa Ltd)

Abstract

The Beacon (Bentonite mechanical evolution) project has been set up to study the performance of inhomogeneous bentonite barriers in the context of disposal of high level radioactive waste and spent fuel in geological repositories across Europe. A key aspect of the performance of bentonite barriers is how the bentonite evolves from its installed state to become a fully functioning long-term barrier. A significant number of experiments have been carried out using bentonite prior to the Beacon project. Some of these studies have considered the mechanical behaviour of bentonite, others have collected data on mechanical behaviour but have not analysed the data. The purpose of this report is to collate information available to the Beacon project that could help advance understanding of the mechanical behaviour of bentonite.

This report summarises current understanding and modelling approaches for bentonite mechanical evolution alongside a database of experimental data that are available for modelling studies. The database has been designed and populated as a collaborative effort between the participants of the Beacon project. There are many experiments listed in the database, at a range of scales (from bench top laboratory experiments to full scale field experiments), a small number of which were designed specifically for studies of bentonite homogenisation. The database contains information on the type of bentonite considered in the experiments, the boundary conditions and heterogeneities within the experiments and also the range of measurements taken in the experiment. This will allow Beacon partners and especially Work Package leaders to interrogate the database and find experiments of interest for consideration in the Beacon project.

Content

1 Introduction

The Beacon (Bentonite mechanical evolution) project has been set up to study the performance of inhomogeneous bentonite barriers in the context of disposal of high level radioactive waste and spent fuel in geological repositories across Europe. A key aspect of the performance of bentonite barriers is how the bentonite evolves from its installed state to become a fully functioning long-term barrier. Predicting this evolution with the necessary degree of confidence requires an understanding of material properties and fundamental processes that lead to the redistribution of bentonite mass within the bentonite component (e.g. buffer, backfill or seal). This process is referred to as homogenisation because it mainly involves moving from the installed bentonite distribution with void spaces and/or areas of bentonite of different dry densities to the final bentonite distribution in which void spaces are filled and density contrasts are no longer significant. The overall objective of Beacon is 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.

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. Rather than necessarily focussing on new experiments, the Beacon project will primarily concentrate on analysing results from previous experiments to ensure that the greatest possible value has been extracted from existing data. New experiments may be used to fill data gaps that have been identified by the initial project work (to be undertaken in Work Package 4).

This report forms deliverable D2.2 of Work Package (WP) 2 of the Beacon project. The purpose of this report is 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 (some of which are ongoing). The report sets out the context for the work in Beacon and how the work contained in this report relates to the overall project (Section 2). It then summarises current conceptual understanding of bentonite mechanical evolution, including some of the models currently available to represent this conceptual understanding numerically (Section 3). A brief overview of the available information is presented in Section 4 alongside a description of how that information has been used to build a database, and conclusions are presented in Section 5. The database derived from the data forms is given in Appendix A and all the collected data forms are presented in Appendix B.

2 Context

2.1 The Beacon project

Bentonite is used as part of the Engineered Barrier System (EBS) in many geological disposal concepts for radioactive waste. However, the different safety functions assigned to the bentonite may differ in different concepts and will depend to some degree on the components in which bentonite is used. A common feature of all of the uses of bentonite is the assumption that bentonite swells, exerting a swelling pressure on the surrounding host rock and other components in contact with it. This swelling pressure depends on the dry density of the bentonite as well as the composition of both the bentonite and the groundwater. Current safety assessment approaches often assume spatially uniform bentonite properties and hence homogeneous swelling pressure. However, when the bentonite is installed in the repository, there are, inevitably, initial contrasts in dry density as a result of the practicalities of emplacement. Examples of initial density contrasts are a technological void surrounding the bentonite in Andra’s tunnel plug, and the KBS-3 deposition tunnel backfill, which is composed of blocks surrounded by pellets, with the blocks having higher dry density than the pellets. Therefore, the dry density distribution of bentonite is not homogeneous at the end of the installation phase. One of the main objectives for the Beacon project is to build an understanding of how the dry density distribution might evolve in the post-closure phase. Related questions are:

- Does it evolve towards a homogeneous distribution?
- Does any remaining the inhomogeneity affect performance? and
- Which factors affect the degree of homogenisation that is achieved?

To help build this understanding of processes that lead to homogenisation of the bentonite, the Beacon project aims to develop and test tools necessary to predict the changes in a bentonite barrier from installation to a steady state condition and the likely performance of the barrier. Development and testing of tools will be undertaken in Work Packages 3 and 5, and these work packages will exploit the large amount of data already available from experimental studies into bentonite in the context of radioactive waste disposal.

2.2 Aims of this report

The report documents the information that has been made available to the Beacon project by the project partners and associated organisations. The information relates to experiments at a variety of scales and also modelling studies that have been undertaken. It is outside the scope of this report to conduct a detailed comparison of modelling approaches; this will be covered in a forthcoming deliverable D3.1. However, some brief discussions of modelling approaches are provided in Section 3.2.

This report uses information supplied by Beacon partners on experiments that have been carried out in previous projects to build a database of experiments which can be used during the Beacon project and beyond. The report documents the available data but, as agreed with Beacon partners who attended the WP2 workshop held in London on 23rd and 24th October

2017, this report does not attempt to propose any experiments for consideration within the Beacon project. This will be left to the Work Package leaders to undertake, based on the information contained herein. This report provides a summary information on a range of experiments, as well as clear referencing to the underlying reports which contain further information, to facilitate the process of selecting datasets for modelling within Beacon.

3 Current Understanding of Bentonite Mechanics

3.1 Conceptual model of mechanical evolution

Stress within a bentonite component of the repository EBS is a consequence of its swelling caused by resaturation of the initially emplaced partially-saturated bentonite within a confined space (e.g. defined by the host rock, the waste container, seals or other engineered structures). Therefore, the mechanical evolution is very closely related to the hydraulic evolution and the interactions between water and the swelling clay (smectite) present. The bentonite typically specified in EBSs for radioactive waste disposal consists primarily of the smectite mineral montmorillonite. In addition to smectite, bentonite typically includes other minerals such as quartz (and other silica polymorphs), feldspar, other layer silicates (e.g. kaolinite, illite, mica), carbonates, sulphides, sulphates and organic matter (Apted et al, 1995; Hicks et al., 2009). Understanding the atomic scale structure of smectite clay layers and their interaction with water molecules provides a conceptual understanding as to the macro-properties of bentonite and how it responds to factors such as water content, temperature and the presence of solutes.

Two atomic structural units can be defined from which most clay minerals (including smectites), are formed (Grim, 1968). The first is an ‘octahedral’ sheet (O in Figure 3-1), consisting of aluminium, iron or magnesium surrounded by oxygen and hydroxyls in an octahedral configuration. The second is a sheet consisting of predominantly silicate tetrahedrons (e.g. Grim, 1968, T in Figure 3-1). Smectite is a swelling clay mineral in which one octahedral sheet lies between two tetrahedral sheets forming a “2:1” T-O-T structure. These layers then stack up to form clay mineral grains with an “interlayer” system that may contain water, exchangeable (and hydrated) cations such as sodium, calcium and magnesium, and organic molecules. Water interacts with stacks of 2:1 layers in two ways. Firstly, water can enter the interlayers and secondly, water can surround the stacks, either as “double layer water” close to the surface of the stacks, or as “free water” around the edges of the stacks and other mineral grains (Bradbury and Baeyens, 2002). The interlayers exist due to a charge deficit across the T-O-T layers that results from isomorphous substitution of Al by Mg in the octahedral sheets. The incorporation of different hydrated cations and water molecules around the 2:1 layers of smectite enables the mineral to possess variable interlayer spacing (d(001) values in X-ray diffraction patterns). Values of d(001) vary as a function of relative humidity, generally in a step-wise fashion (e.g. MacEwan and Wilson, 1980; Wilson et al., 2004; Ferrage et al., 2007).

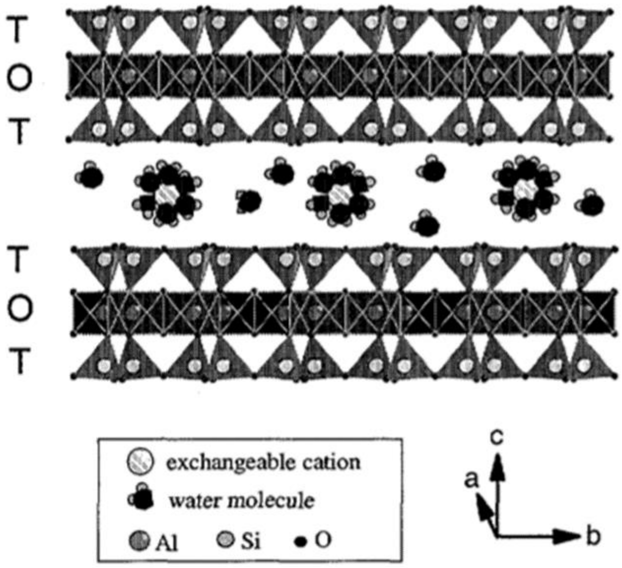

Figure 3-1: Schematic representation of the montmorillonite structure (Bradbury and Baeyens, 2002).

Swelling
There are two processes that result in the generation of swelling pressures (Bradbury and Baeyens, 2002). Re-hydration of the interlayer cations is the main swelling mechanism at close separation of the 2:1 layers and can generate hundreds of MPa of swelling pressure. Once the interlayer separation distance exceeds 1nm, electrical double layer repulsion becomes the primary swelling mechanism, with swelling pressures of several MPa being generated.

Suction
In a classical porous medium, suction is the driving mechanism for flow in an unsaturated porous medium and is a result of surface tension in water droplets in the pore space of the medium. In bentonite, water in the voids between clay mineral grains and other particles will create a suction pressure, but there will be additional mechanisms for generation of suction caused by the physico-chemical forces associated with the atomic structure of the clay which create a driving force for water to enter the system.

Flow properties
In a standard porous medium, where water exists in pore space, flow of water through the medium is described by a hydraulic conductivity. In bentonite, a fraction of the water exists in pore space and the remainder is held either within the interlayers or at the edges of the clay grains. There is not a single agreed-upon conceptual model for how water flows through bentonite (e.g. Kröhn, 2016) and therefore different authors use different material properties to describe flow (e.g. hydraulic conductivity, vapour diffusivity). Whichever process model is assumed, the movement of water through the bentonite will be determined by the strongest forces acting on the water, and the micro-structure is likely to play a significant role in this.

At the macro-scale, a qualitative conceptual model of the mechanical evolution of bentonite within a geological repository can be described as follows:

- Following emplacement within a geological environment, bentonite will be exposed to water influx from the host rock (of different magnitudes in different geologies) and potentially heat from any waste;
- The water influx will cause swelling of the bentonite, which in turn will generate stresses within the bentonite (the chemistry of the water will affect the amount of swelling);
- Heating will cause expansion of the bentonite grains and grain structure as well as the water which will generate stress within the bentonite;
- Heating will also cause drying close to the heat source, which will generate stress in the bentonite. Temperatures above 100°C could induce precipitation of cementing agents, changing the strength and swelling properties of the bentonite over the volume of bentonite the experiences high temperature (Wilson et al, 2011);
- The bentonite will deform elastically under stress conditions below the plastic failure limit, but when stress exceeds the plastic failure limit, bentonite will deform plastically;
- This deformation will cause a redistribution of mass of the bentonite within the system, which can change the dry density distribution from that initially emplaced.

3.2 Mathematical models of bentonite mechanics

The majority of modelling approaches for representing bentonite mechanics are based on a modification of the Cam Clay model (Roscoe and Schofield, 1963), which is a thermodynamically-derived model to represent the elastic and plastic deformation of saturated, non-swelling soils. The Modified Cam Clay model (MCC; Roscoe and Schofield, 1963) adapts the Cam Clay model to have a continuous yield surface so that it is more suitable for implementation in numerical codes. The most widely used approach for extending the MCC model to partially saturated materials, allowing representation of swelling, is the Barcelona Basic Model (BBM; Alonso et al. 1990). The BBM can be viewed as a generalisation of the MCC to partially water saturated conditions and includes suction and mean stress as independent state variables. A further extension to the BBM is the Barcelona Expansive Model (BExM; Alonso et al. 1999) which accounts for two structural levels in the bentonite associated with micropores and macropores. These models are often coupled to models for fluid flow and/or vapour transport as well as heat transport to represent the fully coupled behaviour of the bentonite.

Explicit representation of micro-scale processes is not normally considered in macro-scale modelling and instead processes are represented by empirical relationships derived from experimental data.

A range of models are used by Beacon participants, which are based on the Cam Clay and Barcelona approaches, with different modifications. They are summarised in Table 1and more detail on these models can be found in Appendix B4. A more detailed report on the different constitutive models will be produced in Work Package 3.

Table 1: Modelling approaches used by Beacon partners

Approach	Proponent	Key features	Applications
Double structure framework for unsaturated, expansive clays (Appendix B4.6)	Imperial College	Adopts and expands on the BExM approach.	Good fit to lab scale homogenisation tests.
HBM (Hysteresis Based Material) model (Appendix B4.4)	Clay Tech	Developed for 1D swelling tests in water saturated conditions. Uses Darcy's law. Clay potential Ψ, defined as stress (σ) + suction (s) as a range of values for a given void ratio dependent upon strain history. Shear strength and swelling pressure are based on empirical data.	Good fit to 1D lab scale homogenisation tests.
Elastic plastic cap model (Appendix B4.5)	Clay Tech	Similar idea to the Cam Clay model but has a more complex definition of the yield and failure surface, and the flow rule is not associated at lower stresses and is associated at higher stresses.	Good fit to lab scale homogenisation tests. Good fit to lab scale swelling tests but model underestimated homogenisation in self-sealing experiment.
Thermoelastoplastic laws (TEP) (Appendix 4.12)	Clay Tech	Based on the BBM with updated TEP laws to allow void ratio dependence of swelling	Good fit to lab scale homogenisation tests. Used to analyse TBT; CRT; and Febex in situ test (in progress). It has also been used for HM analyses of the KBS-3H concept (in progress).
Hypoplasticity (Appendix B4.2)	Charles University and Czech Technical University	Based on the Cam Clay model, this is a double structure model	Good reproduction of results from constant hydraulic gradient permeability tests.
Internal Limit Model (ILM) (Appendix B4.10)	Quintessa	Based on the Modified Cam Clay model with empirical relationships to relate dry density, swelling, plastic failure and suction.	Good fit to lab tests from SEALEX experimental programme (stress and displacement). Less good fit to SEALEX field scale experiments, but these experiments didn't perform as expected. Good fit to stress, dry density and water content data from FEBEX-DP.

4 Available Information

4.1 Compiling information into the database

The process for collecting and compiling information into the database involved:

1. Designing a data form to collect appropriate information;
2. Requesting that Beacon partners fill out the data form for any studies they feel could be relevant to Beacon;
3. Collation of the completed data forms into a preliminary database;
4. Discussion of the database at a workshop and definition of additional fields that would aid future selection of experiments for study within Beacon;
5. Request for additional information to complete additional fields in database;
6. Finalisation of the database.

The process relies on the judgement of the Beacon participants as to which experimental datasets may be relevant to Beacon. All the completed data forms that were supplied have been included in Appendix B. Information was also supplied in other formats:

- abstracts to the Beacon kick-off meeting in Lithuania, June 2017;
- a list of experiments on bentonite previously compiled by Andra;
- a brief literature review covering a number of experimental studies.

Where sufficient information was available, new data forms were created from this additional information. For some experiments, however, little information other than the name of the experiment was found to be readily available. These experiments are recorded in the database but most of the data fields are blank.

The data forms can be categorised into forms that describe experiments, forms that describe modelling approaches and forms that describe application of models to experimental studies. The database has been designed to provide information about experiments. Therefore, only the forms that describe experiments have been included as entries in the database, although in a small number of cases, forms that describe application of models to experimental studies have been included in the database where the experiments were not already documented in another form. Different contributors chose to complete the forms at different levels of detail. Some forms collate information from a large number of small experiments, others give more detail on a single experiment. The level of detail has been preserved in the database.

The data forms have been entered into the database in three categories: laboratory experiments, mock-up experiments and in-situ experiments. The laboratory experiments include experiments designed to measure material properties, as well as experiments that simulate scaled-down repository conditions.

4.2 Database fields

The fields in the database (Table 2) were agreed upon in the Beacon WP 2 London workshop (October, 2017) and are designed to help Work Package leaders in WP 3 and WP 5 to pick experiments for consideration during the Beacon project. Each data form has been numbered to allow quick referencing between the database and the data forms. The name of the experiment, and responsible organisation and contact person were recorded so that if further information is required, there is an obvious route to finding it. The dates and duration of the experiment were requested so that users of the database can understand how long ago the experiment was carried out (this might affect data quality and ease of finding all the required information about the experiment), and how long the experiment ran for, which might affect the processes that can be studied using the experiment.

Disposal programmes in different countries and different repository concepts consider different types of bentonite and in different forms (blocks, pellets etc). Information on the type of bentonite was requested so that it is clear which experiments are relevant to programmes in different countries.

The availability of characterisation data for the material properties of the specific type of bentonite used in the experiment is an important criterion for assessing whether the experiment is suitable for use in a modelling exercise within Beacon. Comments on availability of a range of material parameters were requested as well as the opportunity for entering any additional material characterisation data that is available. The scale of the experiment was also requested.

The purpose of the experiment is a useful field in the data form, included to allow provision of context on how and why the experiment was set up and on the types of measurements that were made; this may influence how transferable the data are to studies of bentonite mechanical evolution and homogenisation. As the Beacon project is concerned with how the mechanics of bentonite affects the homogenisation of the bentonite, information on the nature and extent of heterogeneity in related properties within the experiment was requested.

Boundary conditions of experimental systems were requested, including details of the water chemistry used, as this an important consideration.

The availability of key parameters (e.g. water content, dry density) that could be used to understand the mechanics of bentonite evolution was requested, including whether the parameters are measured in both time and space; having both temporal and spatial information is key to understanding how the mass of bentonite is redistributed during resaturation. Information was also requested on the quality of the data, recognising this is a judgement made by the author of the database entry.

Finally, information on the extent to which the experiments have already been modelled has been requested.

Table 2: Agreed list of data fields for database on bentonite experiments.

Field	**Example**
Data form number	e.g. 1.2 (completed by editors)
Name of experiment	e.g. EB, FEBEX
Organisation	e.g. SKB, Andra
Name of contact	e.g. Kate Thatcher
Start and end date	e.g. 30/05/2012 - ongoing
Duration	e.g. 2 months
Bentonite type	e.g. MX-80, Serrata, 70:30 MX-80:sand mixture
Bentonite form	e.g. Blocks, pellets, blocks and pellets
Availability of material parameters	Tick list (Yes-Y or No-N): Swelling pressure, retention curve, shear strength, tensile strength, hydraulic conductivity, microstructure, other
Scale of experiment	e.g. laboratory, URL, mm, cm, m, 10s m
Purpose of experiment	e.g. resaturation, homogenisation
Evidence of heterogeneity	e.g. initial voids, initial density contrast, developing heterogeneity on resaturation
Boundary conditions	e.g. artificially hydrated, fully confined
Water chemistry	e.g. deionised, local groundwater
Data available	Tick list (Yes – Y or No – N): Water content, pore pressure/suction, relative humidity, strain, dry density, stress, other. Also indicate whether initial, final and/or time series available and whether the data is spatial
Data quality	e.g. good quality, unreliable
Modelling	e.g. never modelling, modelled in EBS TF

4.3 Discussion of database contents

The database has largely been completed by Beacon participants with a close connection to the experiments that have been reported. In some cases (those which do not have an identified contact name), entries have been constructed by the authors of this report, from information reported by participants. Not all fields in the database have been completed for all experiments.

Inputs have been received from around 30 organisations covering most of the countries participating in Beacon, as well as some limited information from organisations outside of Europe. The diverse nature of the origin of the information contained in the database is very welcome and indicates that there is likely to be information that is relevant to a wide range of waste disposal organisations.

Information on the dates and duration of the experiments is not complete; the information that is available shows that most experiments have been carried out since the mid-1990s. Thus there is a record of experiments undertaken over the last 20 years. A significant proportion of the most recent experiments are ongoing, or the experimental programme itself is ongoing. Experiment durations range from a few days to many years, with at least 5 experiments lasting more than 10 years.

More than 10 different types of bentonite have been studied in the experiments, with MX-80 being the most commonly reported. A few experiments have been conducted on a range of bentonites, which may allow comparison of the behaviour of different bentonites. Experiments consider bentonite as blocks, pellets and powder and in some cases mixtures of all three.

Information on the availability of material parameters is not complete, but for the majority of cases, swelling pressure information is available for the different types of bentonite. The next most commonly available information categories relate to bentonite hydraulic conductivity values and water retention curves. In some cases, bentonite strength information and information on the microstructure is available, but these data are often not reported.

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 bentonite.

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 boundary conditions on the experiments are a mixture of artificial and natural wetting; all laboratory tests and around half the field tests have artificial wetting, and the remaining field tests have natural resaturation. Most of the experiments are carried out using either artificial or natural groundwaters, the chemistry of which is dependent upon the particular geological setting that is being considered for disposal. A small number of laboratory experiments, designed principally to improve material characterisation of the bentonite, have been performed with deionised water. A small number of laboratory experiments have been conducted with a range of water salinity. Almost all the experiments were carried out under confined / constant volume conditions, and some also had heaters.

Initial and final water content of the bentonite were measured in almost all of the experiments, although final measurements are clearly not yet available where the experiment is on-going. Both time-series data and spatial data on water content are available from around half of the experiments.

Around 75% of the experiments for which information is provided have data on pore pressure or suction, and, where these data are present, it is generally available in both time series and spatially within the bentonite. Relative humidity data are available in around half of the experiments for which information has been provided, generally as time series and in several spatial locations. Strain was measured in around one third of the experiments, whilst these measurements are often time series, there are only a small number of experiments with spatial information on strain. The majority of experiments recorded dry density at the start of the experiment and also provide some information on spatial distribution of dry density, but only a few experiments provide a time series of dry density measurements. Stress was measured in the majority of experiments, in both time series and spatially. There are several experiments that only measured axial stress and not radial stress but there are more experiments that measured both.

Twelve of the datasets contributed to the Beacon project have been identified by the Beacon partners who contributed them as not suitable for modelling in Beacon, due to reasons such as insufficient data coverage or because the experiment was not designed to measure mechanical effects. Around 75% of the experiments for which information is provided are judged to have good or very good data quality.

A large number of the experiments in the database have been modelled previously. Some of this modelling has been undertaken within modelling research programmes (e.g. DECOVALEX, EBS Task Force) and a number of different models and codes have been used to model a single experiment. In other cases, experiments have been modelled by individuals with analytic solutions or scoping calculations. Further details of the modelling have not been included in the database, but the dataforms and references provide links to more details on previous modelling. It would be useful to review previous modelling for the experiments that are considered for modelling tasks in Beacon.

5 Conclusions

This report summarises current understanding and modelling approaches for bentonite mechanics alongside a database of experimental data that are available for modelling studies. The database has been designed and populated as a collaborative effort between the participants of the Beacon project. There are many experiments listed in the database, at a range of scales (from bench top laboratory experiments to full scale field experiments), a small number of which were designed specifically for studies of bentonite homogenisation, but the majority of which were originally designed for other purposes. Nevertheless, these experiments provide a valuable source of information on the mechanical properties of bentonite and the likely mechanical evolution of bentonite within a repository. The database contains information on the type of bentonite considered in the experiments, the boundary conditions and heterogeneities within the experiments and also the range of measurements taken in the experiment. This will allow Beacon partners and especially Work Package leaders to interrogate the database and find experiments of interest for consideration in the Beacon project. Furthermore, knowing experiments that have been undertaken previously, decisions on new experiments to be undertaken within the Beacon project itself can be taken in the light of understanding derived from international work on bentonite derived to date.

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Appendix A: Database derived from forms

Appendix B Reference No	Name/title	Organisation	Name of contact	Start and end dates	Duration	Bentonite type	Bentonite form	Availability of material parameters							Scale	Purpose of experiment	Evidence of heterogeneity	Boundary Conditions	Water Chemistry	Water Content				Pore pressure /suction				Relative humidity				Strain				Dry density				Stress						Other	Data quality	Modelled?
								Swelling	Retention curve	Shear strength	Tensile strength	Hydraulic conductivity	Microstructure	Other						Initial	Final	Time Series	Spatial	Initial	Final	Time Series	Spatial	Initial	Final	Time Series	Spatial	Initial	Final	Time Series	Spatial	Initial	Final	Time Series	Spatial	Initial	Final	Time Series	Spatial	Radial	Axial			
1.1	Analysis of microstructural images of bentonite samples	Hokkaido University													Lab																																	
1.2	Artificial wetting tests	VTT, Posiva	Veli-Matti Pulkkanen	2011-2012	3-57 days	MX-80, (Cebogel pellets in some tests)	Blocks (uniaxially and isostatically compacted), pellets (different types), slurry	Mx-80 (Y)	Mx-80 (Y)	Mx-80 (partially)	Mx-80 (partially)	Mx-80 (Y)	Mx-80 (Y)		Lab (cylinder with 36 cm radius, 39 or 47 cm height)	Swelling and homogenisation of bentonite in downscaled buffer geometry including compacted blocks and different installation gap fillings (pellets, slurry)	Density and water content profiles in post-mortem analyses	Stainless steel chamber, wetting from bottom valve (flooding of the installation gap)	Different water salinities, (tap water, groundwater, groundwater simulants)	Y	Y	N	Y	N	N	N	N	N	N	N	N	N	N	N	N	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	Axial displacement of the top lid	Good	Yes (some tests in the series have been modelled)
1.3	Bentogaz	CEA, Andra	Jean Talandier			MX-80	Blocks (Mx80/ sand mixture)/ pellets (pure MX-80)/ interfaces	Y	Y	Y	Y	Y			Lab	HM-Gas behaviour	Differences in radial and axial responses during hydration	Constant volume cell/slow water saturation	Synthetic Bure water	Y	Y	Y		Y	Y	Y	Y	N	N	N	N	N	N	N	N	Y	Y			Y	Y	Y	Y	Y	Y	Axial swelling pressure, gas transfer	Good (well-defined geometry, material already characterized during ESDRED project. Swelling pressure, liquid and gas pressures recorded)	Yes (for some of them-HM)
1.4	Bentonite homogenisation	BGS	Jon Harrington	3 experiments performed between 01-10-2014 to 02/12/2016	146 – 347 days	MX-80	Single block	Y	N	N	N	Y	N	Complete	Lab (cylindrical sample dimensions: length =120 mm, diameter = 60 mm)	Hydration behaviour of bentonite examining the spatial and temporal development of porewater pressure, stress and permeability	Yes in both stress and porewater pressure data	Constant volume, 1D flow	DI water	Y	Y	N	N	Y	Y	Y	Y	N	N	N	N	N	N	N	N	Y	Y	N	N	Y	Y	Y	Y	Y	Y	Swelling pressure, porewater pressure, permeability	A number of highly instrumented tests have been at different hydraulic gradients. All tests performed under controlled temperature (isothermal) conditions, with inflow (and where appropriate outflow) monitored with time.	Yes (limited)

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								Swelling	Retention curve	Shear strength	Tensile strength	Hydraulic conductivity	Microstructure	Other						Initial	Final	Time Series	Spatial	Initial	Final	Time Series	Spatial	Initial	Final	Time Series	Spatial	Initial	Final	Time Series	Spatial	Initial	Final	Time Series	Spatial	Initial	Final	Time Series	Spatial	Radial	Axial			
1.5	Bentonite re-saturation project	Radioactive Waste Management Funding and Research Centre, SKB	Patrik Sellin	?	164 days	Na Bentonite (Kunigel V1)		Y	N	N	N	N	N		Lab	Homogenization of a block-pellet system	Yes, both in swelling pressure and final dry density	Flooded with water at low head	Distilled water as well as 0.5 M NaCl	Y	Y	Y	N	N	N	N	N	N	N	N	N	N	N	N	N	Y	Y	N	Y	Y	Y	Y	Y	Y	N	Swelling pressure, resistivity	Good (well-defined geometry, THM material characterisation, large number of sensors to follow HM evolution, has not been used before as benchmark)	Yes (scoping calculations)
1.6	Block-pellet homogenization in KBS-3V buffer	Posiva	Veli-Matti Pulkkanen			MX-80									Lab																					Y	Y		Y							Swelling pressure		
1.7	Buffer homogenisation project	Clay Technology AB, SKB	Mattias Åkesson/Ann Dueck	2008 to now	months - 2.5 years	MX-80, Calcigel	Blocks (block and powder - only Calcigel)	Y						Friction*	Lab (cm-dm)	Study the homogenisation processes	Initial voids, initial density contrast	Confined conditions	De-ionized water	Y	Y	N	Y	Y	Y	Y	N	N	N	N	N					Y	Y	N	Y	Y	Y	Y	Y	Y	Y		Good (small scale, simple geometries, well defined boundary conditions, suitable for modelling)	Yes (HM)
1.8	Centrifuge physical modelling test	CRIEPI				Na Bentonite									Lab experiment using																	Y	Y	Y	Y													Yes (THM)
1.9	Characterization of material properties	Clay Technology AB, SKB	Mattias Åkesson/Ann Dueck	1995-2013	weeks - months	MX-80	Blocks or powder	Y	Y	Y				*	Lab (compilation) (cm-dm)	Compile material model parameters for HM modelling		Mainly confined conditions	De-ionized water	Y	Y	N	N	N	N	N	N	N	N	N	N					Y	Y	N	N	Y	Y	N	N	Y	Y	Oedometer tests considered only	Good (suitable for characterization, evaluation of model parameters and modelling)	No

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								Swelling	Retention curve	Shear strength	Tensile strength	Hydraulic conductivity	Microstructure	Other						Initial	Final	Time Series	Spatial	Initial	Final	Time Series	Spatial	Initial	Final	Time Series	Spatial	Initial	Final	Time Series	Spatial	Initial	Final	Time Series	Spatial	Initial	Final	Time Series	Spatial	Radial	Axial			
1.10	Clay hydration characterisation using microfocus x-ray CT	SCK-CEN													Lab																																	
1.11	CTU lab experiments	CTU	Jiří Svoboda			Ca-Mg	Blocks, Pellets, Powder	Y	Y				? Y		Lab - cylinder d=30mm (or 120mm), h=20mm	Permeability and swelling pressure measurement in constant volume cell	Pellet samples; Heterogenous samples (dual density) planned as part of other WP	Artificial saturation, constant volume cell	Distilled water or Natural ground water (Josef URL)	Y	Y	N										N	N	N	N	Y	Y	N	N	Y	Y	Y	N	N	Y	Swelling pressure. Spatial dry density can be measured in future tests.	Good (great calibration and validation tool for material models. Highly controlled boundary conditions and well defined material.)	Yes (some of them)
1.12	CUNI laboratory test	Charles University	David Mašín			B75 Czech Ca-Mg		Y	Y	N	N	Y	Y		Lab	Swelling under constant load, free swelling experiments, oedometric compression curves	Element tests, no heterogeneities	Oedometric	Natural groundwater	Y	Y											Y	Y	Y	N	Y	Y	Y	N	Y	Y	Y	N	N	Y		Good	Yes (intermediate model calibration, not all data available yet, calibration to be finalised)
1.12	CUNI laboratory test	Charles University	David Mašín			B75 Czech Ca-Mg		Y	Y	N	N	Y	Y		Lab	Vapour equilibrium water retention curves	Element tests, no heterogeneities	zero stress	Natural groundwater	Y	Y	Y		Y	Y	Y		Y	Y	Y		Y	N	Y	N	Y	Y	Y	N	Y	Y	Y	N	Y	Y		Good	Yes (intermediate model calibration, not all data available yet, calibration to be finalised)

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								Swelling	Retention curve	Shear strength	Tensile strength	Hydraulic conductivity	Microstructure	Other						Initial	Final	Time Series	Spatial	Initial	Final	Time Series	Spatial	Initial	Final	Time Series	Spatial	Initial	Final	Time Series	Spatial	Initial	Final	Time Series	Spatial	Initial	Final	Time Series	Spatial	Radial	Axial			
1.13	Effects of heterogeneities on the hydromechanical behaviour of bentonite	Andra	Jean Talandier			MX-80	pellets/ blocks	Y	Y	Y	Y	Y	Y		Lab	HM-Gas behaviour	heterogeneities in pellets mixture + initial voids															Y	Y	Y	N		Y	N										Yes
1.14	Experimental characterization of cement bentonite interaction	University of Bern				MX-80									Lab																																	
1.15	FORGE	Clay Technology AB, SKB	Mattias Åkesson/Ann Dueck	2009-2013	days - weeks	MX-80, Wyoming Na/ Ca	Blocks or powder	Y				Y		*	Lab (mm-cm)	Study response in bentonite due to external fluid/gas pressurization	Density re-distribution in compacted bentonite	Controlled pressurized fluid/gas, confined conditions	Water (initially de-ionized)	Y	Y	N	N	Y	Y	Y	N	N	N	N	N					Y	Y	N	Y	Y	Y	Y	N	N	Y	Gas transfer	Good (small scale, simple geometries, well-defined boundary conditions so tests with applied water pressures suitable for modelling)	Yes (analytical)
1.16	FSS laboratory tests+mock-up	CEA, Andra	Jean Talandier			WH2 MX-80	Pellets	Y	Y	Y	Y	Y			Lab/ mock-up	HM-Gas behaviour	Initial dry density variable	Slow water flow to saturate	Synthetic Bure water/cementeous water	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	N	N	N	Y	Y			Y	Y	Y	Y	Y	Y	Swelling pressure	good (data available at several scales from few centimeters to meter scale)	No
1.17	Gas release of bentonites	GRS	Klaus Wieczorek	Jan. 2015, ongoing	3 years (planned)	Various	Bentonite powder	N	N	N	N	N	N		Lab	Quantify gas release capacity and verify origin of released gases for 15 bentonites	No	Powder and solution in gastight containers at 120 °C, fully confined	Diluted caprock solution, 150 g/l salinity	Y	Y	Y	N	Y	Y	Y	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	Temperature, gas pressure, swelling pressure (post-	Not applicable for Beacon purposes	No
1.18	Microstructure and anisotropic swelling behaviour of	IRSN, Laboratoire Navier				MX-80									Lab																																	

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								Swelling	Retention curve	Shear strength	Tensile strength	Hydraulic conductivity	Microstructure	Other						Initial	Final	Time Series	Spatial	Initial	Final	Time Series	Spatial	Initial	Final	Time Series	Spatial	Initial	Final	Time Series	Spatial	Initial	Final	Time Series	Spatial	Initial	Final	Time Series	Spatial	Radial	Axial			
1.19	Microstructure of saturated bentonites	Hokkaido University				?									Lab																																	
1.20	Physico-chemical controls on initiation and evolution of desiccation cracks	University of California				?									Lab																																	
1.21	Re-saturation of bentonites	GRS	Klaus Wieczorek	Oct. 2001 - Sep. 2003	25 months	MX-80	Compacted powder	N	N	N	N	N	N		Lab	Gather detailed data on the transient water content distribution in the bentonite	No	Artificial saturation, ambient temp., fully confined	Äspö solution	Y	Y	Y	Y	N	N	N	N	N	N	N	N	N	N	N	N	Y	N	N	N	N	N	N	N	N	N		Good - but no mechanical data	Yes
1.22	SB (laboratory tests)	GRS, Nagra	Klaus Wieczorek	Jan. 1995 - Dec. 2007		Calcigel	Granular sand/bentonite mixture	Y	N	N	N	Y	N		Lab	Qualify sand/bentonite mixtures as material for engineered barriers			Pearson water																											gas breakthrough pressure		Yes
1.23	SEALEX laboratory tests	IRSN				MX-80	Powder and pellets								Lab					Y	Y	Y	N	Y	Y	Y	Y													Y	Y	Y		Y	Y			Yes
1.24	Sealing Site Investigation Boreholes Phase II: laboratory program	Clay Technology AB, RWM	Mattias Åkesson/Ann Dueck	2016	weeks - months	Wyoming Na, MX-80	Blocks or powder	Y				Y		*	Lab (cm)	Study impact of different saline solutions on swelling pressure and hydraulic conductivity		Controlled saline conditions, confined conditions	De-ionized water and saline solutions with different ions and strength	Y	Y	N	N	N	N	N	N	N	N	N	N					Y	Y	N	N	Y	Y	Y	N	N	N	Hydraulic conductivity, swelling pressure	Good (small scale, simple geometry, well-defined boundary conditions with different cat ions and ion strengths, suitable for MC modelling)	No

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								Swelling	Retention curve	Shear strength	Tensile strength	Hydraulic conductivity	Microstructure	Other						Initial	Final	Time Series	Spatial	Initial	Final	Time Series	Spatial	Initial	Final	Time Series	Spatial	Initial	Final	Time Series	Spatial	Initial	Final	Time Series	Spatial	Initial	Final	Time Series	Spatial	Radial	Axial			
1.25	Swelling pressure development of compacted	LEMTA, BRGM, LIEC	Jean Talandier			Kunipia-G	block	Y	Y			Y	Y		Lab	Microstructure evolution on wetting path			Aqueous solutions with different ionic strength	Y	Y	Y	Y													Y	Y											Yes
1.26	Swelling pressure material test	CRIEPI				Na-type + Ca-type									Lab					Y	Y	N	N	Y								Y	Y		N											Swelling pressure		No
1.27	THEBES	JyU, Aalto University	Markku Kataja	1.2.2015-ongoing	4	MX-80 + purified (BP Biomedicals)	Small scale samples compacted from powder	Y	N	N	?	Y	N		Lab	Non-intrusive measurement of time evolution of dry density and water content for model validation purposes.	Sample heterogeneity directly measured	Simple	NaCl solution	Y	Y	Y	Y	N	N	N	N	N	N	N	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	Y		Good (Time series data of strain (displacement), dry density and water content inside the sample during wetting process)	Yes. Modelling efforts ongoing.
1.28	Transu	Posiva Oy, Saanio & Riekkola Oy	Veli-Matti Pulkkanen	2011	32-133 days	MX-80	Compacted blocks, pellets	Mx-80 (Y)	Mx-80 (Y)	Mx-80 (partially)	Mx-80 (partially)	Mx-80 (Y), Ibeco RWC (Y)	Mx-80 (Y)		Lab	Study of saturation behaviour of buffer	Initial density heterogeneity between block and pellets	Artificial hydration	?	Y	Y	Y	Y	Y	Y	Y	Y	N	N	N	N	Y	Y	Y	Y	N	N	N	Y	Y	Y	Y	Y	Y	Y			
1.29	Water retention behaviour of compacted bentonites	Andra	Jean Talandier			Various	Pellets								Lab																									Y	Y	Y	Y	Y	Y			Yes
1.30	X-Boy	Posiva Oy, Saanio & Riekkola Oy	Veli-Matti Pulkkanen	2010-2011	69-122 days	MX-80	Compacted blocks, pellets	Mx-80 (Y)	Mx-80 (Y)	Mx-80 (partially)	Mx-80 (partially)	Mx-80 (Y), Ibeco RWC (Y)	Mx-80 (Y)		Lab	Study of early saturation behaviour of buffer	Initial density heterogeneity between block and pellets	Artificial hydration	?	Y	Y	Y	Y	N	N	N	N	N	N	N	N	N	N	N	N	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	Temperature		
1.31	X-ray CT visualization of a clay liner	Kumamoto University				Na bentonite	Granular								Lab					Y	Y	Y		N	N	N	N					N	N	N	N					N	N	N	N	N	N	Temperature		

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								Swelling	Retention curve	Shear strength	Tensile strength	Hydraulic conductivity	Microstructure	Other						Initial	Final	Time Series	Spatial	Initial	Final	Time Series	Spatial	Initial	Final	Time Series	Spatial	Initial	Final	Time Series	Spatial	Initial	Final	Time Series	Spatial	Initial	Final	Time Series	Spatial	Radial	Axial			
2.1	BBI	VTT, Posiva	Veli-Matti Pulkkanen	5.5.2015-6.7.2015	2 months	MX-80, Ibeco RWC, Cebogel	Blocks, pellets	Mx-80 (Y)	Mx-80 (Y)	Mx-80 (partially)	Mx-80 (partially)	Mx-80 (Y), Ibeco RWC (Y)	Mx-80 (Y)		Lab (1/6 scale)	Interaction between the buffer and the backfill, formation of flow paths, erosion	Density and water content profiles in post-mortem analyses, flow channels	Single point-wise water inlet in buffer, flow rate 0.1 l/min, several water outlets in backfill, plexi-glass walls in steel frame, isothermal conditions (ambient temperature)	Salinity of 1 % (NaCl solution)	Y	Y	N	Y	N	N	N	N	N	N	N	N	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	Water sampling at outlet (eroded mass), video monitoring of flow paths, wetting patterns	Good	No
2.2	FEBEX mock up	CIEMAT	María Victoria Villar	Feb-97	>18 years	FEBEX	Blocks	Y	Y			Y	Y	Solid & pore water chemical composition	Mock up (large-scale test)	Research on bentonite barrier behaviour	RH and P sensors	Artificial saturation, two reduced-scale heaters	Granitic low-salinity	Y		N	N	Y	Y	Y	Y	Y	Y	Y	Y			N	N	Y		N	N	Y	Y	Y	Y	Y	Y	Temperature	Very good	Yes
2.3	Mock-up-CZ	CTU	Jiří Svoboda			Czech Ca-Mg + sand + graphite	Blocks, Powder	Y	N (Febex or B75 can be used instead)	Y		Y	?Y		Mock up (lab test)	Halfscale deposition place test	Initial void, Blocks and Powder parts	Artificial saturation	Artificial granitic	Y	Y	Y	Y									N	N	N	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Swelling pressure, temperature, mineralogical changes, corrosion	Good (finished, comprehensive analysis of final state, geometry and boundary conditions clearly defined, rich dataset for input/ benchmarking/verification of models)	Yes (limited, no fully coupled analysis)
2.4	OPHELIE	EURIDICE, NIRAS/ONDRAF	Geert Volckaert			Fo Ca	bentonite precompacted blocks	Y				Y			Large scale mock-up	simulation of real HLW disposal "old design"		imposed hydraulic and thermal boundaries	controlled	Y	Y	Y	N		Y	Y	Y					Y	Y	Y	Y	Y	Y	N								Temperature	Good (well-characterised, many sensors, has been dismantled)	Yes (THM, 1D)
2.5	REM	Andra		2014-ongoing	ongoing	MX-80	powder/ pellets								Surface experiment	Study the water saturation of pellet/powder mixture of FSS	(Relatively homogeneous mixture)	Artificial saturation, confined in cylinder	?	Y	-	Y	N	Y	-	Y	Y	Y	-	Y	Y	N	N	N	N											Total pressure, temperature	Good (well-defined geometry, material HM characterised, large no. of sensors)	Yes (H, code_bright)

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								Swelling	Retention curve	Shear strength	Tensile strength	Hydraulic conductivity	Microstructure	Other						Initial	Final	Time Series	Spatial	Initial	Final	Time Series	Spatial	Initial	Final	Time Series	Spatial	Initial	Final	Time Series	Spatial	Initial	Final	Time Series	Spatial	Initial	Final	Time Series	Spatial	Radial	Axial			
2.6	SB (mock up)	GRS, Nagra	Klaus Wieczorek	Jan. 1995 - Dec. 2007		Calcigel	Granular sand/bentonite mixture	Y	N	N	N	Y	N		Mock up	Qualify sand/ bentonite mixtures as material for engineered barriers	not at full saturation	Artificial saturation, ambient temp.	Pearson water																												Limited (only deals with sand-bentonite mixtures)	
3.1	40% scale buffer tests	VTT, Posiva	Veli-Matti Pulkkanen	Test 1: Nov '11-Sep '13, Test 2: Nov '11-ongoing	Test 1: 22 months, Test 2: ongoing (status 3.11.17, >6 year)	MX-80	Blocks, pellets	Mx-80 (Y)	Mx-80 (Y)	Mx-80 (partially)	Mx-80 (partially)	Mx-80 (Y), Ibeco RWC (Y)	Mx-80 (Y)		URL (40% scale)	In-situ buffer demonstration at early state, distribution of heat, rate of saturation from the pellet-filled gap to the middle of the buffer block, artificial watering effects, piping and erosion, swelling and buffer uplift.	Test 1: density and water content profiles in post-mortem analyses	Test 1: natural water inflow through bedrock fractures, test 2: artificial wetting (inflow rate 8-10 l/min), heater (up to 90 degC), natural bedrock surrounding the buffer	Test 1: natural groundwater, Test 2: salinity of 10-12 g/l TDS (natural groundwater)	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	Temperature, swelling pressure	Good	No
3.2	BACCHUS I	CEA/DRDD, ANDRA, ONDRAF/NIRAS				Fo Ca									URL					Y	Y	Y	N	Y	Y	Y	Y					N	N	N	N											Swelling pressure, temperature	Good but ended suddenly	Yes
3.3	BACCHUS II	SKN/CEN, ENRESA, ANDRA, CEA				Fo Ca									URL					Y	Y	Y	N	Y	Y	Y	Y					N	N	N	N											Temperature, thermal conductivity		
3.4	BRIE	Clay Technology AB, Chalmers University of Technology, SKB	Mattias Åkesson			MX-80									URL																																Not suitable for mechanical modelling in Beacon (experiment designed to minimise influence of mechanical processes)	Yes

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3.5	CRT	SKB	Mattias Åkesson/ Ann Dueck	1999-2005	5 year	MX-80	Blocks and pellet	Y		Y		Y			Full scale field experiment	To demonstrate technique for retrieving emplaced canisters and to monitor processes during the operational phase	Initial inner slot, initial outer gap with pellet	Artificially hydrated, heater, confined condition	Äspö local groundwater	Y	Y	N	N	Y	Y	Y	Y	Y	Y	Y	Y					Y	Y	N	Y	Y	Y	Y	Y	N	Y	Temperature	Good (well-defined geometry, defined boundary conditions, initial conditions, water uptake and final conditions measured accurately)	Yes
3.6	DOPAS EPSP	CTU, SURAO	Jiří Svoboda			B75 Czech Ca-Mg	Pellets	Y	Y				? Y		Mock up (in situ)	Repository plug test	Voids between pellets, Two types of pellets deposition	Artificial and natural saturation	Natural groundwater	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	N	N	N	Y				Y	Y	Y	Y	Y	Y		Good (can serve as a benchmarking tool, provides data on transient effects and gradual saturation of pellets)	Yes (limited, not fully coupled)
3.7	EB	Enresa, CIEMAT	Antonio Gens	2002-2013	10.5 years	Serrata	Pellets and Blocks	Y	Y	N	N	Y	Y		Full scale field experiment	Study of the hydration of a possible EBS design	Both pellets and blocks used in the same EBS section	Artificial hydration	?	Y	Y	N	Y	N	N	N	N	Y	Y	Y	N	N	N	N	N	Y	Y	N	Y	N	N	Y	N	Y	N	Swelling pressure	Probably suitable as dismantling data available. Artificial hydration process not well controlled	Yes (HM)
3.8	FE (Full-scale Emplacement)	Nagra	Olivier Leupin			Na Bentonite									URL					Y	Y	Y	Y	Y	Y	Y	Y					Y	Y	Y	Y											Temperature, swelling pressure, geophys,	Good (initial conditions well-documented, ongoing measurements of material properties evolution)	Yes
3.9	FEBEX in situ	Enresa	María Victoria Villar	Feb-97	18 years	FEBEX	Blocks	Y	Y			Y	Y	Solid & pore water chemical composition	Full scale	Demonstration and study of near-field components	Y	Natural saturation, two full-scale heaters	Natural granitic groundwater	Y	Y	N	Y	Y	Y	Y	Y	Y	limited	limited	limited			N	N	Y	Y	N	N	Y	Y	Y	limited	limited	limited	Temperature	Good, but limited in final stages	Yes
3.10	GAST	ANDRA, KORAD, Nagra, NWMO	Olivier Leupin			MX-80									Large scale					Y	Y	Y	Y									N	N	N	N											Geophysical measurements	Good but ongoing (initial conditions well documented, mock-up experiment allows for detailed studies, ongoing geophysical measurements)	Yes

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								Swelling	Retention curve	Shear strength	Tensile strength	Hydraulic conductivity	Microstructure	Other						Initial	Final	Time Series	Spatial	Initial	Final	Time Series	Spatial	Initial	Final	Time Series	Spatial	Initial	Final	Time Series	Spatial	Initial	Final	Time Series	Spatial	Initial	Final	Time Series	Spatial	Radial	Axial			
3.11	HE-B	BGR, ENRESA, GRS, NAGRA	Klaus Wieczorek	May 1999 - Dec. 2003	Saturation: 34 months, heating: 18 months	Serrata	Blocks	Y	Y	Y	Y	Y	Y		URL	Study of THM properties in the near field of a heat source	higher dry density / lower water content close to heater	Artificial saturation, max. temp. 100 °C, initial gaps heater/block and blocks/rock	Pearson water	Y	Y	Y	Y	N	N	N	N	Y	N	N	N	N	N	N	N	Y	Y	N	Y	Y	N	N	N	N	N	Gas, geotechnical measurements	Not great (most instruments immediately failed so limited data, leak in injection system)	Yes
3.12	HE-E	NAGRA, GRS, BGR, ENRESA	Klaus Wieczorek	June 2011, ongoing	ongoing	MX-80	Blocks and granular	Y	Y	N	N	Y	N		URL	Investigate early non-isothermal re-saturation period of the buffer and its impact on the THM behaviour	initially two buffer types (blocks/granular) with different density	Natural saturation, max. temp. 140 °C	Opalinus clay water	Y	N	N	N	Y	Y	Y	Y	Y	Y	Y	Y	N	N	N	N	Y	N	N	N	N	N	N	N	N	N	Seismicity, resistivity, temperature	Potentially interesting (ongoing, heterogeneities evolving, but missing data since it has not been dismantled yet)	Yes
3.13	ITT	AECL				MX-80									Large scale in situ						Y	N	Y									Y	Y	Y	N		Y	N	Y	Y	Y	Y	Y					Yes (HM)
3.14	LASGIT	SKB, Posiva, BGS	Jon Harrington	01/02/2005	ongoing	MX-80	Blocks and pellets	Y	N	N	N	Y	N		Field scale mock up	Hydration of the clay and subsequent gas migration behaviour	Yes in the time-dependent development of porewater pressure, stress, suction, canister movement and gas flow behaviour	In-situ test in an Äspö deposition hole, capped with a concrete plug and retaining steel lid which itself is rock anchored to floor.	Combination of in-situ water and local tap water have been used at different times in the experiment	Y	N	N	N	Y	N	Y	Y	Y	N	Y	Y	Y	N	Y	N	Y	N	N	N	Y	N	Y	Y	Y	Y	Swelling pressure, porewater pressure, temperature, suction, permeability, displacement	Good (high level of instrumentation, detailed initial characterization of host rock and bentonite => well defined boundary conditions) Ongoing so spatial data not currently available. Strain data relates to measured displacement of the canister and deformation of the steel retaining lid.	Yes (limited)

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								Swelling	Retention curve	Shear strength	Tensile strength	Hydraulic conductivity	Microstructure	Other						Initial	Final	Time Series	Spatial	Initial	Final	Time Series	Spatial	Initial	Final	Time Series	Spatial	Initial	Final	Time Series	Spatial	Initial	Final	Time Series	Spatial	Initial	Final	Time Series	Spatial	Radial	Axial			
3.15	LIT	CFM Project (GTS Phase IV experiment)	Bill Lanyon	12/05/2014	Until early 2018	Serrata	16 2.5cm high rings (1.65 g/cm3) Inner diameter 43mm outer 82 mm	Y							In situ	Colloid formation and migration	Uneven axial load	Confined in borehole interval	GGW Natural groundwater	Y	-	-	-	Y		Y	Y									Y	-	-	Y	Y	Y	Y	Y		Y	Swelling pressure, erosion, tracer		No
3.16	MCJ	SURAO / CTU	Jiří Svoboda			B75 Czech Ca-Mg	Blocks	Y	Y	Y		Y	? Y		Field-scale (half-scale)	Half-scale deposition place in-situ test	Initial voids	Natural saturation	Natural groundwater	Y	N	Y	Y					Y	N	Y	Y	N	N	N	N	Y	Y	Y	N	Y	N	Y	Y	Y	Y	Temperature		No
3.17	NSC	Andra	Jean Talandier			MX-80	Bricks (Mx80/ sand mixture)/ pellets	Y	Y			Y			Field scale (half-scale)	Water saturation/hydraulic tests at field scale	Initial void, initial dry density distribution	Artificial water injection/direct contact with host rock	Water from Bure site	Y	N	N	N	Y	N	Y	Y	Y	N	Y	Y	N	N	N	N	Y	N	N	Y	Y	N	Y	Y	Y	Y	Swelling pressure, EDZ transmissivity	Good (well-defined geometry, initial THM characterisation of all materials involved, large number of sensors monitoring HM evolution, heterogeneities, not used as a benchmark/ modelling exercise before)	Yes (scoping calculations)
3.18	PGZ2	Andra	Jean Talandier			MX-80	Blocks (MX-80/ sand mixture)/ pellets (MX-80)	Y	Y	Y	Y	Y			In situ (borehole test)	Water saturation/gas transfer	initial void + heterogeneous distribution of total pressure	Natural re-saturation/direct contact with host rock	Water from Bure site	Y	N	N	N	Y	Y	Y	Y	N	N	N	N	N	N	N	N	Y	N	N	N	Y	N	Y	Y	N	Y	Gas transfer		Yes
3.19	PRACLAY	EURIDICE	Robert Charlier	01/01/2010	15 years	MX-80	Blocks	Y	Y	N	N	y	N		Full scale	Seal for a heating experiment with increase of pore pressure	divergence of stresses measured in different points	artificial and natural hydration, constant volume swelling, complex shape		Y	N	N	N	Y	N	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	N	N	N	Y	N	Y	Y	Y	Y	Temperature, swelling pressure	Good (well-characterized bentonite, lots of sensors, strong THM coupling, could be considered as a special in-situ test)	Yes (blind)

Appendix B Reference No	Name/title	Organisation	Name of contact	Start and end dates	Duration	Bentonite type	Bentonite form	Availability of material parameters							Scale	Purpose of experiment	Evidence of heterogeneity	Boundary Conditions	Water Chemistry	Water Content				Pore pressure /suction				Relative humidity				Strain				Dry density				Stress						Other	Data quality	Modelled?
								Swelling	Retention curve	Shear strength	Tensile strength	Hydraulic conductivity	Microstructure	Other						Initial	Final	Time Series	Spatial	Initial	Final	Time Series	Spatial	Initial	Final	Time Series	Spatial	Initial	Final	Time Series	Spatial	Initial	Final	Time Series	Spatial	Initial	Final	Time Series	Spatial	Radial	Axial			
3.20	Prototype	SKB	Mattias Åkesson/Ann Dueck	II: 2003-2011 (I: 2001 - ongoing)	8 years	MX-80 and Milos (backfill)	Blocks, pellets and bentonite/crushed rock (backfill)	Y		Y		Y			Full scale field experiment	To gain experience in designing and constructing a repository in crystalline rock, and to test engineered barriers	Initial inner slot, initial outer gap with pellet, developing heterogeneity on re-saturation.	Natural hydration from the host rock, heater, confined condition	Äspö local groundwater	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	Y	Y					Y	Y	N	Y	Y	Y	Y	Y	N	Y	Temperature	Good (rock and bentonite well characterised)	Yes (THM)
3.21	RESEAL II	SCK-CEN	Antonio Gens	1999-2007	8 years	Fo Ca	Pellets + Powder	Y		N	N		Y		Lab + URL	Study of a seal hydration	Local heterogeneity: powder pellets	Artificial hydration		Y	N	N	N	Y	Y	Y	N	Y	Y	Y	N	N	N	N	N	N	N	N	N	Y	Y	Y	N	Y	Y		Good well-defined geometry and hydration b.c. Limited number of sensors. Not dismantled	Yes (HM)
3.22	SB (in situ)	GRS, Nagra	Klaus Wieczorek	Jan. 1995 - Dec. 2007	13 years	Calcigel	Granular sand/bentonite mixture	Y	N	N	N	Y	N		In situ	Qualify sand/bentonite mixtures as material for engineered barriers	not at full saturation	Artificial saturation, ambient temp.	Pearson water	Y	Y	N	Y	Y	Y	Y	Y	N	N	N	N	N	N	N	N	Y	Y	N	Y	Y	Y	Y	Y	N	N			
3.23	SEALEX	IRSN	?	2012	ongoing	MX-80 sand mixture	blocks	Y	Y	?	?	?	?		In situ	Testing different ways to make seals	Technological void around blocks	Artificial saturation	?					Y	Y	Y	Y	Y	Y	Y	Y									Y	Y	Y	Y	Y	Y			Yes (decovalex)
3.24	TBT	ANDRA, SKB, Clay Technology AB	Mattias Åkesson			MX-80									URL																																Not suitable for mechanical modelling in Beacon (high temperature)	Yes

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								Swelling	Retention curve	Shear strength	Tensile strength	Hydraulic conductivity	Microstructure	Other						Initial	Final	Time Series	Spatial	Initial	Final	Time Series	Spatial	Initial	Final	Time Series	Spatial	Initial	Final	Time Series	Spatial	Initial	Final	Time Series	Spatial	Initial	Final	Time Series	Spatial	Radial	Axial			
4.6	Oedometer compression	CIEMAT	Villar	published 2005	1072 days	MX-80	compacted in the cell		Y			Y		1D compression & swelling coefficients	Lab	Characterisation for MX-80 bentonite as part of the Prototype repository project.	no	laterally confined swelling in oedometer+ load at constant suction	unknown	Y	Y					Y								Y				Y							Y		ok	Useful for calibrating a constitutive model
4.6	Isotropic cell compression	ENPC	Tang	published 2008	unknown	MX-80	compacted in the cell							isotropic compression & swelling coefficients	Lab	Investigate isotropic behaviour under mechanical, hydraulic and thermal loads. Thermal effects are not modelled.	no	laterally unconfined swelling in isotropic cell + loading at constant suction	unknown	Y				Y	Y											Y										mean stress, void ratio in time	ok	Useful for calibrating a constitutive model
	BPT					MX-80																																										
	GMT					Serrata																																										
	KEY					MX-80																																										
	LOT					MX-80								?																																		
	ABM	SKB, Posiva, Clay Technology AB	Mattias Åkesson			11 types																																									Not suitable for mechanical modelling in Beacon (focussed on mineralogical stability)	
	LpHSP					Serrata																																										
	BMT					MX-80																																										
	S&TP					MX-80																																										
	EZ-A					MX-80																																										
	BCE	AECL				Na Bentonite																																										

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								Swelling	Retention curve	Shear strength	Tensile strength	Hydraulic conductivity	Microstructure	Other						Initial	Final	Time Series	Spatial	Initial	Final	Time Series	Spatial	Initial	Final	Time Series	Spatial	Initial	Final	Time Series	Spatial	Initial	Final	Time Series	Spatial	Initial	Final	Time Series	Spatial	Radial	Axial			
	TSX	AECL				Kunigel V1									Full scale																																	
	CSE					Kunigel V1									?																																	
	ESP	AECL				Kunigel V1 + MX-80									Full scale																																	
	RESEAL I					Fo Ca + Serrata									Lab																																	Yes
	CHINA mock up					GMZ																																										
	KENTEX					Jinmyeong Mine																																										
	BIG-BEN	CLAY (SKB), CNWRA (NRC), KPH				Kunigel V1									Large scale lab																																	
	KISE					OT-9607																																										

Appendix B: Data forms and references

Appendix Reference Number	Name of Experiment / Modelling Study	Key References
Section 1: Laboratory experiments (small scale)		
B1.1	Analysis of microstructural images of bentonite samples	Tomioka et al., 2010.
B1.2	Artificial wetting tests	Holt et al., 2011.
B1.3	Bentogaz	Dridi et al., 2016.
B1.4	Bentonite homogenisation	Harrington et al., 2010.
B1.5	Bentonite re-saturation project	Kobayashi, 2017.
B1.6	Block-pellet homogenization in KBS-3V buffer	Dueck et al., 2016.
B1.7	Buffer homogenisation project	Dueck et al., 2017.
B1.8	Centrifuge physical modelling test	Nishimoto, 2011.
B1.9	Characterization of material properties	Dueck et al., 2010.
B1.10	Clay hydration characterisation using microfocus x-ray CT	Van Geet et al., 2005.
B1.11	CTU laboratory experiments	-
B1.12	CUni laboratory test	Sun et al., 2017.
B1.13	Effects of heterogeneities on the hydromechanical behaviour of bentonite	Saba, 2013.
B1.14	Experimental characterization of cement-bentonite interaction	Dolder, 2015.
B1.15	FORGE	Birgersson, 2014.
B1.16	FSS laboratory tests	Bernachy-Barbe et al., 2017.
B1.17	Gas release of bentonites	Jockwer et al., 2008.
B1.18	Microstructure and anisotropic swelling behaviour of compacted bentonite/sand mixture	Saba et al., 2014a.
B1.19	Microstructure of saturated bentonites characterized by x-ray CT	Kawaragi et al., 2009.
B1.20	Physicochemical controls on initiation and evolution of desiccation cracks	Gebrenegus et al., 2011.
B1.21	Re-saturation of bentonites	Kröhn, 2011.
B1.22	SB (laboratory tests)	Rothfuchs et al., 2012.
B1.23	SEALEX laboratory tests	Guerra et al., 2016a.
B1.24	Sealing Sit Investigation Boreholes Phase II:	-

	laboratory programme	
B1.25	Swelling pressure development of compacted bentonite	Yigzaw et al., 2016.
B1.26	Swelling pressure material test	Tanaka, 2011.
B1.27	THEBES	Harjupatana et al., 2015.
B1.28	Transu tests	Pintado et al., 2013.
B1.29	Water retention behaviour of compacted bentonites	Gatabin et al., 2016.
B1.30	X-boy tests	Pintado et al., 2013.
B1.31	X-ray CT visualization of a clay liner	Mukunoki et al., 2016.
Section 2: Mock-up experiments (medium scale)		
B2.1	BBI	-
B2.2	FEBEX mock up	Lanyon et al., 2013.
B2.3	Mock-up-CZ	Svoboda et al., 2010.
B2.4	OPHELIE	Van Humbeeck et al., 2009.
B2.5	REM	Conil et al., 2016.
B2.6	SB (mock up)	Rothfuchs et al., 2012.
Section 3: In situ experiments (large scale)		
B3.1	40% scale buffer tests	Hakola et al., 2015.
B3.2	BACCHUS I	Neerdael et al., 1992.
B3.3	BACCHUS II	Volckaert et al., 1996.
B3.4	BRIE	Fransson et al., 2014.
B3.5	CRT	Kristensson et al., 2015.
B3.6	DOPAS EPSP	Svoboda et al., 2016.
B3.7	EB	Mayor et al., 2014.
B3.8	FE	Müller et al., 2017.
B3.9	FEBEX in situ	ENRESA, 2006.
B3.10	GAST	Spillman et al., 2016.
B3.11	HE-B	Göbel et al., 2007.
B3.12	HE-E	Gaus et al., 2014.
B3.13	ITT	Priyanto et al., 2008.
B3.14	LASGIT	Cuss et al., 2008.
B3.15	LIT	Fernandez et al., 2005.
B3.16	Mock up Josef	Šťástka et al., 2017.
B3.17	NSC	de la Vaissière, 2014a.
B3.18	PGZ2	De La Vaissière, 2014b.
B3.19	PRACLAY	Dizier et al., 2016.
B3.20	Prototype	Johannesson, 2014.
B3.21	RESEAL II	Gens et al., 2009.
B3.22	SB	Wieczorek et al., 2017.
B3.23	SEALEX	Mokni et al., 2016.
B3.24	TBT	Åkesson, 2012.
Section 4: Modelling studies		
B4.1	BAT	Leoni et al., 2017.

B4.2	Development of THM model for expansive soils	Mašín, 2014.
B4.3	EBS Taskforce: Sensitivity and Code Comparison Task	Schäfers et al., 2017.
B4.4	EBS Taskforce: Homogenization Task – HBM model description	Åkesson, 2017.
B4.5	EBS Taskforce: Homogenization Task – Plastic Cap model	Börgesson et al., 2014.
B4.6	G. Ghiadistri PhD research: Expansive Model	Georgiadis et al., 2005.
B4.7	G. Ghiadistri PhD research: OED-ISO Calibration Tests	Georgiadis et al., 2005.
B4.8	G. Ghiadistri PhD research: TX Calibration Test	Georgiadis et al., 2005.
B4.9	G. Ghiadistri PhD research: EBS Validation Test	Georgiadis et al., 2005.
B4.10	ILM	Thatcher et al., 2016.
B4.11	Numerical evaluation on the bentonite re-saturation process	Takayama et al., 2017.
B4.12	SR-site: Homogenisation Calculations	Åkesson et al., 2010a.
B4.13	SR-site: Mechanical Evolution	SKB, 2011.

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Appendix B 1: Laboratory experiments

Project Acronym Analysis of microstructural images of bentonite samples	**Location** -	**Type** lab-test
Lead organiser Hokkaido University	**Start date** -	**End date** -
Main partners involved in the project JAEA, Research Centre for Deep Geological Environments	**Characteristics of swelling clay**	**Water Saturation** Artificial
Instrumentation X-ray microscope, micro-CT	**Main elements related to homogenization**	**Interfaces with other material**
Modelling Yes/no: Groups/Codes :	**Main processes studied** ☐T ☐H ☐M ☐Swelling pressure ☐Gas transfer ☐Other	**Reference concept if pertinent**
Main objectives of the experiment		
General description In this study, a microfocus X-ray computed tomography (micro-CT, X-ray microscope) was used to examine compacted montmorillonite samples under dry and water-saturated states. The images thus obtained were analyzed by a computer code developed for this study to obtain the information on the size and shape of montmorillonite grains in the samples before and after the water saturation.		
Main learning points concerning bentonite homogenization / mechanical evolution and relevance for the project From the results of the image analysis, it can be supposed that the outer montmorillonite sheets of grains swelled and formed a gel, whereas the inner montmorillonite sheets did not change significantly in the water-saturation process.		

How could this work inform a new experimental or modelling study in BEACON?
References (ideally with web links) Tomioka S., Kozaki T., Takamatsu H., Noda N., Nisiyama S., Kozai N., Suzuki S. and Sato, S., "Analysis of microstructural images of dry and water-saturated compacted bentonite samples observed with X-ray micro CT", Applied Clay Sciences, Vol. 47, pp. 65-71, 2010
Recommendations for BEACON project

Project Acronym Artificial wetting tests #3, 5, 6, 25, 26 and 27 (test series 2011-2012)	**Location** Lab facilities at VTT, Espoo, Finland	**Type** Lab-test
Lead organiser Posiva Oy	**Start date** Test #3: 24.5.2011 Test #5: 21.6.2011 Test #6: 19.8.2011 Test #25: 6.9.2011 Test #26: 25.9.2012 Test #27: 16.10.2012	**End date** Test #3: 9.6.2011 Test #5: 17.8.2011 Test #6: 6.9.2011 Test #25: 24.9.2011 Test #26: 12.10.2012 Test #27: 7.12.2012
Main partners involved in the project VTT Technical Research Centre of Finland	**Characteristics of swelling clay** See Table 1.	**Water Saturation** Artificial
Instrumentation 16 sensors for: • radial pressure • axial pressure • axial displacement • temperature	**Main elements related to homogenization** Initial heterogeneity of density: • zone filled by compacted block • zone filled with pellets	**Interfaces with other material** Bentonite/stainless steel
Modelling Yes Groups/Codes: Abaqus FEM	**Main processes studied** ☐T ☐H ☐M ☒Swelling pressure ☐Gas transfer ☐Other	**Reference concept if pertinent** KBS-3V repository design

Main objectives of the experiment or modelling study

The purpose of this study was to investigate the swelling behaviour of artificially wetted highly compacted bentonite buffer blocks used in deposition holes for nuclear waste containment. The target was to make a preliminary study if homogeneous and rapid swelling of the bentonite is possible to achieve in the gap between the buffer and the rock wall of the deposition hole by artificial wetting during construction and handling in the deposition tunnels.

General description

The artificial wetting tests were performed in cylindrical wetting chambers made from stainless steel with inner diameter of 360 mm, wall thickness of 10 mm and outer height of 390 mm or 470 mm (Figure 1). In total, Eighteen different test scenarios were investigated, including: variation of gap size, use of three different pellet types, use of three different bentonite slurry fillings, use of saline water compared to tap water, and uniaxial compared to isostatic buffer blocks. The duration of the tests ranged from 3 days to 57 days.

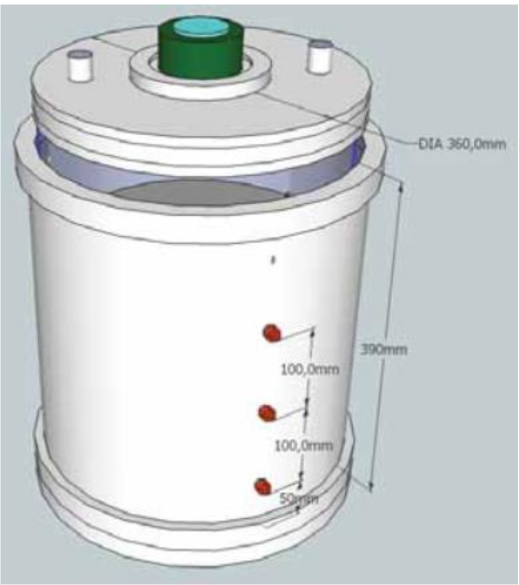

Figure 1. Schematic illustration of the artificial wetting test chamber

Note that only certain tests may be relevant for homogenization studies due to the used materials and the test duration. Tests #3, 5, 6, 25, 26 and 27 (tests series 2011-2012) might be of potential interest for this purpose. An overview of the initial conditions of these tests are provided in Table 1. However, in order to conduct homogenization analysis the reported tests firstly need to be assessed carefully in terms of the saturation of the different parts of the blocks and pellet fill at termination of the tests.

Bentonite components: The initial properties of the bentonite elements used in the relevant artificial wetting tests are summarized in Table 1 below.

Table 1. Summary of relevant artificial wetting tests

Test # (2011-2012)	Test duration [days]	Disk block manufact-uring method	Disk block bentonite type	# disk blocks [-]	Initial block dry density [kg/m^3]	Initial block water content [%]	Disk block height [mm]	Disk block diameter [mm]	Gap width [mm]	Gap fill material	Pellet manufact-uring method	Pellet dimensions	Initial pellet fill dry density [kg/m^3]	Initial pellet water content [%]	Water type
3	16	Isostatic	MX-80	1	1797	16,5	300	260	50	Cebogel QSE pellets	Extrusion	L=8-14 mm, d=6.3 mm	861	21,9	Tap water
5	57	Isostatic	MX-80	2	1781	17,6	200	290	35	MX-80 pellets	Roller-compaction	L=12 mm, W=12 mm, H=5.5 mm	914	16,8	Tap water
6	18	Isostatic	MX-80	1	1797	16,5	300	260	50	MX-80 pellets	Roller-compaction	L=12 mm, W=12 mm, H=5.5 mm	914	16,8	Tap water
25	18	Isostatic	MX-80	1	1797	16,5	300	260	25 - 75	MX-80 pellets	Roller-compaction	L=12 mm, W=12 mm, H=5.5 mm	-	16,9	Tap water
26	16	Isostatic	MX-80	1	1797	16,5	300	260	50	MX-80 pellets	Roller-compaction	L=12 mm, W=12 mm, H=5.5 mm	-	19,9	Deep saline reference groundwater
27	51	Isostatic	MX-80	1	1797	16,5	300	260	50	MX-80 pellets	Roller-compaction	L=12 mm, W=12 mm, H=5.5 mm	-	19,9	Tap water

Monitoring: In total, 12 pressure sensors (four equidistant positions on the circumference, i.e. 0 °, 90 °, 180 ° and 270 °, for three different height levels, i.e. bottom, medium and top) were installed for measurement of radial pressure. The axial force was measured with a load cell placed on top of the lid. The vertical displacement of the lid was measured by two dial gauges. T-type thermocouples for measuring the temperature of the surrounding air and the cylinder were used to ensure that the pressure sensors were not affected by environment. As an example, the effect of the water type on the radial pressure evolution (tests #26 and #27) is shown in Figure 2.

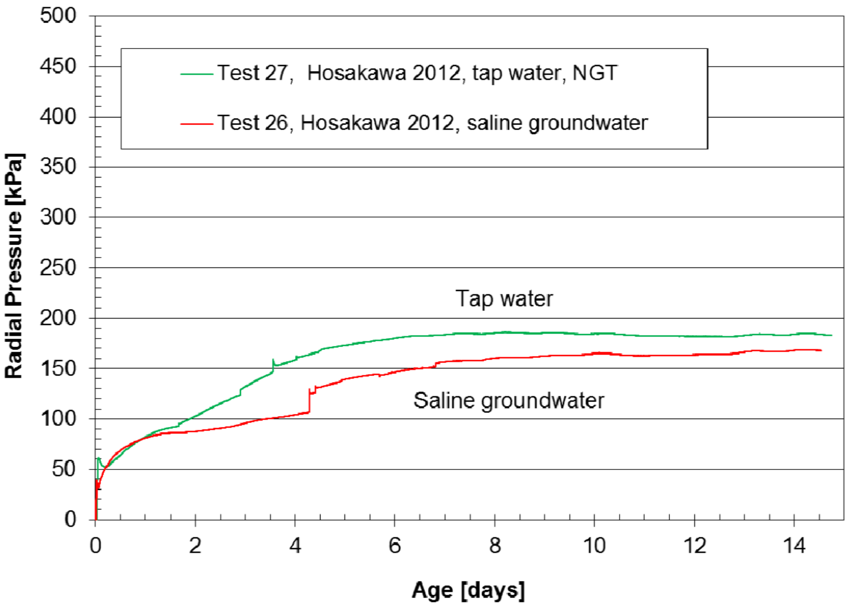

Figure 2. Effect of water type on the radial pressure evolution.

After the wetting tests, material properties of the swollen buffer were measured, including measurements of water content, SHORE hardness, and density. Exemplarily, the horizontal water content distribution measured for tests #3, 6 and 27 is depicted in Figure 3.

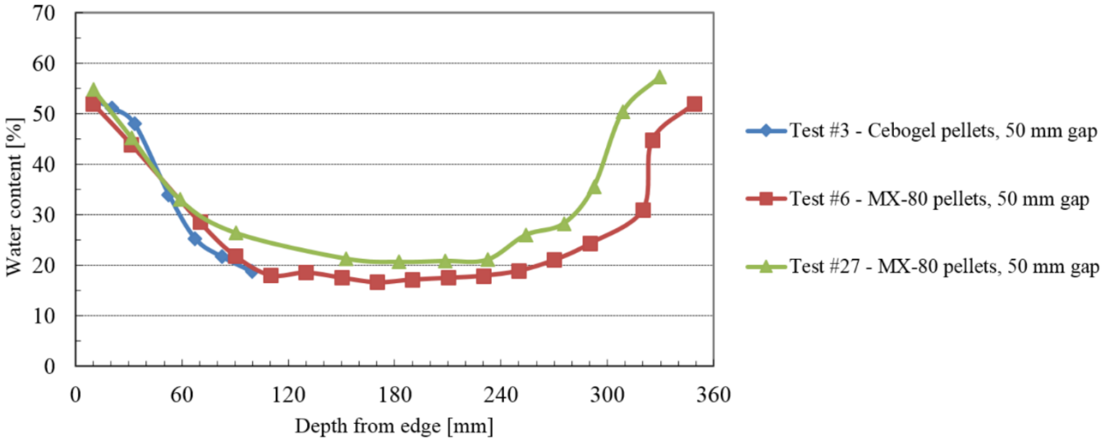

Figure 3. Horizontal water content distribution measured for tests #3, 6 and 27

Modelling: This study also had a portion on 2D modelling of the bentonite swelling during the early ages, with either pellets or water added to the gap. Results from earlier studies conducted in 2010 (Holt et al. 2011) were used to establish the models, which were then verified with test #3 (test series 2011) for time of developing swelling pressure (Figure 3).

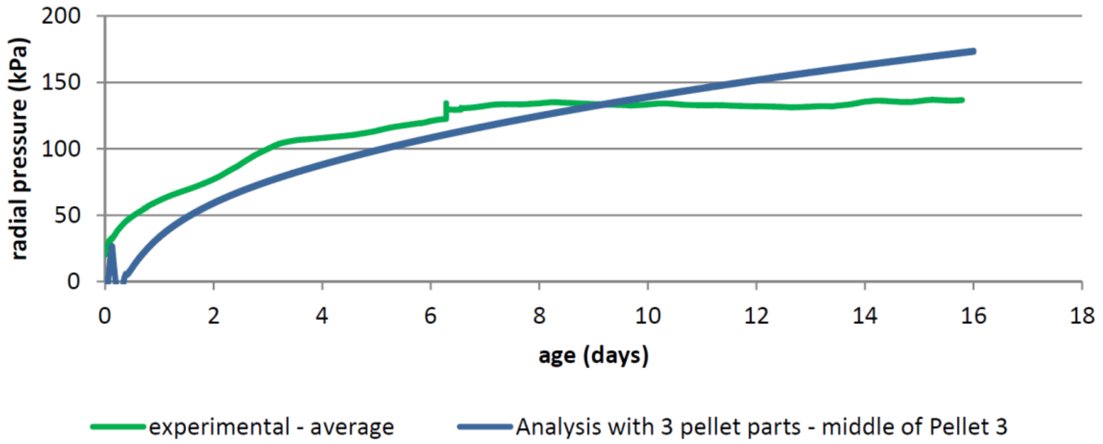

Figure 3. Comparisons between pressure levels of experimental data of test #3 (2011) (average radial pressure) and numerical results (without axial loading). Plots related to a configurations with 3 pellets parts of 10 mm each.

Main learning points concerning bentonite homogenization / mechanical evolution and relevance for the project

The results showed that the use of gap filling bentonite material combined with artificial wetting can provide radial pressure over 100 kPa within the first days. Bentonite pellets were effective at generating and maintaining swelling pressure, especially in the larger gap size of 50 mm. Eccentric alignment did not cause detrimental effects or severely uneven generation of pressure. Saline groundwater resulted in less swelling pressure, both of the buffer alone and when in combination with pellet filling.

How could this work inform a new experimental or modelling study in BEACON?

Persisting inhomogeneity. Tests were performed under wide varity of conditions. Modelling work conducted so far for the early age behaviour could be extended in WP5.

References (ideally with web links)

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Recommendations for BEACON project

Project Acronym Bentogaz	**Location** CEA Saclay	**Type** Lab-test
Lead organiser CEA	**Start date** 2008	**End date** 2016
Main partners involved in the project CEA/Andra	**Characteristics of swelling clay** MX-80 bentonite	**Water Saturation** Artificial
Instrumentation Total/pore pressure sensors, gas injection (flow rate)	**Main elements related to homogenization** Closing of gaps in relationship to gas transfer	**Interfaces with other material** Only steel/bentonite (exp. setup)
Modelling Yes/no: yes Groups/Codes : CEA / Code BIL	**Main processes studied** ☐T ☐H ☐M ☒Swelling pressure ☒Gas transfer ☐Other	**Reference concept if pertinent** Andra

Main objectives of the experiment or modelling study

The present tests aim to characterize gas migration through an interface between two blocs which has been sealed by swelling after or during full water saturation of these blocs. These later are made from a compacted mix of bentonite powder and sand, similar to the one previously tested during the ESDRED project (Gatabin et al., 2006).

General description

The dedicated cells are described in figure 1. In the present tests, hydration is conducted along the vertical plan followed by the gas injection phase performed at the horizontal plan which is designed to match with the interface plan.

- Test B5: this experiment deals with an entire cylinder (B5) with a height of 60 mm obtained by core drilling in the pre-compacted mix sample (Dridi et al., 2015).
- Test B6: a core similar to the B5 sample is cut in half. The resulting two cylinders B6-1 and B6-2 of 30 mm height are introduced and superposed with minimum clearance in the confining cylinder. Interface between the two samples is positioned in the same horizontal plan of the gas injection ports (figure 1) (Dridi et al., 2015).
- Test B7 and B8: two cylinders of 30 mm height are separated by a 3 mm thick gap after introduction in the confining cylinder (Dridi et al., 2016).

In experiments B5, B6 and B8, gas breakthrough test is performed using the step-by-step method just after the end of the hydration phase. Helium pressure is regularly incremented in the upstream circuit (connected to a 1 l tank) until gas detection in the downstream circuit (0.5 l tank initially at P_{atm}).

In the B7 test, gas injection is conducted under constant flow rate (0.1 ml/min) from the start of the hydration phase.

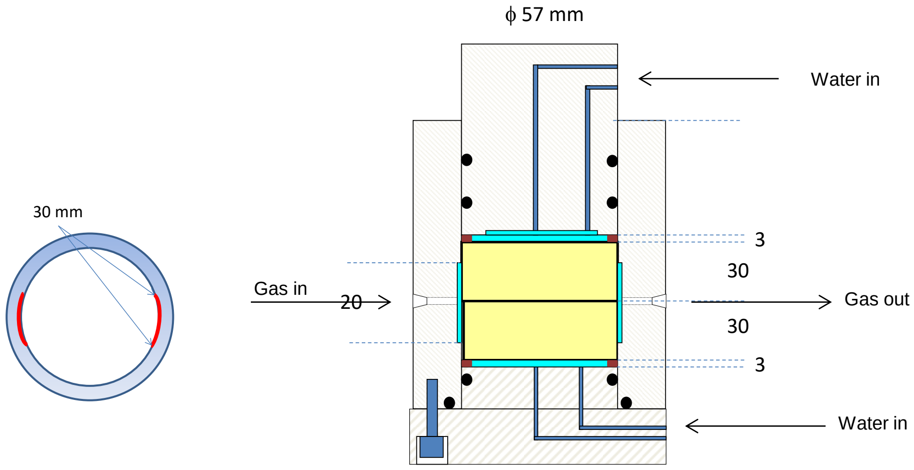
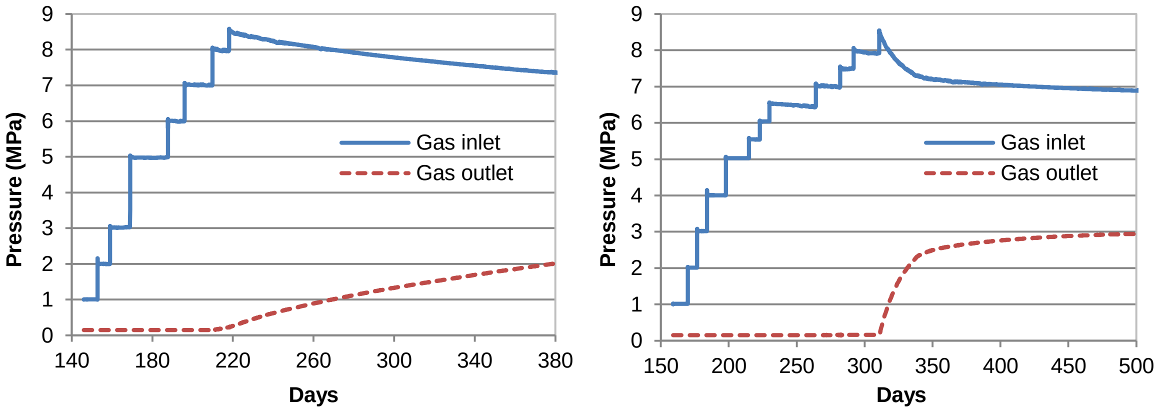


Figure 1: Description of the interface tests (B5, B6, B7 and B8) : detailed view of the modified oedometric cell (right) and description of the lateral injection ports (left)

Example of results

Concerning the interface effect, gas breakthrough is observed at the same injection in B5 and B6 test, but their post-breakthrough behaviors differ, figure 2. The gas pathways are probably different as they can take place throughout the contact interface in the B6 experiment. Nevertheless, after dismantling, no visible trace of the interface is distinguished. This later seems to be completely sealed under the swelling of the hydrated materials.



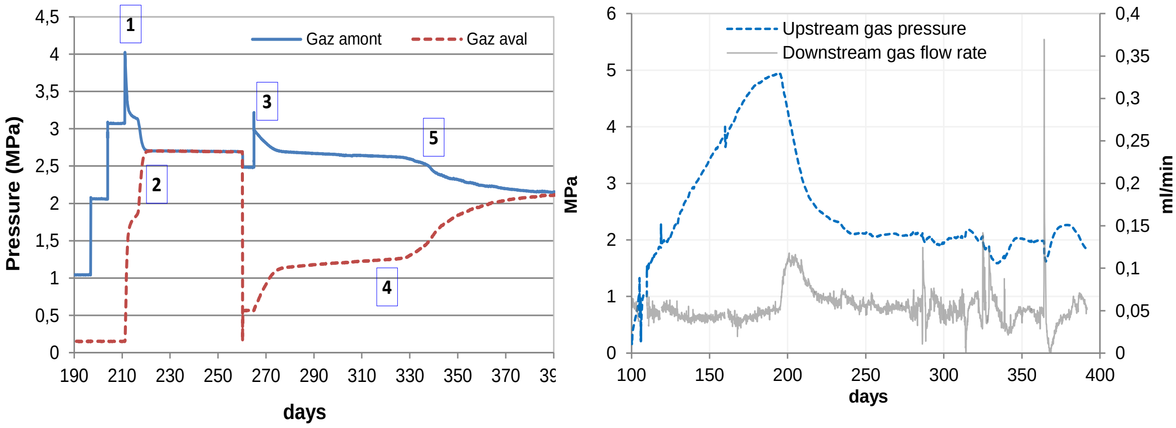
a) Without gap (B5)

b) thin gap (B6)

Figure 2: Gas pressures evolution during breakthrough test B5 and B6

In the B8 test (figure 3.a), gas breakthrough is occurred at a lower injection pressure (less than 4 MPa). The very thick initial interface (3 mm) between the two samples may have constituted a preferential pathways for gas migration during the test. After dismantling, initial trace of the interface is still visible (recognized as a less dense area).

During the B7 test (figure 3.b), no evidence of the interface sealing is observed since a positive gas flow is still recorded in the downstream. The imposed gas flow at the upstream has probably generated a local drying at the interface in competition with the applied vertical hydration. Furthermore, a partial gas breakthrough is recorded after a continuous build-up of the upstream gas pressure. This later is mainly related to a partial sealing of the interface.



a) thick gap (B8)

b) thick gap and constant gas flow (B7)

Figure 3: Gas pressures and gas flow evolution during breakthrough test B8 and B7

Main learning points concerning bentonite homogenization / mechanical evolution and relevance for the project

The obtained results showed that interface (or gap) width controls its clogging ability and hence its resistance to gas breakthrough. But, this influence has to be related to the dimensions of the tested materials (scale effect). The resulting bulk density of the structure may be a good indicator.

How could this work inform a new experimental or modelling study in BEACON?

- All the tests were performed on a well-defined geometry and on the same material already characterized during the ESDRED project.
- During the tests, axial swelling pressure and both liquid and gas pressures had been recorded. Data may be confronted to modelling results in a benchmark exercise.

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Internal reports :
- **(Gatabin et al., 2006)**. C. GATABIN, G. TOUZE G, P. BILLAUD, C. IMBERT, W. GUILLOT. ESDRED Project –Module 1. Selection and THM Characterisation of the Buffer Material. CEA ref: Technical Report RT CEA DPC/SCCME 05-704-B. Andra ref E.NT.0GME.05.0005/B, November 2006.
- **(Dridi et al., 2015)**. W. DRIDI, C. GATABIN, W. GUILLOT. Etude des transferts de gaz dans le mélange bentonite-sable (FT Bentogaz). Rapport de synthèse des essais bentogaz 2, 5 & 6. DPC/SECR/NT/2015/045 indice A. Décembre 2015.
- **(Dridi et al., 2016)**. W. DRIDI, C. GATABIN, W. GUILLOT. Etude des transferts de gaz dans les interfaces. Rapport de synthèse des essais bentogaz 7 & 8. DPC/SECR/NT/2016/025 indice A. Juin 2016.

Recommendations for BEACON project / What would I do differently, were I to repeat my earlier study?

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Project Acronym Bentonite homogenisation	**Location** British Geological Survey	**Type** Laboratory
Lead organiser BGS	**Start date** 2015	**End date** 2017
Main partners involved in the project SKB	**Characteristics of swelling clay** Mx80 bentonite	**Water Saturation** Artificial
Instrumentation 19 sensors • Pore pressure • Total stress	**Main elements related to homogenization** Small scale lab experiments monitoring pressure development during hydration	**Interfaces with other material** Bentonite/stainless steel
Modelling Yes/no: limited Groups/Codes : BGS advection dispersion modelling	**Main processes studied** ☐T ☒H ☒M ☒Swelling pressure ☐Gas transfer ☐Other	**Reference concept if pertinent** KBS-3V

Main objectives of the experiment or modelling study

Questions regarding the long-term performance of bentonite have risen in prominence in recent years with the advent of a series of projects addressing specific issues associated with 'homogenisation' including erosion, variations in density and development of swelling pressure e.g. BELBAR. However, the role of porewater pressure, it's spatial development and impact on swelling potential, self-sealing and permeability have yet to be adequately explored. Previous experiments associated with both single and dual density bentonite systems [Zihms & Harrington, 2015; Harrington & Horseman, 2003; Horseman & Harrington, 2004; Cuss et al., 2011; Graham et al. 2014] present data indicating that stress homogenisation is difficult to attain within the duration of these tests. Field scale experiments (Cuss et al, 2011) present data which suggest that under normal field conditions much slower hydration times are likely, an observation borne out in the decommissioning of a number of long-term field experiments, which have all shown a large degree of heterogeneity in dry density, saturation and stress distributions [Kristensson & Borgesson, 2015; Paconsky et al. 2007; Svoboda and Vasicek 2010; Villar et al., 2005]. These results suggest the processes governing hydration are both complex and potentially non-uniform.
As such, the accurate description of key parameters (e.g. swelling pressure, permeability, strength, friction coefficients etc.) may all be affected by both temporal constraints encountered by the development and distribution of pore water pressure within the buffer and by the methodology and duration of testing. Indeed, such slow time dependent phenomena may account for a significant component of the heterogeneity observed in many small- and full-scale experiments where systems remain stubbornly out of hydraulic equilibrium.
To examine this issue, the British Geological Survey was approached by Svensk Kärnbränslehantering (SKB) and asked to undertake a small experimental programme to measure the development of pore water pressure within a KBS3 specification bentonite clay. To help reduce test durations, it was agreed with SKB to impose a hydraulic gradient across the samples (constrained within a constant volume cell, see below 2) in order to promote the inflow of water and development of pore water pressure (the latter was independently monitored at multiple locations within and along the circumference of cylindrical clay samples). During this process, the development of swelling pressure was monitored continuously along with flow into and out of the

clay. In this way, the issues outlined above regarding the long-term fate of heterogeneities within bentonite have been explored.

General description

To simulate the boundary conditions of the KBS3 disposal concept, all samples were volumetrically constrained, with experiments undertaken in a constant volume cell, Figure 1. Conceptually, this apparatus reproduces some of the main features of the repository near-field, including the borehole, canister and conductive fractures intersecting the host rock wall. The apparatus comprises six main components: (1) a thick-walled stainless steel pressure vessel, (2) a fluid injection system, (3) a backpressure system, (4) five total stress sensors to measure radial and axial stress, (5) 13 independent porewater pressure sensors, and (6) a microcomputer-based data acquisition system. The pressure vessel comprises a dual-closure tubular vessel manufactured from 316 stainless steel and pressure-tested at 69 MPa. Each end-closure is secured by twelve high tensile cap-screws which can be used to apply a pre-stress to the specimen if required.

The 60 mm internal bore of the pressure vessel is honed to give a polished surface, with all ports, except those for the direct measurement of stress, containing porous plugs. Total stress is measured through a series of load cells mounted on the outside of the vessel connected to the sample through high modulus tungsten carbide rods.

A central filter is embedded at the end of a 6.4 mm diameter stainless steel tube terminating at the mid-plane of the sample. The end of the filter is profiled to match a standard twist drill which is used to produce the hole in which the rod is located.

Volumetric flow rates into and out of the sample are controlled or monitored using a pair of high-precision ISCO-260, Series D, syringe pumps operated from a single digital control unit. The position of each pump piston is determined by a digital encoder with each step equivalent to a change in volume of 16.6 nL, yielding a flow accuracy of 0.5% of the set-point. Movement of the pump piston is controlled by a micro-processor, which continuously monitors and adjusts the rate of rotation of the encoded disc using a DC-motor connected to the piston assembly via a geared worm drive. This allows each pump to operate in either constant pressure or constant flow modes.

Total stress and porewater pressure sensors are hard-wired directly to a National Instruments data acquisition system. A programme written in LabVIEWTM elicits data from the pump at pre-set time intervals of 2 minutes. The same data acquisition system systematically logs outputs from both load cells and pressure transducers to provide a detailed time series dataset.

Significant care was taken in the design of the experimental system to minimise the chance of trapping residual gas within the tubework connecting each transducer to the vessel body. As can be seen in Figure 1 each transducer was fitted with a valve to allow venting of the system and the removal of residual gas. This was undertaken when the system was pressurised as part of the calibration procedure. To minimise evaporation the sample was placed within the rig immediately after calibration. A cut-through of the vessel and schematics showing the relative positions of the filters, Table 1, and stress sensors is shown in Figure 2.

All tests were performed using deuterium (^2H_2O) and distilled water as the injection and backpressure permeants respectively. While physically similar to water, deuterium was selected as the injection fluid to facilitate post-mortem flow-mapping of the hydration pathways. This worked, undertaken in collaboration with colleagues from Sir Peter Mansfield Imaging Centre, School of Medicine, University of Nottingham, is ongoing and is not included in this report.

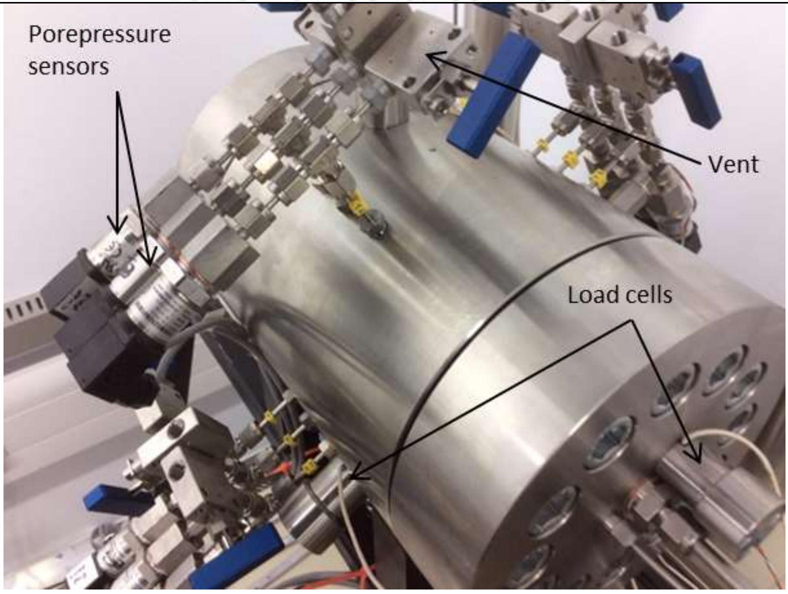


Figure 1 *Photograph showing the main body of the constant volume cell. Radial porewater pressure sensors and their accompanying drains are visible around the periphery of the vessel.*

Array	Sensor name	Axial distance from injection face (mm)	Rotation around bore of vessel (degrees)
Total stress	Injection load cell	0	-
Total stress	Radial 1 load cell	15.2	0
Total stress	Radial 2 load cell	60	120
Total stress	Radial 3 load cell	104.8	240
Total stress	Backpressure load cell	120	-
Radial porewater array 1	Radial 1	38.6	330
	Radial 2	38.6	60
	Radial 3	38.6	150
	Radial 4	38.6	240
Radial porewater array 2	Radial 5	60	330
	Radial 6	60	60
	Radial 7	60	150
	Radial 8	60	240
Radial porewater array 3	Radial 9	81.4	330
	Radial 10	81.4	60
	Radial 11	81.4	150
	Radial 12	81.4	240
Central filter	Middle	60	-

Table 1 *Relative positions of total stress and porewater pressure filters. Axial distance is to the centre point of each sensor. Angular rotation is anti-clockwise with the Zenith taken vertically at the top of the vessel at the Radial 1 load cell position, see* **Figure 2**.

Results

To date 3 tests have been performed. In test Mx80-Ho-1, after an initial period of hydration the sample was subject to an injection pressure of 10 MPa and backpressure left to evolve. In test Mx80-Ho-2, the sample was similarly allowed to hydrate, this time for 18 days at a low water (1 MPa) before injection pressure was increased to 10 MPa. In this test the downstream boundary pressure was maintained constant at 1 MPa. Again, in test Mx80-Ho-3 the sample was allowed to hydrate before the injection pressure was increased to its ‘reference’ pressure. In this case 5.0 MPa. As in test Ho-2 the backpressure was maintained constant at 1 MPa throughout. An example of the results, taken from test Ho-2, are presented in the following sections.

Test Mx80-Ho2 was designed to examine the development of stress, porewater pressure and to track the evolution in permeability during hydration. To this end, the sample was installed into the apparatus and allowed to passively hydrate drawing in deuterium from all radial, axial and central filters. After 4.3 days of passive hydration, the sample had developed a moderate total stresses ranging from 1.3 to 4.7 MPa. As mentioned above, in contrast to test Mx80-Ho1, backpressure was maintained constant through test Mx80-Ho2, in order to allow the evolution in permeability during hydration to be measured. Towards this end, water pressure was initially raised to 1.0 MPa in both the injection and backpressure filters. Total stress was allowed to evolve for a further 13.9 days (ranging in value from 4.8 to 6.8 MPa), at which point, the injection pump was increased to the target value of 5.0 MPa, **Figure** .

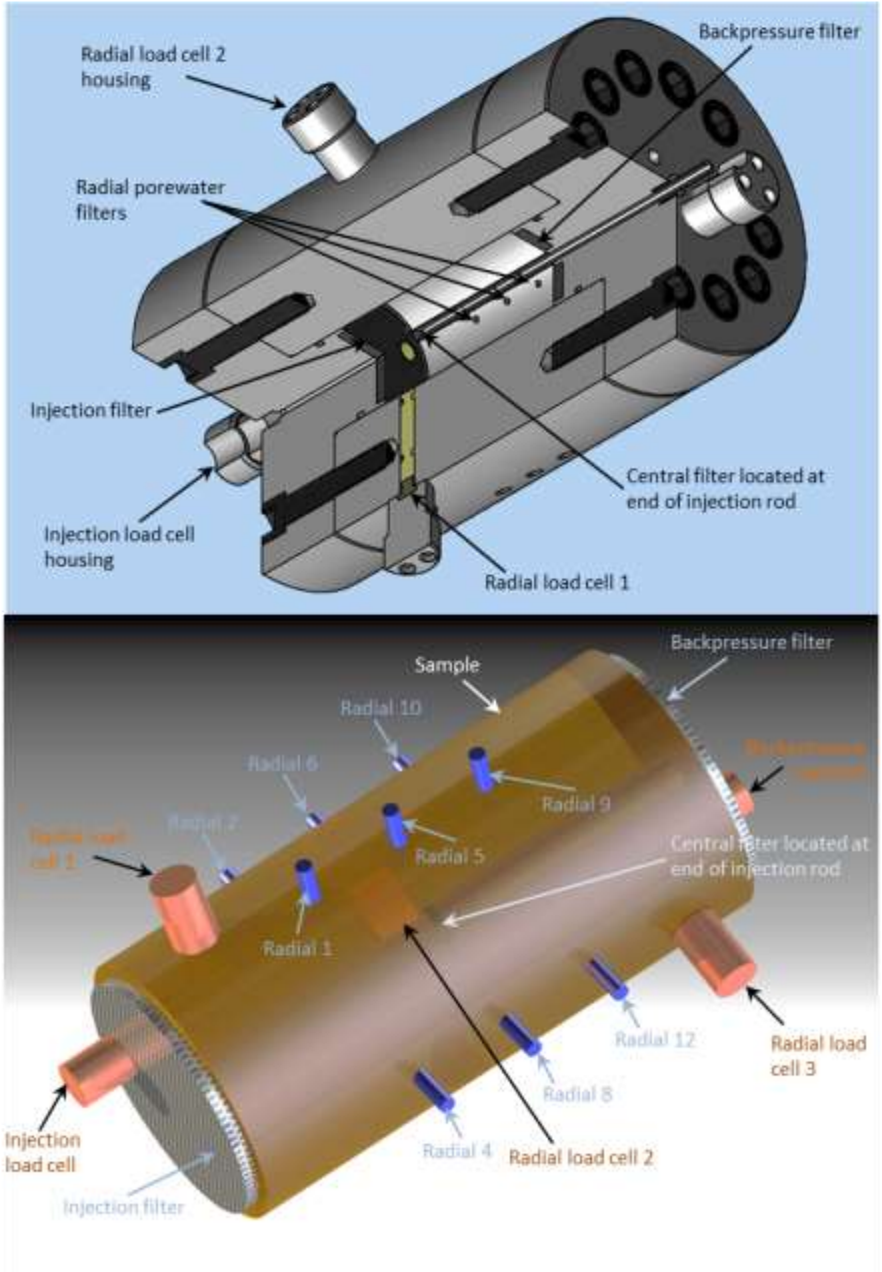


Figure 2 *[A] Cut-away diagram of the constant volume pressure vessel showing major experimental components. [B] rendered image of a sample showing the relative positions of the load cells and pore pressure filters.*

Figure A shows the development of stress as the sample hydrates. Following the increase in water pressure at day 18.2, total stress values asymptote around day 30, at values ranging from 7720 to 13150 kPa. While **Figure** A infers porewater pressures are much larger than most values of total stress, this is in fact not the case. **Figure** B shows effective pressure, i.e. swelling pressure, assuming the applied porewater pressure gradient is felt uniformly through the sample. While this is a gross simplification, it nicely illustrates that even though the system remains out of porepressure equilibrium, total stress remains positive. It is also evident from **Figure** that while differential stress remains similar following the increase in porewater pressure at day 18.2, the distribution in stress anisotropy changes, with the difference in stress greatest between axial measurements following the increase in porewater pressure.

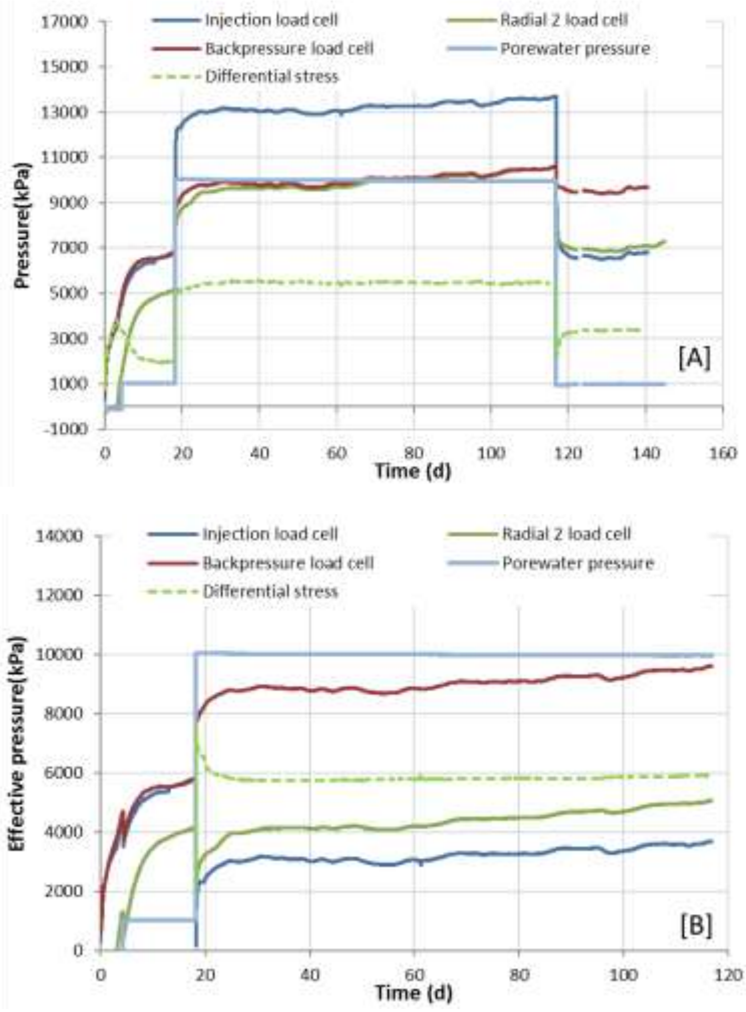


Figure 3 *[A] development of axial and mid-plane stress within sample Mx80-Ho2. Differential stress is defined as the difference between the maximum and minimum stress. [B] development of effective stress (swelling pressure) assuming a linear gradient (where appropriate) of porewater pressure for each phase of testing.*

The initial asymptote in total stress from day 30 continues until around day 55. From this point forward, all stress sensors show a small but progressive increase in value, similar in magnitude to that of porewater pressure sensor no.4. Figure 3 illustrates this behaviour, with radial stress sensor 1 plotted against porepressure sensor no. 4. The gradient of the line is 1.01 with an r^2 value of 0.83, indicating a strong coupling between the absolute value of stress and local changes in porewater pressure. This time dependent behaviour provides clear evidence of hydraulic disequilibrium, the long-time dependent nature of hydration and its integral coupling to the stress state.

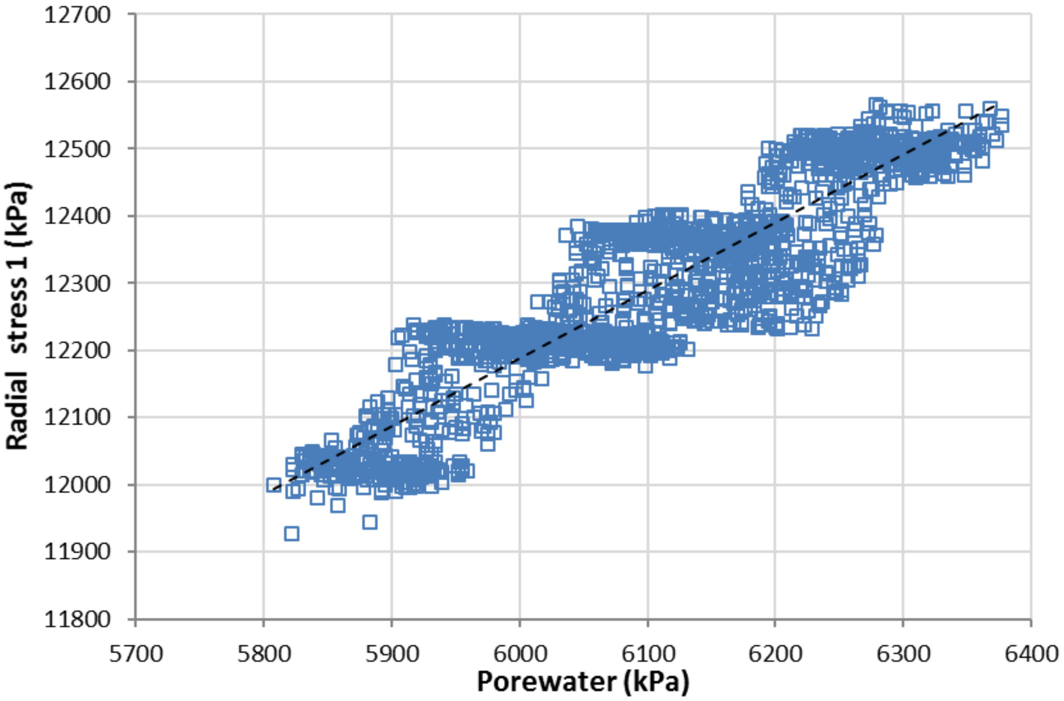


Figure 3 *Cross-plot of stress vs. porewater pressure from day 55 to 116. The gradient of the line is 1.01 with an* r^2 *value of 0.83, indicating a strong coupling between the absolute value of stress and changes in porewater pressure.*

Figure shows the temporal and spatial development of radial stress in sample Mx80-Ho-2. The axes of the graph have been orientated with that of the sample, in effect, providing a perspective equivalent to that of looking along the major-axis of the core. In contrast to test Mx80-Ho-1, the data shows very little stress bias during the early stages of the test, day 18. However, by day 40 (22 days after the gradient in porewater pressure was applied), a strong stress bias is observed towards radial 1. As hydration progresses, radial stress continues to increase, with the rate of increase greatest at sensors 2 and 3 as the hydration front moves through the sample.

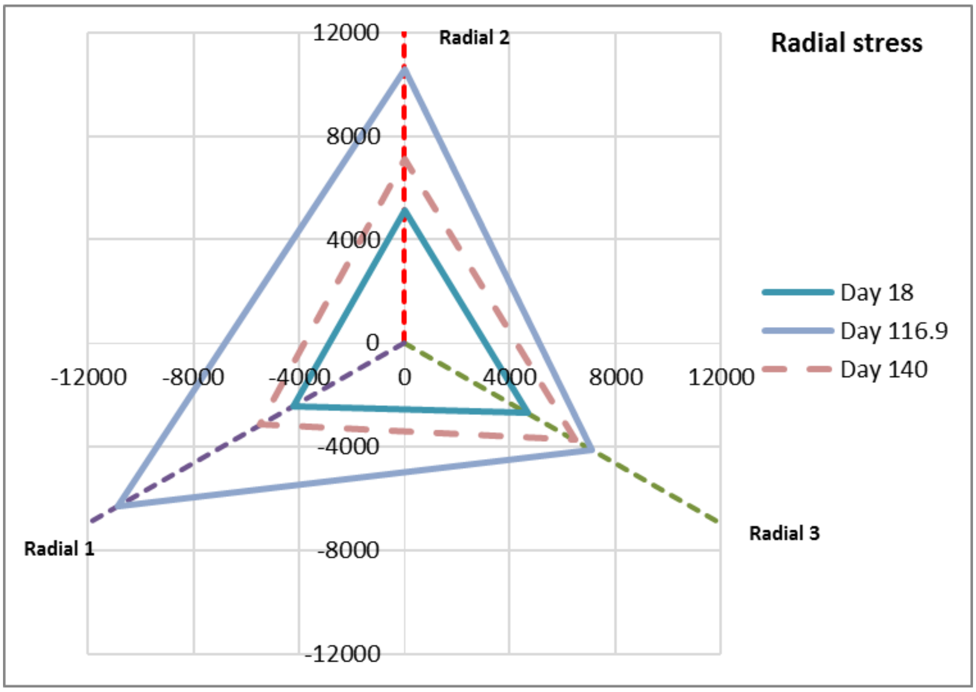


Figure 5 *Spider plot showing the temporal development of radial stress within sample Mx80-Ho2. Radial 1, 2 and 3 are located closest to the injection filter, mid-plane and backpressure ends of the sample respectively. Note, the magnitude of the stress response is denoted by the vector measured*

along the respective axis. When stress is equal at all points in the sample, the data plots as an equilateral triangle.

To examine the distribution of deuterium during hydration, the test was prematurely stopped, the hydraulic gradient removed, and the injection pressure reset to 1 MPa at day 117. Figure shows that by day 140, radial stress is more uniform with values ranging from 6310 kPa (radial 1) to 7480 kPa (radial 3).

Figure shows the spatial and temporal development of porewater pressure in and around the clay. The top left graph shows pressure traces from all 14 transducers and illustrates the complex way in which porewater pressure develops in the sample. This is exemplified by the individual spider plots which provide snap-shots in time from days 40 to 116.

Similar to **Fel! Hittar inte referenskälla.** Mx80-Ho1, the pressure data in the top left-hand graph of **Figure** shows a series of rapid pressurisation events as the hydration front, moving through the sample, connects with each circumferential filter. However, this period of pressurisation is relatively short lived and the rate of increase quickly declines to a much slower value. Interestingly, the gradient for each pressure trace, during this 'second' phase of pressurisation, appears fairly similar, suggestive of a uniformly distributed background response.

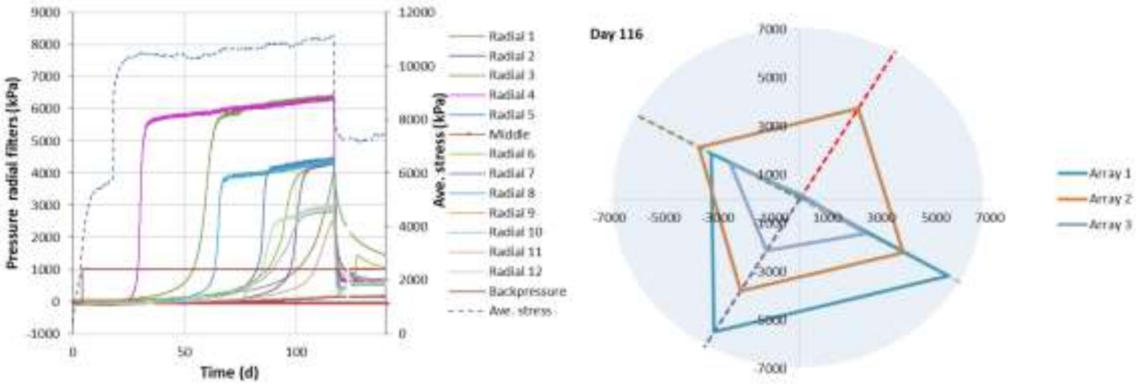


Figure 6 *Left graph shows the temporal development of porewater pressure around the circumference of sample Ho-2. Right graph shows a spider diagram illustrating the spatial development of water pressure. Note, arrays 1, 2 and 3 are located closest to the injection filter, mid-plane and backpressure ends of the sample respectively. The axes of the spider plot are orientated as if viewing the sample end on along the major-axis of the core.*

However, inspection of the spider plots in **Figure** also show a strong anisotropy in the development of porewater pressure in sample Mx80-Ho-2. This anisotropy continues through the test, illustrated by data from days 100 and 116, which show the development in pressure in arrays 2 and 3 (along the dotted green and red axis) which is absent in the development of pressure within array 1, i.e. the hydration front is not moving in a predictable and uniform way through the clay.

Figure shows a plot of permeability based on in- and outflow data for sample MxHo-2. The high permeability values at the start of the constant head test reflects both hydration of the clay and the uptake of water into storage. The high initial value of permeability based on the outflow data may stem from compression of the clay fabric and backpressure filter as the water pressure applied at the injection system is transmitted through the core. Intuitively, if such a kick had originated from displacement of porewater from within the bentonite, there should be a series of inflections in the pore pressure traces around this time. However, close inspection of the data has failed to identify any such phenomena. In addition, elastic compression of the backpressure filter would likely yield a relatively short-lived response (shown by the fact that the backpressure load cell attains its initial asymptote around 30 days) and displace only a small volume of water.

However, data from the test suggests around 1 cm^3 of water is discharged in the first 12 days of testing following the increase in water pressure at day 18. This is far too large to be accounted for by compression of the sintered discs. More likely scenario is that as injection pressure instantaneously increases (at day 18), it locally exceeds the value of stress potentially resulting in a small amount of side-wall flow between the vessel body and clay. However, the rapid development and transmission of stress seen throughout the clay would limit the impact of this response, and return the system to matrix dominated behaviour.

Whatever the cause, the data clearly shows that by day 118, flow in and flow out are not equal and that the permeability of the system, and indirectly the degree of homogenisation of the sample, continues to evolve, remaining in disequilibrium long after the apparent development of total stress within the clay.

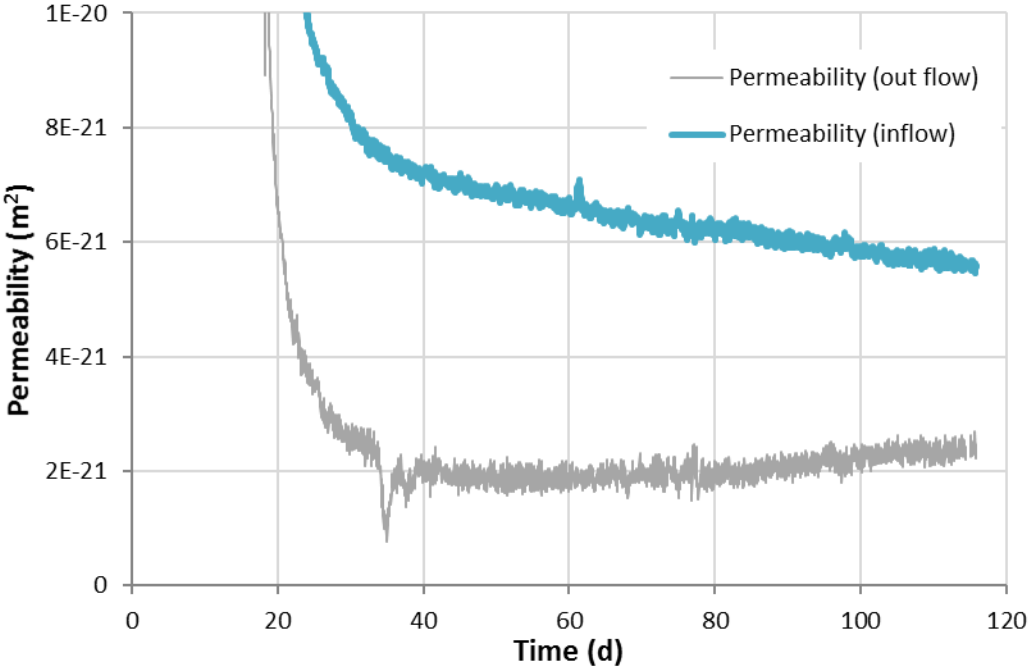


Figure 7 *Permeability of sample Ho-2 as a function of time. Data indicates time dependent development of permeability as pore pressure within the clay develops.*

Main learning points concerning bentonite homogenization / mechanical evolution and relevance for the project

Three highly-instrumented laboratory tests examining the hydration response of compact bentonite have been undertaken. The data clearly shows that hydrating the clay, attaining hydraulic equilibrium and homogenising stress and porewater pressure responses within such materials, is both complex and time consuming.

Data shows that hydraulic equilibrium within even relatively small blocks of bentonite takes much longer than anticipated to achieve any kind of hydraulic homogenisation and the impact of this on both the properties measured and the long-term attributes of the barrier e.g. swelling pressure and permeability, remains unclear.

In contrast the development of stress within these systems is rapid though again often non-uniform. The localised development of stress close to points of water injection, induce reflected stresses observed throughout the clay. These can be easily mistaken for the development of swelling stress elsewhere in the system, leading to the incorrect assumption of equilibration and stress homogenisation. However, this is not the case and the actual development of stress is both non-uniform and strongly time dependent. As such, the development of swelling pressure can be a poor proxy for equilibrium and should be treated with caution.

Similarly, porewater pressure develops very slowly, probably exploiting inhomogeneity within the clay, with inflections (both positive and negative) in pressure evolution difficult to explain from a mechanistic perspective. Data shows strong evidence for localised water flow, with different pressure traces observed for filters at the same plane/distance from the injection point. A pronounced asymmetry in the porewater pressure response is also observed between pressurisation and depressurisation, the cause of which is also unclear.

Measured permeability appears to develop slowly, although the early transmission of fluid across the sample, following the application of the hydraulic gradient, also suggests some degree of localised flow. This localisation of flow is borne out in the porewater pressure data, which continues to exhibit a large degree of heterogeneity even after a hundred plus days of testing.

How could this work inform a new experimental or modelling study in BEACON?

Clearly the fundamental physics governing the movement of water through bentonite remains poorly understood. Similarly, our knowledge on the processes controlling the development of stress, porewater pressure and permeability is incomplete, even at the laboratory scale. It therefore seems likely that the heterogeneity observed in laboratory scale tests also accounts for much of the heterogeneity observed in field scale experiments (Cuss et al. 2011), a significant part of which relates to the limited duration of the tests and the timescales involved in attaining true hydraulic and stress equilibrium.

References (ideally with web links)

All references quoted can be found in experimental report below. This contains a preliminary analysis of the data from tests Mx80-Ho1 and Ho2. Test Ho-3 has not been written up at this point but the data can be made available if required.

Harrington, J.F. and Tamayo-Mas, E. (2016). Observational evidence for the differential development of porewater pressure within compact bentonite and its impact on permeability and swelling pressure. British Geological Survey Report CR/16/160.

Recommendations for BEACON project

Understanding the development of hydration and porewater pressure within the bentonite, its impact on final homogenisation and transport/mechanical behaviour, and the evolution of such processes within complex repository systems remain a challenge, with further work required to elucidate some of the key processes within the clay.

Project Acronym Bentonite re-saturation project	**Location** Kajima technical research institute, Tokyo, Japan	**Type** lab-test
Lead organiser Radioactive Waste Management Funding and Research Center	**Start date** August 2008	**End date** In progress
Main partners involved in the project SKB	**Characteristics of swelling clay** Japanese Na bentonite (Kunigel V1) Montmorillonite content: 60wt% Pre-compacted blocks Sand/Bentonite:3/7 Bulk dry density: 1.6Mg/m^3 Initial water content: 8-10% Pellets Bentonite only Dry density of pellets 1.9Mg/m^3(10mm) 2.1Mg/m^3(2mm)	**Water Saturation** Kajima technical research institute ; Artificial
Instrumentation • swelling pressure • resistivity • volume of feeding water • fixed-point shooting	**Main elements related to homogenization** Initial heterogeneity of density: • zones filled by compacted brick and zone filled with pellets • Initial gaps • Ionic strength of feeding liquid	**Interfaces with other material** Bentonite/Acrylic resin
Modelling Yes: scoping calculations Groups/Codes : Kobe Univ. and Kajima/ DACSAR, COMSOL	**Main processes studied** ☐T ☒H ☒M ☒Swelling pressure ☐Gas transfer ☐Other	**Reference concept if pertinent** JAEA Report in 2000
Main objectives of the experiment or modelling study • The objective is evaluation of an effect of phenomena which will occur in the bentonite barrier during resaturation period on the long term performance. The resaturation period was defined as the period from the closure of geological disposal facility of radioactive waste to its full-saturation.		
General description		

A box-type cell and a specimen measuring 700 mm in width, 200 mm in height and 150 mm in depth were used. The specimen was composed of 50 mm cubic blocks and pellets with a maximum diameter of 20 mm. The bulk dry density of the cubes was approximately 1.6 Mg/m^3, and that of the pellets was approximately 1.1 Mg/m^3. The blocks were a mixture of Na bentonite (Kunigel V1) and silica sand (sand content: 30 percent by mass), and the pellets were Na bentonite (Kunigel V1) only. Distilled water or NaCl water solution (0.5 M) was fed from the bottom of the cell with a 20 cm head difference, and the seepage status was determined from changes in resistivity. The left side of the cell, which was 175 mm wide, was filled with pellets, and the blocks were laid in a staggered arrangement in the other area as shown in Figure 1. To evaluate the effectiveness of the filling pellets on the promotion of saturation, a specimen composed only of blocks was also tested with distilled water. The test conditions are summarized in Table 1.

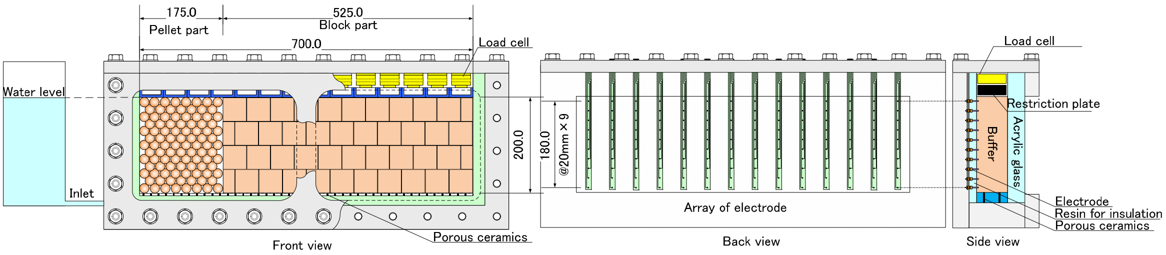


Figure 1 Test apparatus overview

The 14 load cells used were set horizontally between the specimen and the cell lid, and 127 electrodes were set in an array on the back panel of the cell to allow the degree of saturation to be estimated from measured resistivity as shown in Figure 2. The relationship between resistivity and the degree of saturation was determined in advance.

Wenner's four-electrode method (1916) was applied to measure resistivity. Every fourth one of the 127 electrodes was selected, and resistivity at various points in the specimen was measured. The electrode arrangement was determined in consideration of the block arrangement.

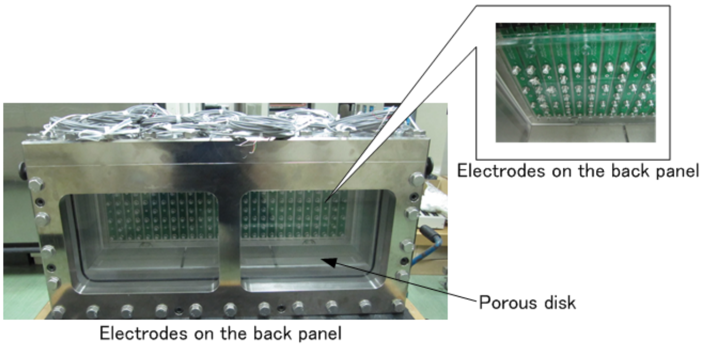


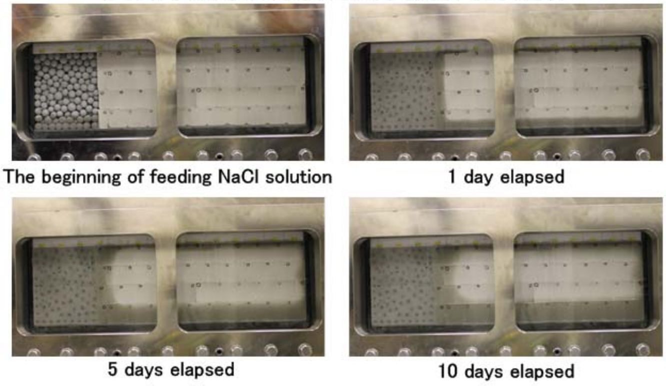
Figure 2 Electrodes on the back panel

Table 1 Test conditions

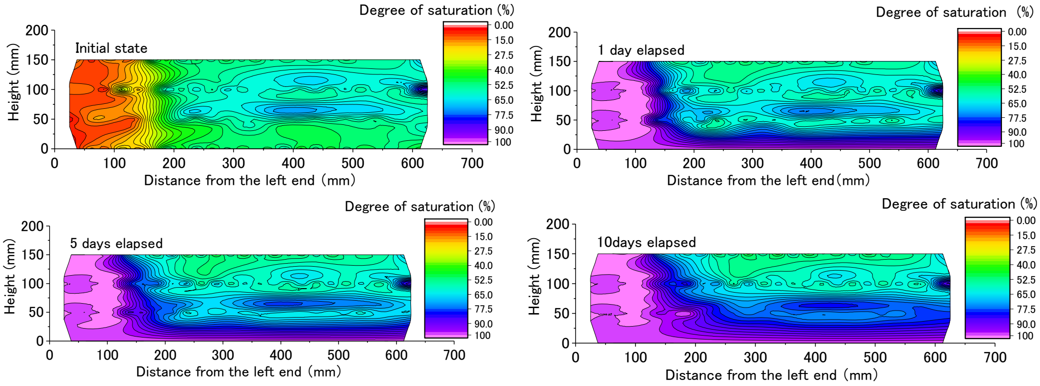
Specimen	Liquid	Inlet	Water head difference	Bentonite
Block and pellet	Distilled water	Bottom	200 mm	Kunigel V1
	NaCl water solution (0.5 M)			
Block	Distilled water			

Results

Figure 3 shows photos comparing the progress of NaCl water solution seepage with temporal changes in distribution of the degree of saturation as calculated from resistivity. The temporal changes were consistent with the observation results. These changes are also shown in Figure 4, with the degree of saturation calculated from resistivity. The seepage of NaCl solution was faster than that of distilled water, and resistivity data indicate that groundwater permeated the gaps between the blocks after filling the inter-pellet voids. Distribution of the degree of saturation in the block-only specimen is shown in Figure 5. Void air trapped in the center of the specimen caused a low-saturation region to remain there. Comparison of the results shown in Figures 4 (a) and 5 indicate that the filling pellets contributed to homogeneous saturation.

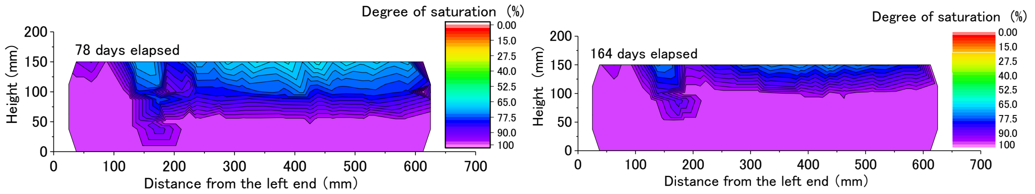


(a) Photo observation

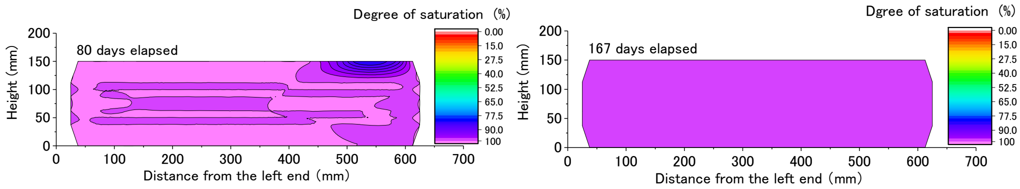


(b) Degree of saturation calculated from resistivity

Figure 3 Comparison of seepage observation and measurement of saturation (NaCl 0.5 M)



(a) Distilled water



(b) NaCl solution

Figure 4 Distribution of degree of saturation (block and pellet)

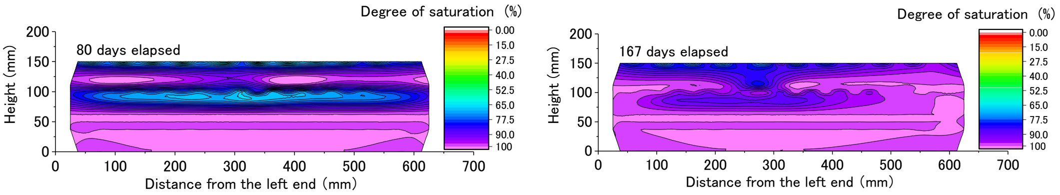
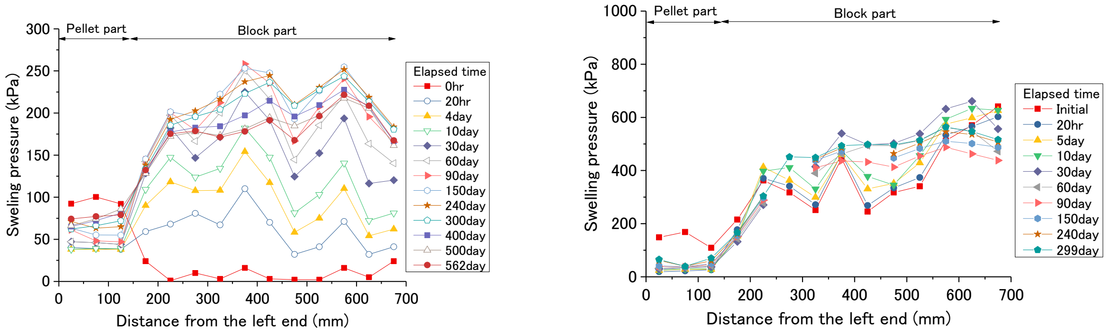


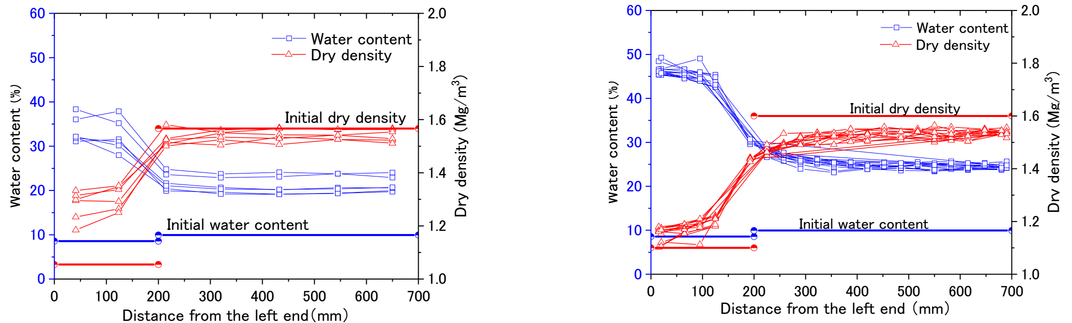
Figure 5 Distribution of degree of saturation (block)

Temporal changes in swelling pressure are shown in Figure 7. It should be noted that the initial values differed because they were generated by the setting of the cell lid. In both cases, the distribution of swelling pressure smoothed over time. As the dry density of the pellets was lower than that of the blocks, swelling pressure decreased with proximity to the pellets. Dry density distribution was evaluated in post-test core sampling as shown in Figure 8. The homogenization of dry density with distilled water progressed faster than that observed with NaCl solution.



(a) Distilled water (b) NaCl water solution

Figure 7 Distribution of swelling pressure



(a) Distilled water (b) NaCl water solution

Figure 8 Distribution of water content and dry density

Main learning points concerning bentonite homogenization / mechanical evolution and relevance for the project

Buffer materials with heterogeneity of dry density due to construction will not be homogeneous even if the buffer will be saturated sufficiently. The residual density distribution can be estimated by stress-strain relation of buffer materials.

How could this work inform a new experimental or modelling study in BEACON?

This experiment has a well-defined geometry. The initial characterization THM all the materials involved has been known. A large number of sensors allow to follow the hydromechanical evolution of the bentonite core.

This experiment has not been proposed before for a benchmark or as a modelling exercise.

Many kinds of phenomena which will occur in resaturation period are investigating by means of various test system, which is from laboratory test to field scale test, in the Bentonite resaturation project. These are complementary relation and these results are useful to understand the bentonite behaviour during resaturation process comprehensively.

References (ideally with web links)

- Kobayashi, I.: Experimental evaluation to determine rates of groundwater seepage into buffer materials, Proc. of the 7th international conference on clays in natural and engineered barriers for radioactive waste confinement, 2017 (submitted)

All of the test results of the project are described in the below report, which was written in only Japanese unfortunately;

- http://www.enecho.meti.go.jp/category/electricity_and_gas/nuclear/rw/library/2016/28fy_kougakukakusyou_2kansyouzai.pdf

Recommendations for BEACON project/ What would I do differently, were I to repeat my earlier study?

Project Acronym Block-pellet homogenization in KBS-3V buffer – laboratory scale test	**Location**	**Type** lab-test
Lead organiser Posiva	**Start date**	**End date**
Main partners involved in the project Saanio & Riekkola Oy	**Characteristics of swelling clay** MX-80 blocks and pellets	**Water Saturation** Artificial
Instrumentation	**Main elements related to homogenization**	**Interfaces with other material**
Modelling Yes/no: Groups/Codes :	**Main processes studied** ☐T ☐H ☐M ☐Swelling pressure ☐Gas transfer ☐Other	**Reference concept if pertinent** KBS-3V

Main objectives of the experiment

Introduction

In the KBS-3V repository design the main component of the bentonite buffer in deposition holes is a stack of bentonite blocks. There is a gap between the blocks and the rock wall, which is filled with bentonite pellets, forming a filling that has clearly lower clay density than the blocks (Juvankoski 2012). In current Posiva and SKB designs, the same holds for the deposition tunnel backfill. As the buffer saturates, the ensuing swelling pressure will reduce the density difference, but numerous tests have shown that some inhomogeneity will persist. This creates a challenge for proving the performance of the buffer, as the inhomogeneity needs to be addressed in some manner.

In the present work, the extent of persisting block–pellet density inhomogeneity is assessed by laboratory tests. The simplest way to address the inhomogeneity in buffer performance assessment is if we can show that the extent of persisting inhomogeneity is small enough, so that the lowest density point in the buffer is sufficient to fulfil required performance.

General description

Method

In our tests, the materials match Posiva's buffer design with MX-80 bentonite blocks and pellets, which are saturated with a simulant of expected groundwater in Posiva's Olkiluoto repository. In a cylindrical cell, pellets are placed on top of a cylindrical block. The axis of the cylindrical test then corresponds to the actual buffer in the radial direction (Figure 1). Laboratory scale tests allow precise monitoring of the swelling pressure during homogenization, and full saturation is reached in a reasonable time (a few months). First tests have been performed with a lower block-to-pellet volume ratio than exists in the repository (1:1 in test, 3.3:1 in repository). 50 mm of pellets corresponds to actual repository pellet gap, whereas more than 50 mm of block will start to take impractically long to saturate.

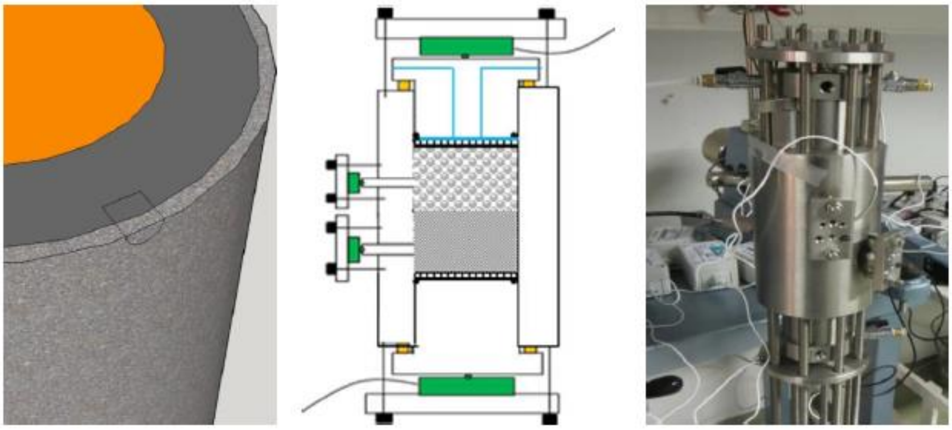


Figure 1. Illustration of the correspondence between the laboratory test and the buffer (left). Schematic of the homogenization test (middle). Photograph of the test (right).

Main learning points concerning bentonite homogenization / mechanical evolution and relevance for the project

Results

Swelling pressure was measured during the test, with the test stopped when no change is seen. Gradual increase of pressure on the pellet side was seen for surprisingly long, compared to (Dueck 2016) (Figure 2). Test was terminated at 161 days with clearly higher pressure on the block side, but strikingly similar axial and radial pressure on both sides.

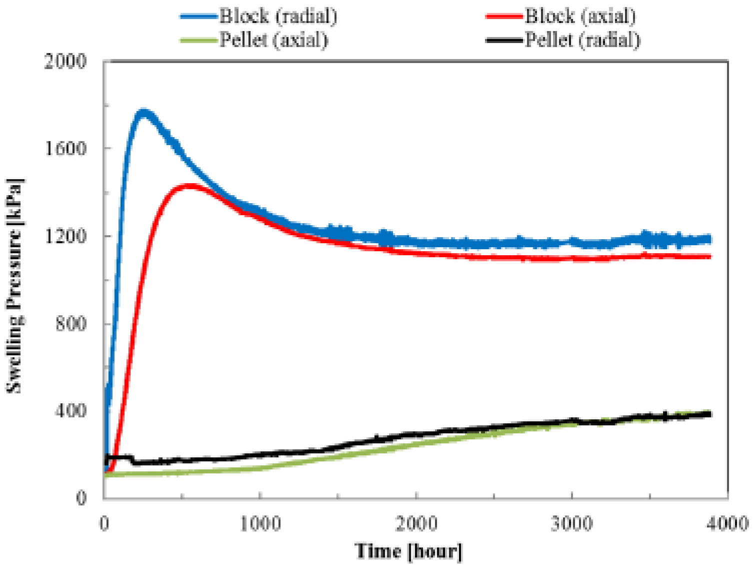


Figure 2. Swelling pressure and saturation evolution in the block–pellet homogenization test. A distinct swelling pressure gradient remains between the block and pellet ends.

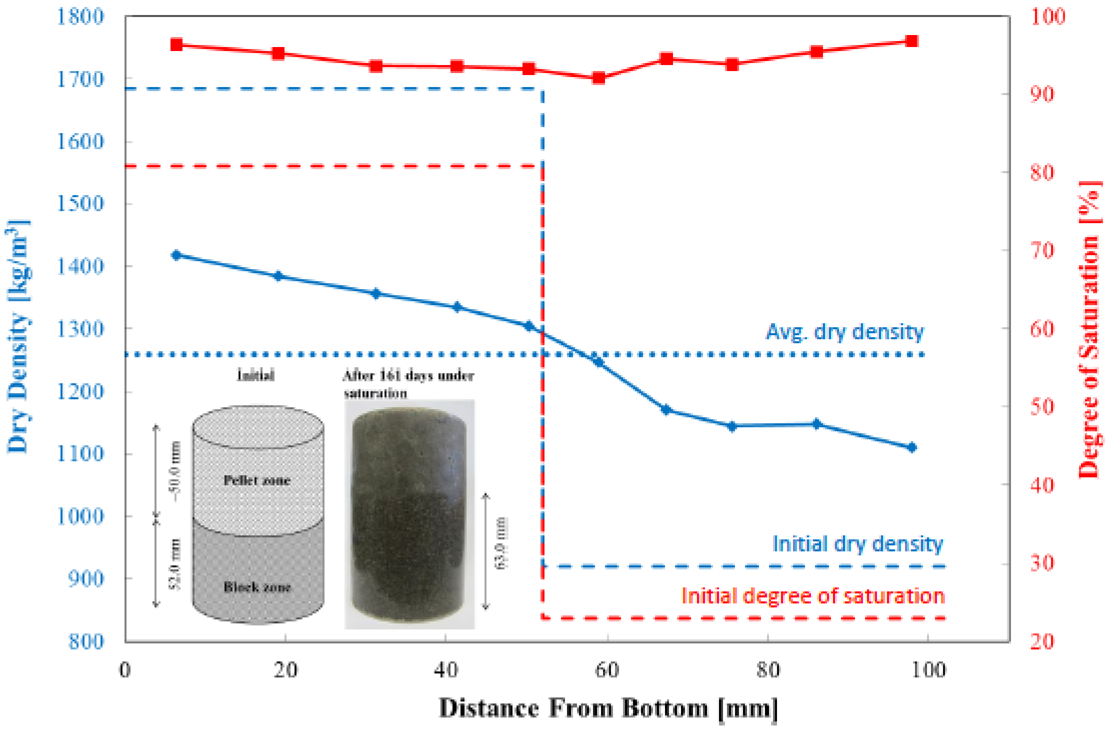


Figure 3. Post-mortem. Dry density profile at termination shows the persisting inhomogeneity (solid blue line). Degree of saturation (solid red line) shows practically full saturation. The block has developed a distinct density gradient, whereas the pellet zone was compressed to occupy the range 63–100 mm and has more even density distribution.

Post-mortem analysis of the density inhomogeneity shows that homogenization occurs, but not fully, with ~12 % difference persisting between the lowest density and the average density (Figure 3). Taken directly, this is an overtly pessimistic estimate of actual buffer inhomogeneity, mostly due to the lower block–pellet ratio.

Conclusions & Outlook

The axial pressure difference (1200 kPa – 400 kPa) arises from contact friction between the bentonite and the cell wall. This raises the question how much of the observed density inhomogeneity is due to the bentonite itself, and how much is due to a small-scale artefact of the laboratory system. If a similar size system is set up as radial outward homogenization (Dueck 2016), with pellets lining the outside of a cylindrical block, hoop stress produces another size-dependent artefact due the radius of curvature being much smaller than in the real buffer. Tests in small scale are, however, necessary to cost-effectively assess homogenization with different materials and conditions. Therefore, there is need to assess, and eliminate or subtract, finite size artefacts.

To assess the finite size effect, a repeat test to the one reported has been setup in a cell of diameter 100 mm, where the first test cell was 70 mm in diameter. The effect of contact friction should depend strongly on the diameter. The second test is ongoing. So far, the observed axial pressure difference is less and the measured swelling pressures are somewhat higher (Figure 4).

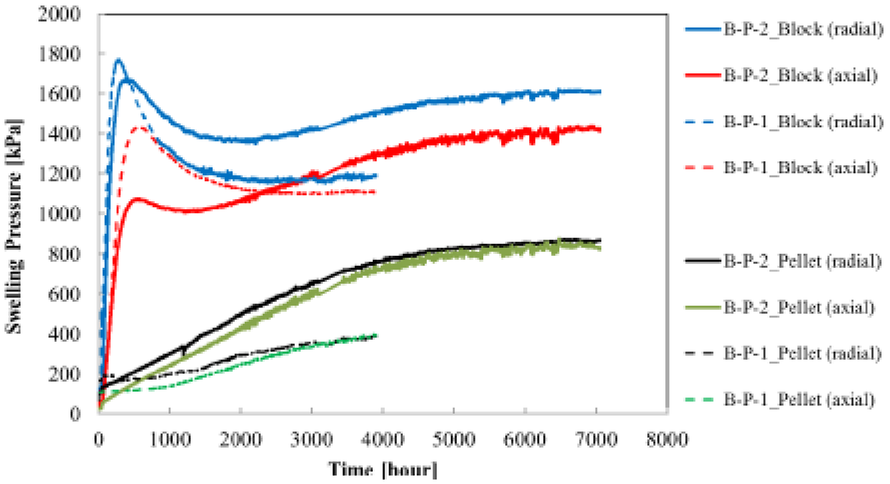
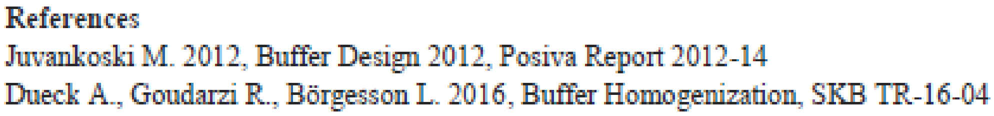


Figure 4. Finite size effect. Pressure evolution in the finished block–pellet homogenization test (B-P-1) with 70 mm diameter cell compared with otherwise identical test ongoing in 100 mm diameter cell (B-P-2).

How could this work inform a new experimental or modelling study in BEACON?

References (ideally with web links)



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Recommendations for BEACON project

Project Acronym Buffer homogenisation project	**Location** Clay Technology Laboratory	**Type** Laboratory test
Lead organiser Clay Technology AB/SKB	**Start date** The project Buffer homogenisation started in 2008.	**End date** The project is still on going.
Main partners involved in the project	**Characteristics of swelling clay** Two bentonites were used for the tests: • the commercial Wyoming bentonite with the brand name Volclay MX-80 (from American Colloid Company), • the commercial bentonite Calcigel (from Clariant, previous Süd-Chemie AG).	**Water Saturation** The specimens were saturated and in equilibrium with de-ionized water.
Instrumentation • Stress (load cells) • Water volume/pressure (Volume/pressure controller)	**Main elements related to homogenization** The compiled data contain laboratory test results on homogenisation of bentonite, mainly swelling into voids/gaps or density re-distribution from an initial saturated state.	**Interfaces with other material** Laboratory tests were run to determine friction between bentonite and other contact surfaces, e.g. steel with and without grooves.
Modelling Yes: Modelling of laboratory test results. Groups/Codes: Clay Technology (L. Börgesson) has modelled some of the tests with a hydro-mechanical Abacus-model.	**Main processes studied** ☐T ☒H ☒M ☒Swelling pressure ☐Gas transfer ☐Other	**Reference concept if pertinent**

Main objectives of the experiment

Swelling of buffer blocks and buffer homogenisation are important functions to guarantee the requirements of the buffer after full water saturation. It is important to understand and predict the final condition of the buffer after the swelling and homogenisation, which occurs both during the initial saturation and after a possible loss of bentonite caused by for example erosion.

During several years this SKB project has been running with the objective to increase the knowledge of the homogenisation processes.

General description

The laboratory tests made in the project Buffer homogenisation can be divided into four parts: fundamental swelling tests, measurements of friction between bentonite and other surfaces, homogenisation after loss of bentonite in self-healing tests, and homogenisation tests in long steel tubes. The presentation below is concentrated on fundamental swelling tests in the so called HR-series, on measurements of friction and on homogenisation after loss of bentonite in self-healing tests.

Fundamental swelling tests in the HR-series

The fundamental swelling of water saturated bentonite specimens has been studied in different well-defined tests including axial swelling with constant radius, radial outward swelling with constant height, and radial inward swelling into a cylindrical cavity with constant height, illustrated in Figure 1.

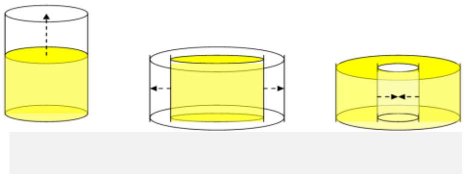

Figure 1. *Illustration of the geometry of the test types carried out in the series with fundamental swelling tests.*

In the tests in the HR-series the initial degree of saturation was high and swelling started directly, i.e. no saturation took place in the test device before the swelling phase. After preparation the specimens were mounted into the actual test device and de-ionized water was applied. Water was only applied to the upper part of the specimens at axial swelling, only applied to the radial filter at radial outward swelling and at the radial inward swelling applied to the radial filter and also filled into the cavity. After the tests the specimens were dismantled and cut in slices for determination of water content and density distribution in the direction of swelling. Examples of test results are given in Figures 2 and 3.

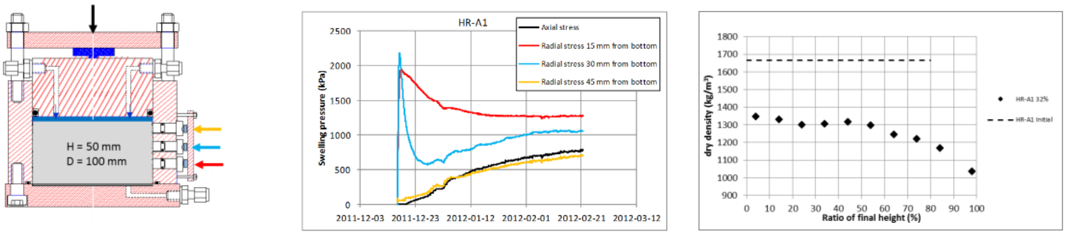

Figure 2. *Illustration of the axial swelling tests (left) and an example of test results from one of the tests with the stress evolution (middle) measured at the positions marked with arrows to the left and the initial and final dry density distributions after dismantling (right) (Dueck et al. 2014).*

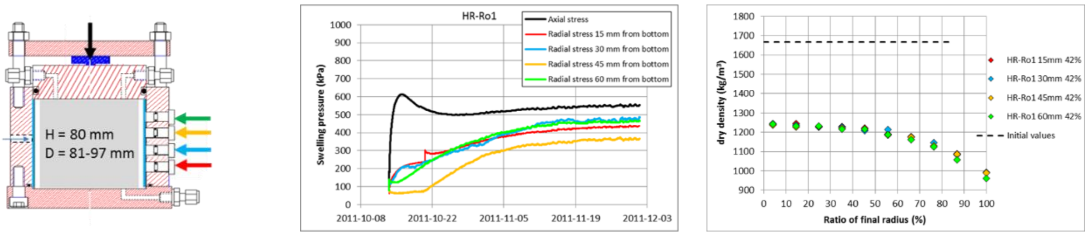

Figure 3. *Illustration of the radial outward swelling tests (left) and an example of test results from one of the tests with the stress evolution (middle) measured at the positions marked with arrows to the left and the initial and final dry density distributions after dismantling (right) (Dueck et al. 2014).*

Material: Mainly MX-80 but also Calcigel.
Dimensions: Diameter 97-100 mm and height 40 - 80 mm.
Approximate dry density at start: 1660 - 1680 kg/m^3.
Type of water at equilibrium: De-ionized water.
Data: Distribution of density and water content in the direction of swelling (i.e. height or radius) and time evolution of measured stresses. A total of 7 tests on MX-80 and 6 on Calcigel have been completed.
References: Dueck et al. 2014, 2016 and 2017.

Measurement of friction between bentonite and other surfaces

Test series with measurements of friction between confined specimens at saturation and different types of surfaces have been run. Bentonite specimens were saturated with a minimum of swelling in a swelling pressure device and after the saturation the friction tests were run. During the friction test the swelling pressure device was placed in a load frame where the ring surrounding the specimen was fixed while the specimen was moved upwards with a constant rate, i.e. the specimen was pushed upwards through the confining ring, and the force to keep the ring in place was measured as well as the deformation and the swelling pressure. The inner surface of the confining ring was prepared in different ways; e.g. plain steel, lubricated steel or steel surface with grooves. After the test the water content and density were measured on the dismantled specimen.

Material: Mainly MX-80.
Dimensions: Diameter 50 mm and height 20 mm.
Range of dry density at start: 1000 - 1650 kg/m^3.
Type of water at equilibrium: De-ionized water.
Data: Evaluated friction angle, swelling pressure, density and water content. A total of 19 tests have been completed on MX-80 and 2 on Calcigel.
References: Dueck et al. 2011, 2014, 2016 and 2017.

Homogenisation after loss of bentonite in self-healing tests - medium scale laboratory test

The self-sealing ability of large and irregular cavities has been studied in two completed (and two still ongoing) medium scale tests. The two tests, SH1 and SH2, having the same boundary conditions were started in December 2012. The non-instrumented SH2 was finished and dismantled after 17 months in May 2014 and the instrumented SH1 was running for 33 months until August 2015. A sketch of the test set-up and photos of the device and bentonite rings are shown in Figure 4.

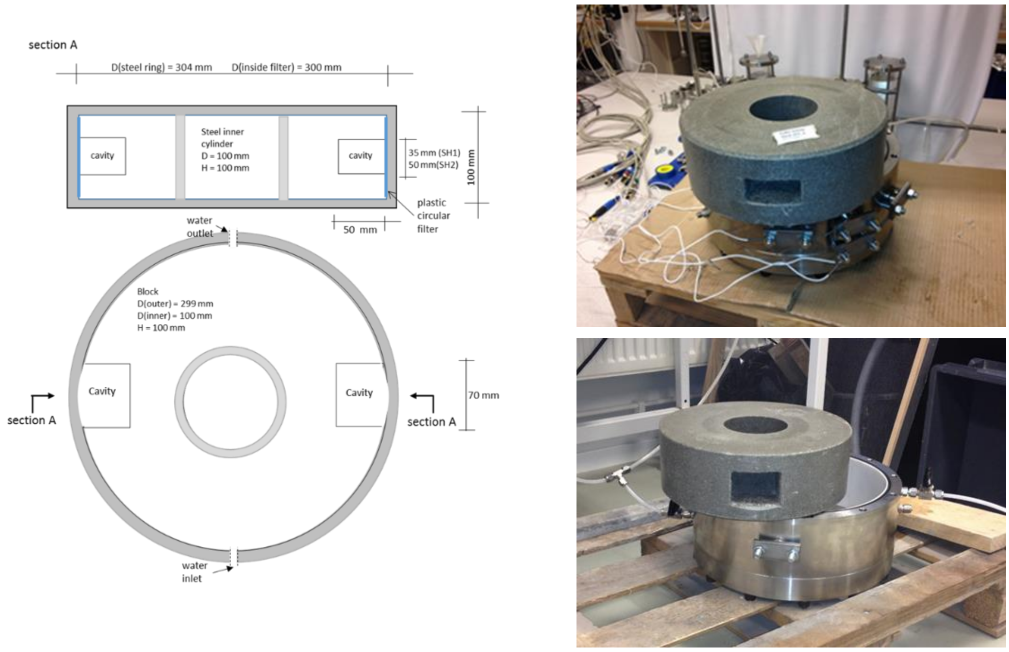

Figure 4. *A sketch of the set-up used for the SH1 and SH2 (left) and photos of the test device and the bentonite rings with the cut cavities (right). In the sketch the dimensions of the outer and inner steel cylinders and the bentonite block with the cavities are shown as well as the plastic filters and the locations of the water inlet and outlet (Dueck et al. 2016).*

The blocks were prepared with a high degree of saturation. The tests started by filling the filters and cavities with water and a water pressure was applied during part of the test duration. At dismantling the sampling was made along lines and continuously within a sector. The results from the sampling at the outermost horizontal level and at mid-height of SH2 are shown in Figure 5.

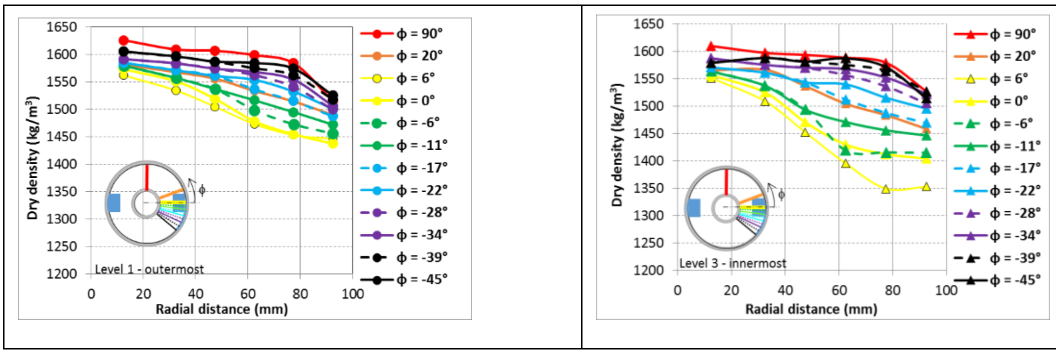

Figure 5. *The resulting distribution of density after dismantling of SH2 at the outermost level (left) and at mid-height (right) of the block and at different angles ϕ from the center of the cavity, shown in the plan view in the lower left part of each diagram (Dueck et al. 2016).*

Material: MX-80.
Dimensions: Outer diameter 300 mm, inner diameter 100 mm and height 100 mm.
Approximate dry density at start: 1660 kg/m^3.
Type of water at equilibrium: De-ionized water.
Data: Distribution of density after dismantling, time evolution of stresses at certain positions of one of the specimens.
References: Dueck et al. 2016 and 2017.

Main learning points concerning bentonite homogenization / mechanical evolution and relevance for the project

Laboratory test techniques suitable for testing the condition of bentonite after swelling and homogenisation have been developed and used in several test series.

The test results show remaining density distributions after equilibrium but also sealing/healing ability of larger irregular voids in blocks of bentonite.

How could this work inform a new experimental or modelling study in BEACON?

Results from the test HR-series and SH-series could be used as modelling tasks to verify material models. Some results can also be used for evaluation of specific parameters of the material models.

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Recommendations for BEACON project

ROCK STRESS- AND TIME-DEPENDENCY IN OVERPACK DISPLACEMENT AND BENTONITE PRESSURE BY CENTRIFUGE PHYSICAL MODELLING TEST IN PREDICTING FUTURE OF NEAR-FIELD

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Abstract

The long-term behavior in the near-field of HLW disposal is governed by coupled thermal-hydraulic-mechanical (THM) processes. In the initial stage of disposal (construction, operation, and initial confinement), THM transition will continue for hundreds of years. These processes influence the displacement of the overpack, the swelling behavior of the buffer, the deformation of the disposal hole, and so on. The displacement of the overpack is influenced by the behavior of bentonite (swelling pressure). The swelling pressure of the bentonite generated is influenced by the depth of the disposal site and the surrounding bedrock. Therefore, it is necessary to demonstrate the behavior of bentonite considering the rock stress including the bedrock, and to evaluate the long-term THM behavior of the near-field in order to improve the reliability of the repository.

To clarify the long term behavior in the near-field, research have been carried out using full-scale tests and numerical analyses 1). The full-scale test is nearly the actual behavior, but the test time is very short in the sense of the evaluation of the long-term behaviors. The numerical simulation is necessary to verify the applicability of the numerical model. If the time acceleration test using the reduced-scale model of the near-field is available on the basis of the centrifugal scaling law 2), then the long-term reliability of the disposal repository can be improved by empirical laboratory data.

The aim of the study is; to conduct the time acceleration test using the centrifugal equipment; to measure the equivalent data of long-term behavior of the overpack, buffer and bedrock; and to evaluate the long-term THM behavior of the near-field in a HLW disposal repository by laboratory measurements. This application is aiming to enhance the reliability of the prediction of the future of the near-field, hence the safety of the geological disposal.

This study focused on the stiffness/deformation of the bedrock/disposal hole and HM processes in the near-field, and the centrifugal tests were conducted using the reduced-scale model of the near-field. The model consisted of an overpack, bentonite buffer, and rock mass. The tests conditions were the centrifugal acceleration of 30 G, the isotropic stress-constraint with confining pressures, the boundary temperature of 25 °C and injection of pore water and were conducted continuously for a maximum of 67 d, which is equivalent to about 165 yr.

In results of the local maximum value of the bentonite pressure in the present tests, these values were obviously different depending on confining pressure ('stress- dependency'). In addition, these values after the local maximum values were not converged in test-time ('time-dependency'). These behaviors are distinctly different from the results under a strain-constraint condition.

These behavior show that the long term behavior in the near-field was changed by the geomechanical interaction between the rock stress and the swelling behavior of the bentonite depending on the depth of the repository and the stiffness of the bedrock.

Project Acronym –	**Location** –	**Type** Laboratory experiment using reduced physical model 3) • Scale: 1/30 • Model: composites (a single model-overpack, ring- and cylinder-shaped buffers, and a cylindrical sedimentary rock mass)
Lead organiser CRIEPI	**Start date** –	**End date** –
Main partners involved in the project · In-house study of CRIEPI, and a partial grant from the Agency for Natural Resources and Energy (ANRE) in the Ministry of Economy, Trade and Industry (METI) of Japan.	**Characteristics of swelling clay** · Blocks compacted Na-bentonite powder (Kunigel-V1). · Overall volume of the bentonite is about 54 mm in diameter by about 127 mm in height, and the initial dry density is 1.74 Mg/m^3 (the dry density after swelling is 1.55 Mg/m^3, including the swelling-filled gap between the overpack, the rock mass and the bentonite).	**Water Saturation** · Artificial (using pressure pump) · The pore pressure of the injected distilled-water is constantly controlled to be half of the confining pressure at the bottom end of the model. The back pressure is also constantly controlled under the consolidation-drainage (CD) condition of 0.5 MPa at the top end of the model.)
Instrumentation · Overpack displacement x1 · Soil pressure of bentonite x1 · Rock strain x8 · Injection water pressure x1 · Ejection water pressure x1	**Main elements related to homogenization** · Initial gaps between overpack and bentonite, and bentonite and rock · Initial joints of bentonite blocks themselves	**Interfaces with other material** · Bentonite/Sedimentary rock · (Bentonite/Overpack)
Modelling* · Yes: coupled THM processes · Groups/Codes : LOSTUF 4) (CRIPE original code) *separately discuss in other study (Sawada et al., 2017) 5)	**Main processes studied** ☐T ☒H ☒M ☒Swelling pressure ☐Gas transfer ☒Other · Overpack displacement · Equivalent elapsed time for the behavior	**Reference concept if pertinent** • HLW disposal hole and buffer material proposed in the report of CRIEPI and FEPC (Federation of Electric Power Companies of Japan) (Ogata et al., 1999) 6).

Main objectives of the experiment or modelling study

The objective of this study is to evaluate the long-term THM behavior of a geological repository for high level radioactive waste disposal, using the centrifugal near-field model test. Based on a centrifuge scaling law, the future behaviors are predicted by the time-acceleration model tests.

The full-scale test is nearly the actual behavior, but the test time is very short in the sense of the evaluation of the long-term behaviors. The numerical simulation is necessary to verify the applicability of the numerical model. If the time acceleration test using the reduced-scale physical model of the near-field is available on the basis of the centrifugal scaling law, then the long-term reliability of the disposal repository can be improved by empirical laboratory data.

The aim of the study is; to conduct the time acceleration test using the centrifugal equipment; to measure the equivalent data of long-term behavior of the overpack, buffer and bedrock; and to evaluate the long-term THM behavior of the near-field in a HLW disposal repository by laboratory measurements.

General description

- Centrifuge physical modelling

a.) Centrifugal scaling law in the static field

The behaviors expected in the near-field can be attributed to two-phase mixtures that consist of the rock/soil and pore fluid if the centrifugal model is the same material as the prototype. In a centrifugal model test, by subjecting 1/*N* scale model to *N* times the earth's gravitational/ centrifugal acceleration (G) based on a centrifugal scaling law in a static field (where *N* is the scale factor and gravity /centrifuge acceleration level), the following are true: (1) the stress-strain behavior of a specimen in the model will be identical to that in the prototype, and (2) the equivalent elapsed time for the migration of underground water that satisfies Darcy's law, the stress due to consolidation and swelling, and the distribution of elastic strain can be shortened to $1/N^2$, compared with the full-scale elapsed time (Table 1) 2, 3). For instance, the behaviors for 100 yr can be simulated in about 6 weeks using a 30 G centrifugal force field. This study treat the behaviors of the near-field as occurring in a static field.

Table 1 Scaling law of centrifugal model test in static field.

Physical properties	Length	Area	Volume	Stress	Young's modulus	Elastic strain	Temp	Viscosity (PF)	Flow velocity (PF)	Time
Model /Prototype	l_m/l	A_m/A	V_m/V	σ_m/σ	E_m/E	$\varepsilon_{em}/\varepsilon_e$	T_m/T	η_{wm}/η_w	u_m/u	t_m/t
Similitude	$1/N$	$1/N^2$	$1/N^3$	1	1	1	1	1	N	$1/N^2$

Temp: temperature, PF: pore fluid, 'm' of index shows the 'model'.

b.) Centrifuge model of near-field and centrifugal equipment

The near-field model (Fig. 1a) 3), which is 1/30 the size proposed in the previous report 6) (Fig. 1b), consists of a single model-overpack, ring- and cylinder-shaped buffers, and a cylindrical sedimenrary rock mass. The overpack and buffers are placed in the bore hole drilled in the rock mass. The overpack is 27-mm diameter by 62-mm height, and 6.16-Mg/m^3 density. The buffer is made by compacting a Na-bentonite powder (Kunigel-V1), after it was oven-dried at 110 °C for 24h. Overall volume of the bentonite is about 54 mm in diameter by about 127 mm in height, and the initial dry density is 1.74 Mg/m^3 (the dry density after swelling is 1.55 Mg/m^3, including the swelling-filled gap between the overpack, the rock mass and the bentonite).

The rock mass is a cylinder with a diameter and length of 180 mm. The disposal borehole of 56.7 mm in diameter by 127 mm in height is then created at the center of the cylinder. This study used Tage tuff, assuming the repository composed of sedimentary soft rock. The physical properties of Tage tuff in the laboratory tests are: about 2.9 GPa (dry) and 1.2 GPa (wet) in the Young's modulus of the uniaxial compressional test, about 1.72 Mg/m^3 (dry) and 2.00 Mg/m^3 (wet) in the density, and about 10^{-11} m/s in the permeability 3).

Nishimoto et al. (2011)[7] developed a geotechnical centrifuge, "CENTURY5000-THM" (Centrifugal Test equipment for Ultra-long time Range of 5000 Years: simulating coupled Thermal-Hydraulic- Mechanical processes) that enables us to perform a long-term operation of up to six months. The main features of the centrifuge are shown in Fig. 2.

c.) Test conditions

The model shown in Fig. 1(a) does not consider the entire disposal repository from the surface to deep underground, but focuses on the area surrounding the overpack. Therefore, the stress corresponding to the lithostatic pressure is supported by the pressure vessel. As for the scaling law of the self-weight stress, we considered only the surroundings of the overpack, including the bentonite buffer and bedrock.

In order to measure the temporal change of the soil pressure of the bentonite (called the ‘bentonite pressure’), and the overpack displacement and rock strain (Fig. 1a). Centrifuge model tests are conducted in a centrifugal force field of 30 G, along with confining pressures (P_c) and injection pressures (P_p) enclosed in the pressure vessel (Table 2). The pore pressure of the injected distilled-water is constantly controlled to be half of the confining pressure at the bottom end of the model. The back pressure is also constantly controlled under the consolidation-drainage (CD) condition of 0.5 MPa at the top end of the model. The tests are under the STRESS-constraint condition, that is, surrounding of the bentonite DEFORM). For comparison, we referred the centrifugal data of Nakamura and Tanaka (2009)[8] under the STRAIN-constraint condition. Their study used a model composed of bentonite and an overpack with a steel container, and did not include the bedrock, that is, surrounding of the bentonite DOES NOT deform.

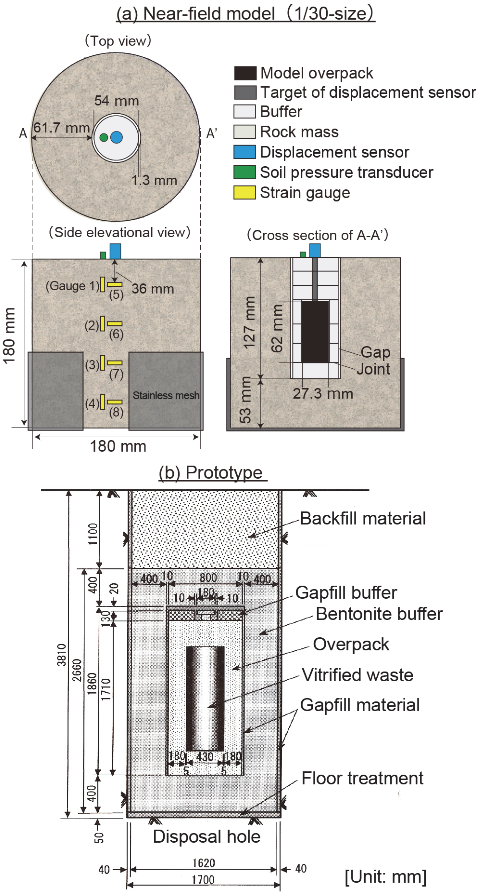

Fig. 1. (a) Near-field model, and (b) the target HLW disposal repository.

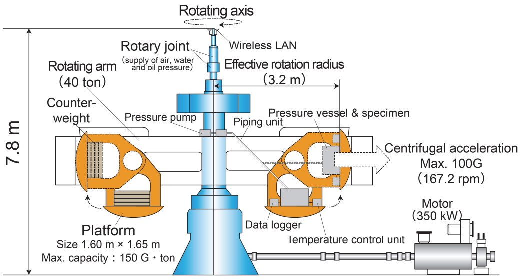

Fig. 2. Schematics of geotechnical centrifuge 'CENTURY5000-THM'

Test procedures are, (1) the predetermined confining pressure is loaded to the model, (2) the centrifugal acceleration of 30 G is applied after all measuring sensor values are steady, and then, (3) pore water injection is started. The model uses initially dry conditions to measure the saturating and swelling processes of the rock mass and bentonite. The tests were conducted continuously for a maximum of 67 d, which is equivalent to about 165 yr.

Table 2 Test conditions of the centrifugal model tests.

Sample No.	TG-03*	TG-10*	TG-11*	TG-14	TG-12*	TG-05*	NT**
Confining pressure, MPa	5.0	6.0	7.0	8.0	9.0	10.0	-
Injection (pore) pressure, MPa	2.5	3.0	3.5	4.0	4.5	5.0	4.9
Back pressure, MPa	0.5						-
Overpack, °C	25						25
Ambience, °C	25						25
Centrifugal acceleration, G	30						30
Test time, d	34	24	39	35	67	40	39
Equivalent time, yr	83.8	59.2	96.2	86.3	165.2	98.6	96.1

*Nishimoto et al. (2016)[3], **Nakamura and Tanaka (2009)[8]

- Result and discussion

As for the results obtained by the tests, figures show the temporal change of bentonite pressure (Fig. 3) and typical strain of rock mass (Fig. 4, TG-10) under the stress-constraint conditions (constant confining pressure). The bentonite pressure are defined as the value obtained when the back pressure is subtracted from the measured soil pressure. The data plotted in the figures set to zero at the starting point of the injection of water. And, this paper describe them using the test elapsed time (lower horizontal axis) in the following paragraphs, unless otherwise noted (the upper horizontal axis is the equivalent time based on G). In addition, Fig. 3 includes plotted the results under the strain-constraint condition obtained from Nakamura and Tanaka (2009) [8].

a.) Temporal change of bentonite pressure

The bentonite buffer placed into the disposal hole of the rock mass swells by the injected water that permeates the bottom and lower half-side of the rock mass, and then fills the gaps and joints in the hole from the lower part sequentially. The bentonite pressure is measured at the top of the model in the tests (Fig. 1a). Therefore, the soil pressure transducer showed little change at the beginning of the tests because the bentonite pressure could only be measured at the top of model after the gaps and joints were filled. Then, the bentonite pressure increased rapidly by the swelling of the bentonite and was measured the local maximum (Fig .3). Beyond the local maximum values were measured, the values changed to gradual decrease and were not convergent through the tests. The general trend of the bentonite pressure were similar between the present tests and Nakamura and Tanaka[6], but the variations in the present study are larger than their result. In addition, the present data clearly had a confining pressure (stress)-dependency in terms of the local maximum value, as well as a time-dependency after the local maximum values because the measured values were not convergent. Similar trend were obtain in the results of the overpack displacement.

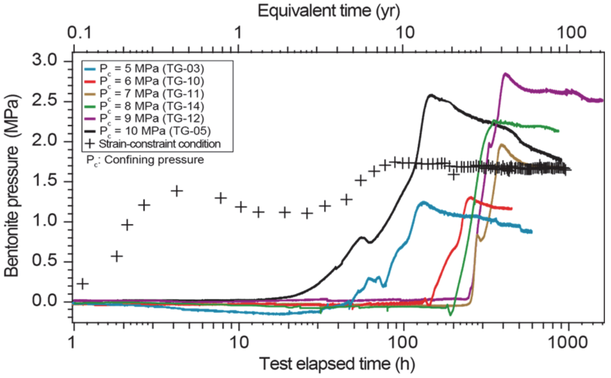

Fig. 3. Temporal change of bentonite pressure.

b.) Temporal change of rock strain

Fig. 4 show the strain of the rock mass in TG-10. As the example of results, the values of Gauge 1-4 are shown in figure (Fig. 1a). Gauge 4 measured the rapid expansive strain after about 10 hours passed, and then the value kept increasing gradually. Gauge 1-3 also showed the rapid expansive strain after a certain period of time, and the strain kept expanding gradually. Similar results were measured in Gauge 5-8. These rapid expansive strains had been sequentially generated from Gauge 4 and 8 toward Gauge 1 and 5; that is, from the gauges on the lower side of the model near the inlet port toward the gauges in the top side near the drainage port. In the present tests, the distilled water with pore pressure was injected into the model of the dry condition. For this reason, the displacement from air to water occurs in the pore that water reached in the model, and then the effective stress decreases. Therefore, it is considered that the measured rapid expansive strain corresponds to the migration of waterline.

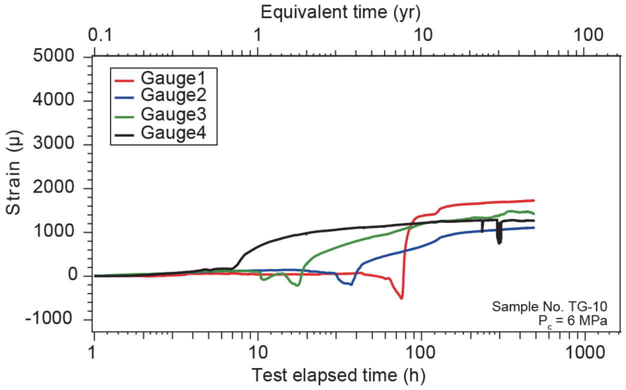

Fig. 4. Temporal change of rock strain.

c.) Stress- and time-dependency of bentonite pressure, rock strain (and overpack displacement)

The long-term behaviors of the near-field are qualitatively considered due to the following factors: (1) the disposal hole drilled in the deep underground shrinks due to the lithostatic pressure; (2) the buffer generates swelling pressure due to the imbibition caused by the resaturation; and (3) geomechanical interactions occur between the bedrock around the disposal hole and the buffer. In terms of the change from the local maximum to the test-end value of the bentonite pressure, the test result of the Nakamura and Tanaka (2009) [8] was convergent when about 40 equivalent years passed (Fig. 3). By contrast, the data under the stress-constraint conditions were not convergent with the gradual change. No observation of the convergence in the test results of TG-12 for the longest period of about two and three months which correspond to 165 equivalent yr. It is considered that the deformation of the disposal hole (host rock) yields to the convergent swelling pressure of the bentonite by the geomechanical interaction between the bentonite and the surrounding bedrock (Fig. 4). In addition, the disposal hole/bedrock surrounding bentonite deforms in the tests under stress-constraint conditions, and it is considered that the stiffness in the bedrock decreases and the suction disappears gradually while the condition changes from dry to wet by the water injection, and then the bedrock softens.

Main learning points concerning bentonite homogenization / mechanical evolution and relevance for the project

In terms of the local maximum of the bentonite pressure (and the overpack displacement) under the stress-constraint conditions, these values were clearly different depending on the confining pressure (i.e., stress-dependency occurred). In addition, the values did not converge until the end of tests after the local maximum were measured (i.e., time-dependency existed). These behaviors are distinctly different from the results of the test in a strain-constrain condition in which the disposal hole surrounding of the bentonite could not be deformed.

How could this work inform a new experimental or modelling study in BEACON?

These data revealed experimentally that the long-term behavior in the near-field was changed by the geomechanical interaction between the deformation stress of the bedrock/disposal hole and the swelling behavior of the bentonite buffer. Based on these results, it is suggested that it is necessary in evaluation studies of the long-term behavior of the near-field to consider the influence of the geomechanical interaction corresponding to the depth of the disposal repository and the stiffness of the bedrock.

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Project Acronym Characterization of material properties	**Location** Clay Technology Laboratory	**Type** Laboratory test
Lead organiser Clay Technology AB/SKB	**Start date** Older and finished projects.	**End date** Older projects.
Main partners involved in the project	**Characteristics of swelling clay** The bentonite used for the main part of the tests were the Na-dominated MX-80 (from American Colloid Company).	**Water Saturation** The specimens considered were saturated and for the main part of the tests they were in equilibrium with de-ionized water.
Instrumentation • Stress (load cells) • Strain (strain gauges) • Water pressure (pressure transducers) • Water volume/pressure (Volume/pressure controller)	**Main elements related to homogenization** The compiled data contain laboratory test results for evaluation of material model parameters to be used in hydro-mechanical modelling of e.g. homogenisation.	**Interfaces with other material**
Modelling No	**Main processes studied** ☐T ☒H ☒M ☒Swelling pressure ☐Gas transfer ☐Other	**Reference concept if pertinent**

Main objectives of the experiment

In this compilation of laboratory data, test results from various projects are included. The main objective with the selected laboratory tests is to suggest results that can be used for hydro-mechanical models of bentonite.

General description

This compilation of laboratory data contains a set of test results which characterize saturated bentonite material and which can be used for evaluation of parameters for hydro-mechanical material models. Test results from the following laboratory test types are suggested and suitable references are also suggested (given in brackets). A short description of the test types and the suggested references are given below.

- Swelling pressure tests (e.g. SKB TR-13-21)

- Oedometer tests (e.g. SKB TR-95-20)
- Triaxial tests and uniaxial compression tests (e.g. SKB TR-10-32 and SKB TR-11-07)
- Creep tests (e.g. SKB TR-95-20)
- Water retention curve determinations (e.g. SKB TR-10-55)

How the homogenisation proceed is an additional important characteristic of the bentonite and results from fundamental swelling tests and friction tests are presented in another WP2input to this project (WP2input CT_lab1 (homogenisation)).

Swelling pressure tests

In the suggested reference the swelling pressure is determined as a result of constant volume tests at atmospheric conditions and the corresponding dry density is determined on the specimens after dismantling. Further details about the suggested tests are:

Dimensions of the specimens: Diameter 35 mm and height 15 mm.
Material: MX-80.
Approximate dry density: 1250 - 1700 kg/m^3.
Type of water at equilibrium: Water with low salt content.
Data: Swelling pressure vs. dry density (tables).
Reference: Olsson et al. 2013 (TR-13-21); Section 2.2.

Oedometer tests

In the suggested reference the specimens are tested by one-dimensional compression and swelling after stepwise change of load at atmospheric conditions. Details from the suggested tests are given below and one example of the test results is given in Figure 1.

Material: Mainly MX-80.
Dimensions: Diameter 50 mm.
Approximate dry density at start: Mainly 1675 kg/m^3.
Type of water at equilibrium: Mainly de-ionized water
Data: Void ratio vs. swelling pressure (diagrams only).
Reference: Börgesson et al. 1995 (TR-95-20); section 2.4.

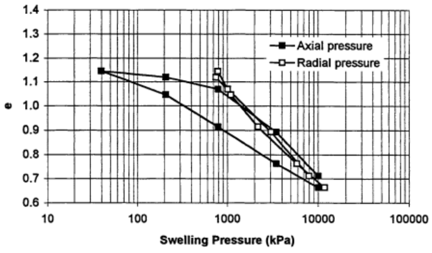

Figure 1. *Void ratio as a function of measured axial and radial pressure at stepwise unloading and loading of MX-80 (KMXAR5) (Börgesson et al. 1995).*

Triaxial tests and uniaxial compression tests

The stress-strain-strength properties are preferably evaluated from triaxial tests. In the suggested reference undrained triaxial tests were run with constant radial pressure and increased axial stress applied by a constant axial deformation rate of $4\text{-}9 \cdot 10^{-6}$ mm/s until failure. Details of the mentioned tests are given below and an example of the test results is given in Figure 2. In addition, valuable test results are also given by Börgesson et al. (1995).

Dimensions of the specimens: Diameter 35 mm and height 70 mm.
Materials: MX-80 and Ca-dominated materials.
Approximate dry density: 1540 - 1640 kg/m^3.
Type of water at equilibrium: Mainly de-ionized water.
Data: Deviator stress at failure vs. effective average stress and deviator stress vs. strain (diagrams).
Reference: Dueck et al. 2010 (TR-10-32); Sections 3.2.4, 3.3.3, 3.4.4 and Appendix 2.

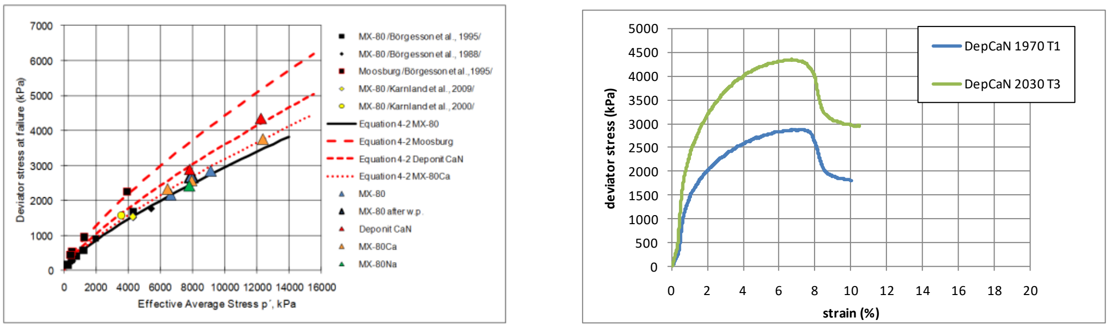

Figure 2. *Results from triaxial tests. A compilation of test results with deviator stress as a function of effective average stress resulting from different tests and models (left) and deviator stress as a function of strain from two tests on a Ca-dominated material (right) (Dueck et al. 2010).*

A measure of the stress-strain-strength properties can also be gained from the uniaxial compression tests (or unconfined compression test). In this test the specimen is compressed axially with a constant rate of deformation with no radial confinement or external radial stress. In the suggested tests the rate of deformation was 0.005 mm/s and more details are given below.

Dimensions of the specimens: Diameter 20 mm and height 40 mm.
Material: MX-80.
Approximate dry density: 1330 - 1660 kg/m^3.
Type of water at equilibrium: Water with low salt content.
Data: Deviator stress at failure vs. dry density, deviator stress vs. strain (tables and diagrams).
Reference: Dueck et al. 2011 (TR-11-07); Section 4.2.

Creep tests

Creep is described as an increase in strain at constant load and constant pore water pressure. In the suggested reference two processes are mentioned; volumetric creep and deviatoric creep and some details are given below:

Material: MX-80.
Approximate dry density: 1000-1640 kg/m^3.
Type of water at equilibrium: De-ionized water.
Data: Deviatoric strain rate vs. time and axial strain at one-dimensional loading vs. time (diagram only).
Reference: Börgesson et al. 1995 (TR-95-20); Section 2.5 and Appendix 3.

Water retention curve determinations

The water retention curve describes the water potential as a function of water content. In the suggested reference the measurements are based on a method with free swelling powder exposed to climates with constant temperature and constant relative humidity. Some further details are:

Dimensions of the specimens: powder specimens of 10g
Material: MX-80.
Data: Water content vs. relative humidity.
Reference: Dueck and Nilsson 2010 (TR-10-55); Sections 3.2 and Figure 3-2 (table and diagram).

Main learning points concerning bentonite homogenization / mechanical evolution and relevance for the project

A data set that characterize and illustrate some of the hydro-mechanical behaviour of saturated bentonite materials are suggested. In addition to base parameters as swelling pressure and strength, the influence of stress path and wetting path are also shown by the results from the oedometer tests and the water retention curves.

How could this work inform a new experimental or modelling study in BEACON?

The suggested laboratory test results can be used to characterize the behaviour of saturated bentonite and it can also be used for the evaluation of some of the parameters needed for hydro-mechanical material models.

References

Börgesson L, Johannesson L-E, Sandén T, Hernelind J, 1995. Modelling of the physical behaviour of water saturated clay barriers. Laboratory tests, material models and finite element application. SKB Technical Report TR-95-20. Svensk Kärnbränslehantering AB.
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Dueck A., Börgesson L., Johannesson L.-E., 2010. Stress strain relation of bentonite at undrained shear. Laboratory tests to investigate the influence of material composition and test technique. SKB Technical Report TR-10-32. Svensk Kärnbränslehantering AB.
Olsson S., Jensen V., Johannesson L.-E., Hansen E., Karnland O., Kumpulainen S., Kiviranta L., Svensson D., Hansen S., Lindén J., 2013. Prototype Repository. Hydro-mechanical, chemical and mineralogical characterization of the buffer and tunnel backfill material from the outer section of the Prototype Repository. SKB Technical Report TR-13-21. Svensk Kärnbränslehantering AB.
Dueck A., Johannesson L.-E., Kristensson O., Olsson S., 2011. Report on hydro-mechanical and chemical-mineralogical analyses of the bentonite buffer in Canister Retrieval Test. SKB Technical Report TR-11-07. Svensk Kärnbränslehantering AB.

Recommendations for BEACON project

Project Acronym Clay hydration characterisation using microfocus X-ray CT	**Location** -	**Type** lab-test
Lead organiser SKN CEN	**Start date** -	**End date** -
Main partners involved in the project Department of Civil Engineering	**Characteristics of swelling clay**	**Water Saturation** Artificial
Instrumentation	**Main elements related to homogenization** 50/50 pellet/powder FoCa mixture	**Interfaces with other material**
Modelling Yes/no: Groups/Codes :	**Main processes studied** ☐T ☐H ☐M ☐Swelling pressure ☐Gas transfer ☐Other	**Reference concept if pertinent**

Main objectives of the experiment

General description

The mixture of bentonite pellets and powder used in this study has a dry density of 1.36 g/cm3 and several µCT scans were taken during the hydration. The resulting data showed the progressive decrease of the density of the pellets, the preferential suction of the pellets and the final homogenisation at complete saturation. A side effect of the µCT scanning, probably related to disconnecting the hydration cell from the injection system during scanning, was the occurrence of fractures. These fractures allowed to measure the swelling of the pellets to be about 50% of volume increase. After drying of the sample, the original difference between pellets and powder did not reoccur. It can be concluded that the hydration of this pellet/powder mixture takes quite some time. Once saturated, no preferential paths seem to be present at the 100 µm scale. From this point of view, the 50/50 pellet/powder Foca mixture is a promising solution for the sealing of shafts of underground nuclear waste storages.

Main learning points concerning bentonite homogenization / mechanical evolution and relevance for the project

How could this work inform a new experimental or modelling study in BEACON?
References (ideally with web links) Van Geet M., Volckaert G. and Roels S., "The use of microfocus X-ray computed tomography in characterising the hydration of a clay pellet/powder mixture", Applied Clay Science, Vol. 29, pp. 73-87, 2005
Recommendations for BEACON project

Project Acronym ---	**Location** Prague, CZ	**Type** Laboratory experiments
Lead organiser CTU in Prague	**Start date** ---	**End date** On-going
Main partners involved in the project CTU	**Characteristics of swelling clay** - Ca-Mg bentonite - Powder, compacted powder,pellets - Various dry densities	**Water Saturation** Artificial, constant pressure
Instrumentation - Total force (pressure) - Permeability	**Main elements related to homogenization** Evolution bentonite saturation and swelling pressure	**Interfaces with other material**
Modelling Yes/no: Limited modelling only. Groups/Codes : Charles University / SIFEL	**Main processes studied** ☐T ☒H ☒M ☒Swelling pressure ☐Gas transfer ☐Other – Mineralogicall changes, corrosion	**Reference concept if pertinent**
Main objectives of the experiment or modelling study Laboratory measurement of permeability and swelling pressure in constant volume apparatus.		
General description The CEG has extensive dataset from measurement of water permeability and swelling pressure in constant volume apparatus (Figure 1). A time series consisting of total pressure development on the top of the cell, hydraulic gradient, initial&final water content, dry density and permeability is available for various materials. For every material the test is performed for several densities therefore, density dependency is also available. The dataset is primarily available for Czech Ca/Mg bentonite in various forms (powder, compacted, pellets) however other materials (such as GMZ) are available too.		

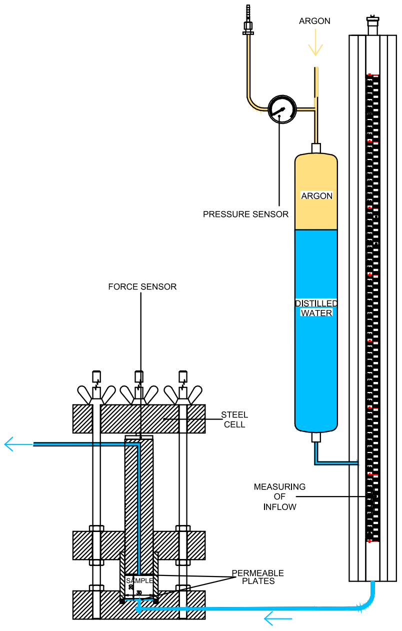


Figure 1 - Apparatus

Main learning points concerning bentonite homogenization / mechanical evolution and relevance for the project

The dataset provides basic material data and the temporary evolution of parameters (from dry material into fully saturated state) during permeability test.

How could this work inform a new experimental or modelling study in BEACON?

Great calibration and validation tool for the material models. Highly controlled boundary conditions and well defined material.

The test can be performed for other bentonites if desired.

References (ideally with web links)

Recommendations for BEACON project

Project Acronym -	**Location** Charles University	**Type** lab-test
Lead organiser Charles University	**Start date** 2014	**End date** In progress
Main partners involved in the project -	**Characteristics of swelling clay** Bentonite B75 (Cerny Vrch) Ca-Mg bentonite, montmorillonite content 60%, linitial water content 10%, samples precompacted to different values of ρ_d.	**Water Saturation** -
Instrumentation -	**Main elements related to homogenization** -	**Interfaces with other material** -
Modelling no	**Main processes studied** ☐T ☒H ☒M ☒Swelling pressure ☐Gas transfer ☐Other	**Reference concept if pertinent** -

Main objectives of the experiment or modelling study

The main objective of the study is description of the mechanical behaviour and retention properties of Czech bentonite B75 from Cerny vrch deposit. Microstructure of the samples pre-compacted to different initial dry densities is studied by different laboratory techniques.

The experimental program consists of water retention curves determined by vapour equilibrium method (VEM), determination of pore size distribution by mercury intrusion porosimetry (MIP) and digital image analysis using environmental scanning electron microscope (ESEM). Further, loading and unloading tests were carried out as well as constant load swelling test in oedometer.

General description

All the samples used in experimental program were prepared by pre-compaction of the bentonite powder at approximate water content of 10%.

WRC

Water retention curves were determined on the samples of three initial dry densities (1,27, 1,6 and 1,8 g/cm^3). After compaction, the samples were oven dried at 110°C. Different hydraulic path were applied to the samples: half of the samples was equilibrated under wetting path and the other half was first equilibrated at the suction of 3,29 MPa and then tested under drying path.

Another set of the samples was equilibrated by VEM directly after compaction and compared to the samples, which were oven dried before VEM testing. An example of retention curves is presented in Fig.1. The effect of initial dry density can be observed in Fig 1(b) and (c).

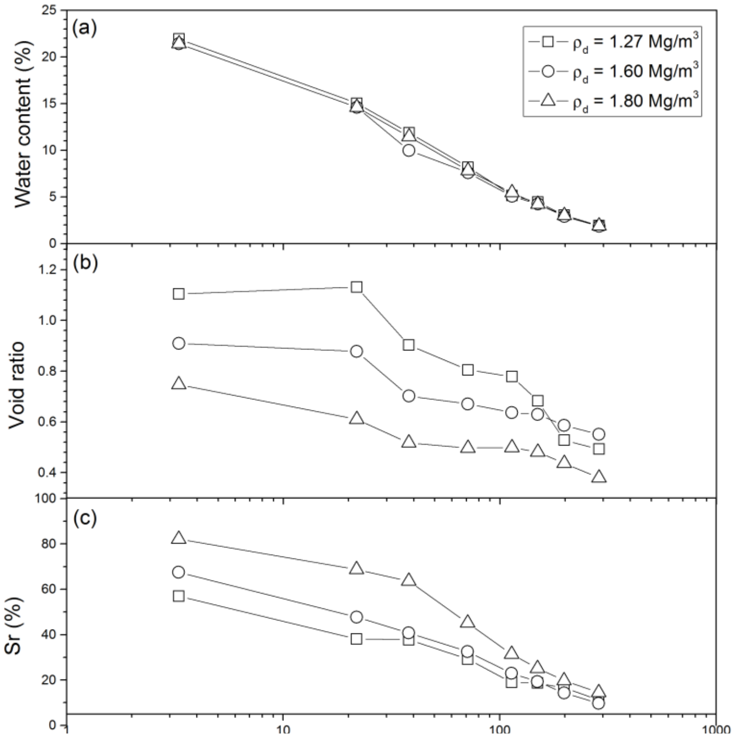


Fig. 1 Water retention curves for three initial dry densities

MIP

Mercury intrusion porosimetry was performed at the Department of Inorganic Technology at the University of Chemistry and Technology Prague (Apparatus Autopore IV, Micromeritics). The samples of two different initial dry densities were equilibrated at suctions of 286.7 MPa, 38 MPa and 3.29 MPa. The samples were then freeze-dried to preserve their microstructure and tested under the mercury pressures between 0.01 MPa (0.1 mm pore radius) and 400 MPa (1.5 nm pore radius).

The results demonstrated the influence of the original dry density on the structure of pre-compacted samples and the change of macrovoids distribution with suction (Fig. 2).

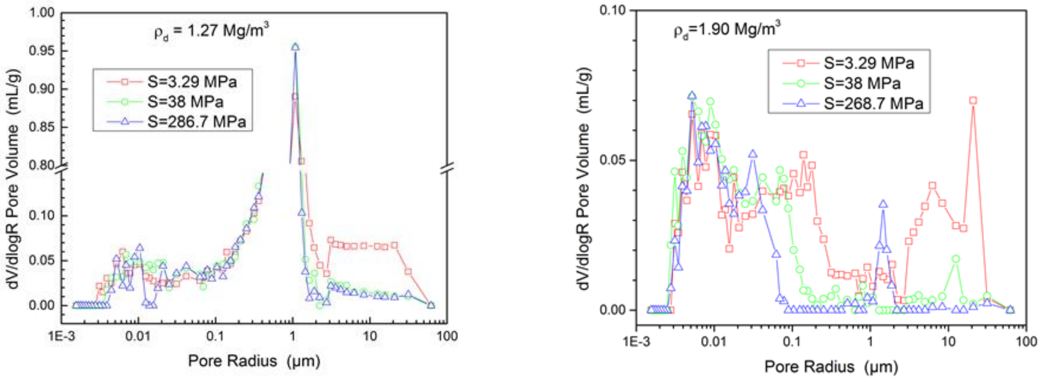


Fig. 2 Pore size distributions determined by MIP.

ESEM

The Environmental Scanning Electron Microscope tests have been performed at the Institute of Scientific Instruments of the Czech Academy of Sciences, Brno. The samples were equilibrated at the suction of 286.7 MPa. The tests were performed at constant temperature of 5°C. The water vapour pressure was imposed directly in the ESEM chamber, which allowed the direct observation of the microstructure response to the suction changes. The vapour pressure was gradually increased from 93 Pa up to 850 Pa (the relative humidity 10 to 97%). After the maximum value of the relative humidity was reached, it was gradually decreased again down to 10%.

The example of micrographs from ESEM is presented in Fig. 3, showing an increase of the interaggregate distance with decreasing suction. The irreversible changes of the distance between aggregates were observed after wetting-drying cycle.

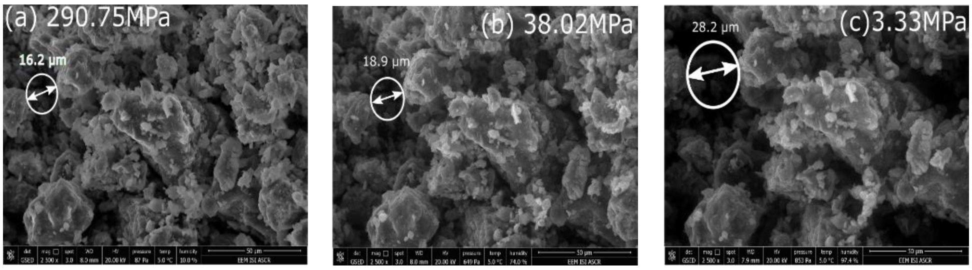


Fig. 3 Example of ESEM micrographs of bentonite compacted to dry density of 1,27 g/cm³

Mechanical laboratory tests

Standard mechanical tests including oedometer loading and unloading tests and triaxial compression tests have been performed on saturated specimens prepared from bentonite pre-compacted to relatively low dry density of 1,25 g/cm³. Fig.4 shows the swelling strain versus time for dry density of 1.25 g/cm³. Swelling under constant load was measured on the samples compacted to different initial dry densities.

The experimental program is still ongoing. The aim of the upcoming tests is to broaden the set of experimental data to combine more effectively the results of different experimental methods. The oedometer tests on unsaturated specimens are planned as well as the compression tests under increased temperature.

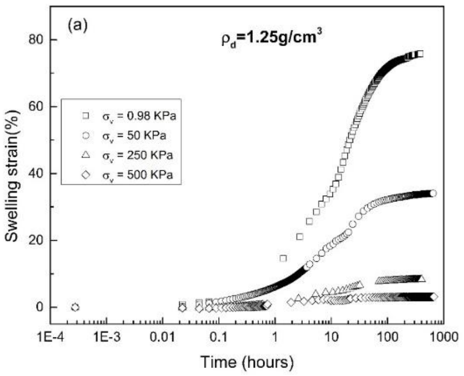


Fig.4 Swelling strain vs. time curves for initial dry density of 1.25g/cm^3

Main learning points concerning bentonite homogenization / mechanical evolution and relevance for the project

The analysis of the results consistently shows that the larger pores in bentonite structure contribute significantly to wetting induced swelling. The smallest micropores are not influenced by the suction value. The initial dry density and vertical load influence the swelling strain substantially.

How could this work inform a new experimental or modelling study in BEACON?

The presented research is focused on microstructural changes associated with wetting and drying of the pre-compacted bentonite samples. It simulates the processes expected in the bentonite barrier in nuclear waste repository. The combination of different methods allows to develop a joint interpretation of the microstructural behaviour of compacted bentonite.

References (ideally with web links)

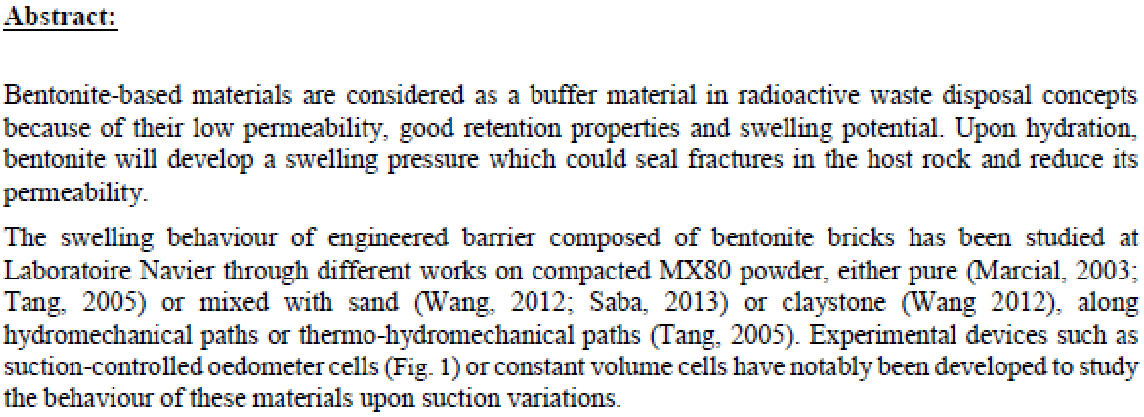
Sun, H., Mašín, D. and Boháč , J. (2017). Experimental characterization of retention properties and microstructure of the Czech bentonite B75. Proc. 19th ICSMGE, submitted.

Recommendations for BEACON project

Further tests should be performed on B75 bentonite. In particular, experiments at elevated temperature are missing to fully calibrate the constitutive model to be used in simulations.

Project Acronym Effects of heterogeneities on the hydromechanical behaviour of bentonite-based engineered barriers : results and current works at Laboratoire Navier	**Location** Laboratoire Navier	**Type** lab-test
Lead organiser Andra	**Start date**	**End date**
Main partners involved in the project Université Paris-Est	**Characteristics of swelling clay** MX80 compacted powder, pure or mixed with sand or claystone	**Water Saturation** Artificial
Instrumentation	**Main elements related to homogenization**	**Interfaces with other material**
Modelling Yes/no: Groups/Codes :	**Main processes studied** ☐T ☐H ☐M ☐Swelling pressure ☐Gas transfer ☐Other	**Reference concept if pertinent**

Main objectives of the experiment



Abstract:

Bentonite-based materials are considered as a buffer material in radioactive waste disposal concepts because of their low permeability, good retention properties and swelling potential. Upon hydration, bentonite will develop a swelling pressure which could seal fractures in the host rock and reduce its permeability.

The swelling behaviour of engineered barrier composed of bentonite bricks has been studied at Laboratoire Navier through different works on compacted MX80 powder, either pure (Marcial, 2003; Tang, 2005) or mixed with sand (Wang, 2012; Saba, 2013) or claystone (Wang 2012), along hydromechanical paths or thermo-hydromechanical paths (Tang, 2005). Experimental devices such as suction-controlled oedometer cells (Fig. 1) or constant volume cells have notably been developed to study the behaviour of these materials upon suction variations.

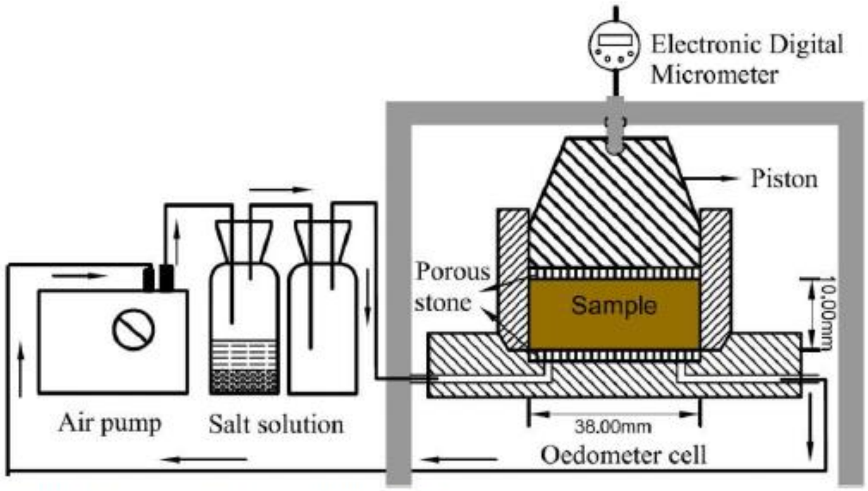


Fig. 1. Suction-controlled oedometer cell (Wang, 2012).

Heterogeneities in bentonite bricks buffers are mainly due to technological voids. These latter reduce the dry density at equilibrium because the material does not get hydrated in true constant volume conditions. Experimental results showed that the swelling mechanisms of bentonite-based materials are the same for pure bentonite and sand/claystone-bentonite mixtures. A unique relationship exists between the bentonite dry density and the swelling pressure at equilibrium (Fig. 2). Therefore, technological voids reduce the swelling pressure of the engineered barrier at equilibrium.

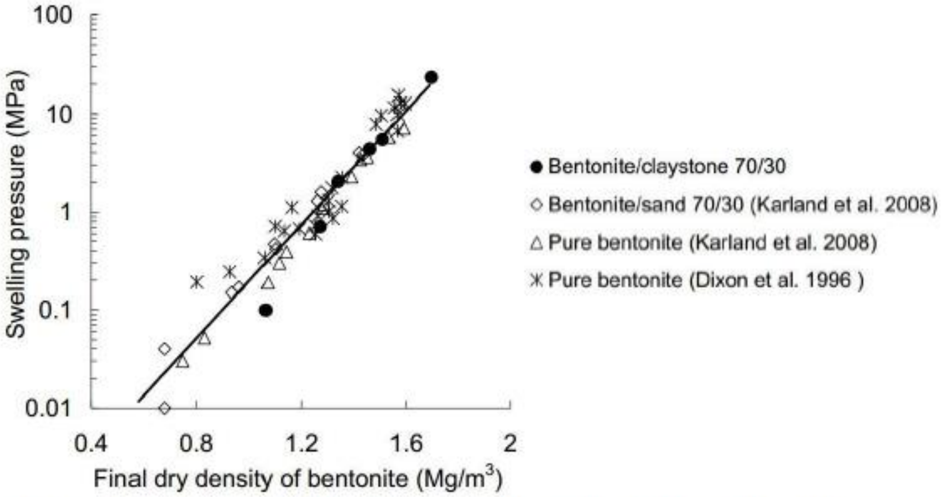


Fig. 2. Swelling pressure versus final dry density of bentonite for mixtures using MX80 bentonite. After Wang (2012).

General description

More recently, bentonite pellets-powder mixtures have been considered as a candidate material for engineered barrier because of operational convenience and reduced technological voids. Hoffmann (2007) evidenced that these mixtures get homogenised upon hydration and that their swelling pressure at equilibrium also depends on dry density. Van Geet et al. (2005) also evidenced the homogenisation of pellets-powder mixtures upon hydration through microfocus X-ray computed tomography.

Works are currently being carried out at Laboratoire Navier to study the performance of pellets-powder mixtures (Fig. 3) used as buffer materials. Molinero-Guerra et al. (2017) highlighted that these mixtures are characterised by heterogeneities at both microscopic and macroscopic scales. In particular, powder's segregation can lead to heterogeneous distribution of powder and pellets, which leads to dry density variation.

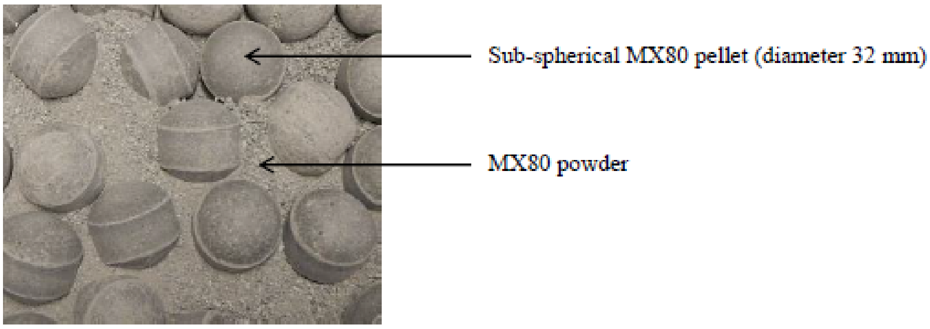


Fig. 3. Bentonite pellets-powder mixture.

In order to assess the influence of heterogeneities on the swelling behaviour of these mixtures during the first steps of hydration, at high suctions, before homogenisation, Discrete Element Method is currently used (PhD Thesis of Darde). Pellets swelling is modelled by imposing a radius increase. Interactions between two pellets in contact are governed by Hertz's law and the Coulomb condition. Young modulus is progressively reduced to take into account stiffness decrease upon hydration. Thus, the swelling behaviour of single pellets as well as their compressibility have been experimentally studied upon suction decrease (Fig. 4)

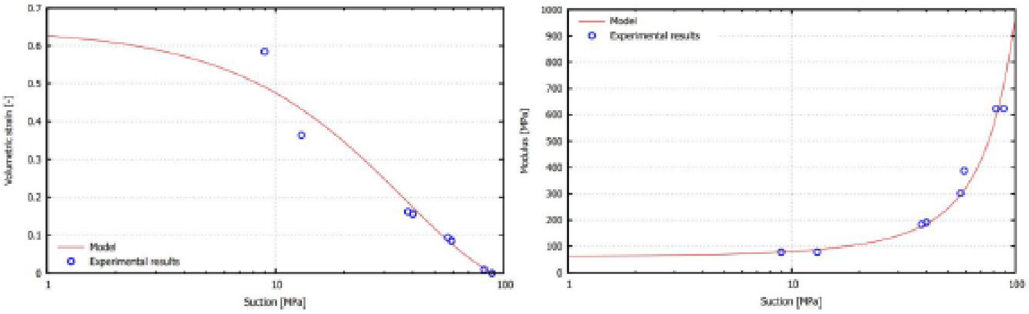


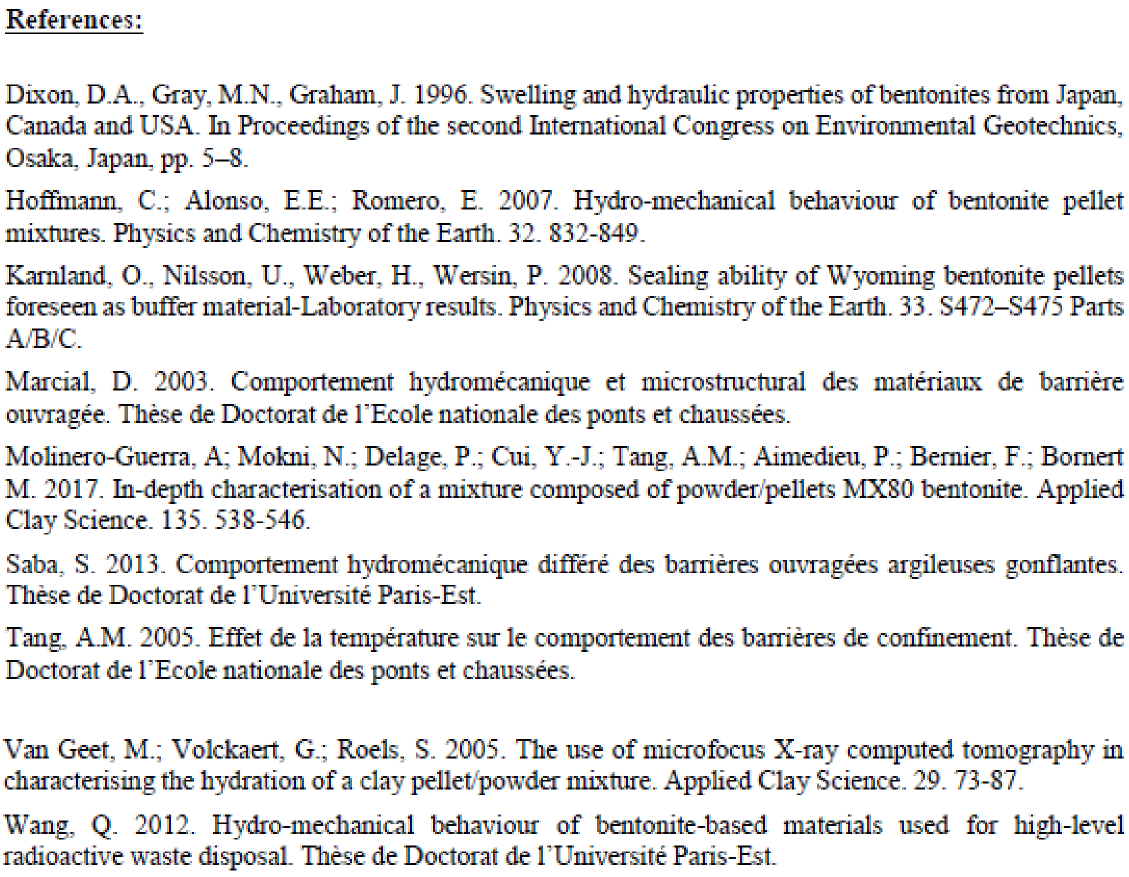
Fig. 4. Volumetric strain and modulus variation of a single pellet upon suction decrease.

Swelling pressure tests on mixtures with varying powder contents will be carried out to determine more relevant material's characteristics for simulations, and to assess the influence of local heterogeneities on the hydromechanical behaviour.

Main learning points concerning bentonite homogenization / mechanical evolution and relevance for the project

How could this work inform a new experimental or modelling study in BEACON?

References (ideally with web links)



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Hoffmann, C.; Alonso, E.E.; Romero, E. 2007. Hydro-mechanical behaviour of bentonite pellet mixtures. Physics and Chemistry of the Earth. 32. 832-849.

Karnland, O., Nilsson, U., Weber, H., Wersin, P. 2008. Sealing ability of Wyoming bentonite pellets foreseen as buffer material-Laboratory results. Physics and Chemistry of the Earth. 33. S472–S475 Parts A/B/C.

Marcial, D. 2003. Comportement hydromécanique et microstructural des matériaux de barrière ouvragée. Thèse de Doctorat de l'Ecole nationale des ponts et chaussées.

Molinero-Guerra, A; Mokni, N.; Delage, P.; Cui, Y.-J.; Tang, A.M.; Aimedieu, P.; Bernier, F.; Bornert M. 2017. In-depth characterisation of a mixture composed of powder/pellets MX80 bentonite. Applied Clay Science. 135. 538-546.

Saba, S. 2013. Comportement hydromécanique différé des barrières ouvragées argileuses gonflantes. Thèse de Doctorat de l'Université Paris-Est.

Tang, A.M. 2005. Effet de la température sur le comportement des barrières de confinement. Thèse de Doctorat de l'Ecole nationale des ponts et chaussées.

Van Geet, M.; Volckaert, G.; Roels, S. 2005. The use of microfocus X-ray computed tomography in characterising the hydration of a clay pellet/powder mixture. Applied Clay Science. 29. 73-87.

Wang, Q. 2012. Hydro-mechanical behaviour of bentonite-based materials used for high-level radioactive waste disposal. Thèse de Doctorat de l'Université Paris-Est.

Recommendations for BEACON project

Project Acronym Experimental characterization of cement bentonite interaction	**Location** -	**Type** lab-test
Lead organiser RWI, Institute of Geological Sciences, University of Bern	**Start date** -	**End date** -
Main partners involved in the project Institute of Forensic Medicine, University of Bern	**Characteristics of swelling clay** MX-80	**Water Saturation** Artificial
Instrumentation X-ray CT imaging	**Main elements related to homogenization**	**Interfaces with other material**
Modelling Yes/no: Groups/Codes :	**Main processes studied** ☐T ☐H ☐M ☐Swelling pressure ☐Gas transfer ☐Other	**Reference concept if pertinent**

Main objectives of the experiment

The emplacement of cementitious material next to clay material generates an enormous chemical gradient in pore water composition that drives diffusive solute transport. Laboratory studies and reactive transport modeling predict significant mineral alteration at and near interfaces, mainly resulting in a decrease of porosity in bentonite. The goal of this project is to characterize and quantify the cement/bentonite skin effects spatially and temporally in laboratory experiments.

General description

A newly developed mobile X-ray transparent core infiltration device was used, which allows performing X-ray computed tomography (CT) periodically without interrupting a running experiment. A pre-saturated cylindrical MX-80 bentonite sample (1920 kg/m3 average wet density) is subjected to a confining pressure as a constant total pressure boundary condition. The infiltration of a hyperalkaline (pH 13.4), artificial OPC (ordinary Portland cement) pore water into the bentonite plug alters the mineral assemblage over time as an advancing reaction front. The related changes in X-ray attenuation values are related to changes in phase densities, porosity and local bulk density and are tracked over time periodically by non-destructive CT scans. Mineral precipitation is observed in the inflow filter. Mineral alteration in the first millimeters of the bentonite sample is clearly detected and the reaction front is presently progressing with an average linear velocity that is 8 times slower than that for anions. The reaction zone is characterized by a higher X-ray attenuation compared to the signal of the pre-existing mineralogy. Chemical analysis of the outflow fluid showed initially elevated anion and cation concentrations compared to the infiltration fluid due to anion exclusion effects related to compaction of the bentonite core that was adjusting to the experimental conditions. Subsequently, the OPC fluid is fully buffered, and a gradually decreasing ionic strength is observed as a result of progressive consumption of hydroxide at the mineral reaction front

Main learning points concerning bentonite homogenization / mechanical evolution and relevance for the project

How could this work inform a new experimental or modelling study in BEACON?

References (ideally with web links)

Dolder F. D., Mäder U., Jenni, A., Schwendener N., "Experimental characterization of cement bentonite interaction using core infiltration techniques and 4D computed tomography", Physics and Chemistry of the Earth, Vol. 70-71, pp. 104-113, 2014

Dolder F. D., "Hydro-mechanical behaviour of bentonite-sand mixture used as sealing materials in radioactive waste disposal galleries", PhD thesis, 2015

Recommendations for BEACON project

Project Acronym FORGE	**Location** Clay Technology's lab, Lund, Sweden	**Type** lab-test
Lead organiser Clay Technology	**Start date** 2011	**End date** 2014
Main partners involved in the project Clay Technology	**Characteristics of swelling clay** MX-80 bentonite, purified Calcium and Sodium montmorillonite	**Water Saturation** Artificial
Instrumentation Axial stress, Water pressure, Flow	**Main elements related to homogenization** Density profiles in samples exposed to (large) external water pressure differences. Non-linear flow- and pressure response due to water, air, and kerosene pressurisation.	**Interfaces with other material** No
Modelling Yes/no: Yes Groups/Codes : Analytical work, see (Birgersson and Karnland, 2014)	**Main processes studied** ☐T ☒H ☒M ☒Swelling pressure ☒Gas transfer ☐Other	**Reference concept if pertinent**

Main objectives of the experiment

The investigation was primarily performed in order to gain insight of the process of gas migration in engineered bentonite barriers, which are adopted in many concepts for storage of radioactive waste. For such barriers to function properly, they are required to be confined volumetrically while still having access to an external water source. Under such conditions a "swelling pressure" develops, giving the barrier efficient sealing properties.

The relevant boundary condition for studying gas migration in bentonite barriers is thus a system open for both water and gas. This requirement, in turn, have the consequence that response due to gas and water pressure gradients actually are not fully separable. The focus of the present study has therefore been extended to include response both due to water and air pressure gradients. In addition to giving direct insight of the gas migration process, these tests also gives useful general information on bentonite material properties. The results of are therefore also of value for e.g. validating material models for bentonite.

The work has been performed on the request of the Swedish nuclear fuel and waste management company (SKB) and has received funding from the European Atomic

Energy Community's Seventh Framework Programme (FP7/2007-2011) under Grant Agreement no230357, the FORGE project.

General description

A large set of pressure and flow response tests in bentonite are reported. The main objective of the study was to gain insight into the process of gas migration in bentonite components. However, because gas pressurization of water saturated bentonite requires consideration of water pressurization, also the latter process was focused upon.

The tests were performed on cylindrical samples of diameter 35 mm and height in the range 2–20 mm, and are divided into three main categories, depending on the externally imposed conditions.

- Externally applied water pressure difference.
- Externally applied air pressure difference.
- Uniformly applied water pressure.

Two main types of injection filter geometries were employed: either the external pressure was applied in a small point-like central filter, or pressurization was performed in a filter covering the full bottom area.

In the tests, evolution of the pressure exerted by the bentonite was recorded. In tests that involved external pressure difference, also fluid flow evolution was measured. In a few cases, the density response due to applied water pressure differences was measured. The main results are as follows:

- Externally applied water pressure differences:
  - Sample pressure depends non-linearly on applied water pressure. The type of sample pressure response is also strongly dependent on type of injection filter geometry.
  - For injection filters of type A, the water flow response is linear in the limit of small external water pressure (Darcy's law). Generally, however, the flow response is non-linear, and depends strongly on injection geometry.
  - Water breakthrough events can be induced. In these, he flow completely changes characteristics as compared to "normal" flow; in particular the flow rates increase tremendously (a factor 10^4 or more). The phenomena is very much reminiscent of piping. The necessary (but not sufficient) criteria for inducing water breakthrough events is that injection pressure exceeds sample pressure. The flow path during water breakthrough is preferably at the interface between sample holder and clay body.
  - Density redistribution in samples exposed to water pressure differences.
  - Observations of hysteresis in sample pressure.
- Externally applied air pressure differences:
  - For applied gas pressures below the (initial) sample pressure, there is no response in the latter quantity. This result is independent of injection geometry.
  - For applied gas pressure below sample pressure, the only transport mechanism is diffusion of dissolved gas.
  - For applied gas pressure above (initial) sample pressure, gas breakthrough events can be induced. In these events, the flow changes characteristic drastically – in particular it increases tremendously. A gas breakthrough is

  analogous to the breakthrough observed in water pressurization. In particular, the flow of gas in a gas breakthrough event preferably occurs at the interface between sample holder and clay body.
  - Rather than inducing a gas breakthrough event when injection pressure exceeds sample pressure, various types of consolidation of the clay body by the gas phase have been demonstrated. In these situations, the increased pressure induces water transport out of the test cell with the result that the volume of the clay body is smaller than the volume of the test cell. The remaining volume is consequently occupied by the gas phase. However, no breakthrough events are induced and gas is only transported through the sample in dissolved form (diffusion).

- In a special test, the pressurizing fluid was kerosene rather than water or air. The response from kerosene pressurization is basically identical to that of air, implying that all types of non-polar fluids have basically the same type of interaction with water saturated bentonite. This interaction is furthermore fundamentally different from the interaction between water and bentonite, demonstrating that gas migration in water saturated bentonite is not a two-phase flow phenomena.
- Uniformly applied water pressure:
  - Hysteresis effects in resulting sample pressure after exposing the sample to pressurization pulses. The trend is that the sample pressure increases after being exposed to water pressurization and the effects seem to be larger in samples of MX-80 bentonite as compared to pure montmorillonite.
  - The response in sample pressure when a uniform external water pressure is applied is always less than the applied pressure. Typically the response is about a factor 0.9 of the applied pressure.

Main learning points concerning bentonite homogenization / mechanical evolution and relevance for the project

The mechanical response of (water saturated) bentonite is to a large degree governed by the properties of montmorillonite interlayer pores.

How could this work inform a new experimental or modelling study in BEACON?

It demonstrates that basically any type of response of (water saturated) bentonite is governed by the properties of montmorillonite interlayer pores.

References (ideally with web links)

Birgersson, M., Karnland, O., 2015. Flow and pressure response in compacted bentonite due to external fluid pressure, TR-14-28, SKB. http://www.skb.se/publikation/2483908/TR-14-28.pdf

Birgersson, M., Karnland, O., 2014. Summary of Clay Technology's work within FORGE, in: Sellin, P. (Ed.), Experiments and Modelling on the Behaviour of EBS. FORGE Report D.3.38. https://www.bgs.ac.uk/forge/docs/reports/D3.38-R.pdf

Recommendations for BEACON project

Take these observations into account in e.g. further model development.

Since these test are small scale, have simple geometries, and have well defined boundary conditions, they are very suitable for model testing.

Project Acronym FSS lab-tests	**Location** CEA Saclay	**Type** Lab-test
Lead organiser CEA	**Start date** 2014	**End date** 2017
Main partners involved in the project CEA, Andra	**Characteristics of swelling clay** WH2 MX80 bentonite pellet/crushed pellet mix	**Water Saturation** Artificial
Instrumentation Swelling pressure, local pore and total pressure, relative humidity	**Main elements related to homogenization** Local stresses, representative volume for granular materials	**Interfaces with other material** Steel/Bentonite (exp. setup)
Modelling No	**Main processes studied** ☐T ☐H ☒M ☒Swelling pressure ☐Gas transfer ☐Other	**Reference concept if pertinent** Andra

Main objectives of the experiment or modelling study

The objectives of the experimental programme were to study the swelling pressure of a MX80 pellet/crushed pellet mix representative of the material considered for Andra's repository engineered barriers. As a byproduct coming from back analysis for the Beacon project, elements regarding the representative volume for the characterization of such a granular material and the heterogeneities of the stress field are provided.

A demonstration of the filling process of a full-scale sealing was carried out in the framework of the DOPAS-FSS project, using bentonite under granular form. This material, call FSS material in the following, is composed of MX-80 bentonite under the form of roughly spherical ϕ 32 mm pellets mixed with crushed pellets. Target dry density values are obtained for samples of approximately the same size by varying the pellet to crushed pellet mass ratio. In one of the examples it is compared with another material (called PGZ material), composed of ϕ 7 mm pellets mixed with powder, whose representative volume is in the order of 100 times smaller.

General description

Swelling pressure tests were carried out using constant volume cells (Figure 1) of three different diameters (ϕ57 mm, ϕ120 mm, ϕ240 mm) and different heights, resulting in different sample volumes. Resaturation of the samples is achieved using synthetic site water representative of the waters found at the Meuse-Haute Marne URL, at atmospheric pressure through the bottom of the sample.

1. Representative volume

The dry density vs. swelling pressure reference curve was established for the FSS material mostly using ϕ120 mm, V≈720 cm³ tests containing from 16 to 20 pellets (Figure 2). Around density 1.52, swelling tests were performed using different samples sizes that show different behaviors (Figure 3). Although all tests show similar curve shapes (same phenomenology, that appears to depend mostly on the dry density and hydration geometry), and time scaling that depend on the sample thickness, final value also seems to depend on the sample diameter. This fact may point out an effect of non-representative volume, itself a consequence of incomplete homogenization (the average dry density is not enough to predict final swelling pressure).

Divergence of the curves between the FSS and PGZ material (Figure 2) at higher dry densities would seem to indicate that the extent of homogenization is lower at higher density levels, but would require additional information.

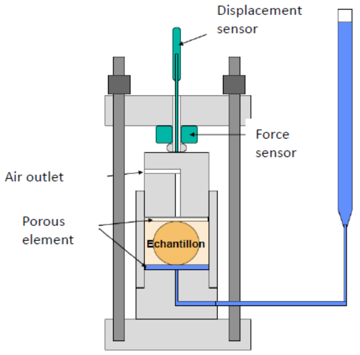


Figure 1: Principle schematic of the ϕ57 mm constant volume cell used in the experiments. It contains a single pellet for the smallest studied samples. Other diameters share the same basic design.

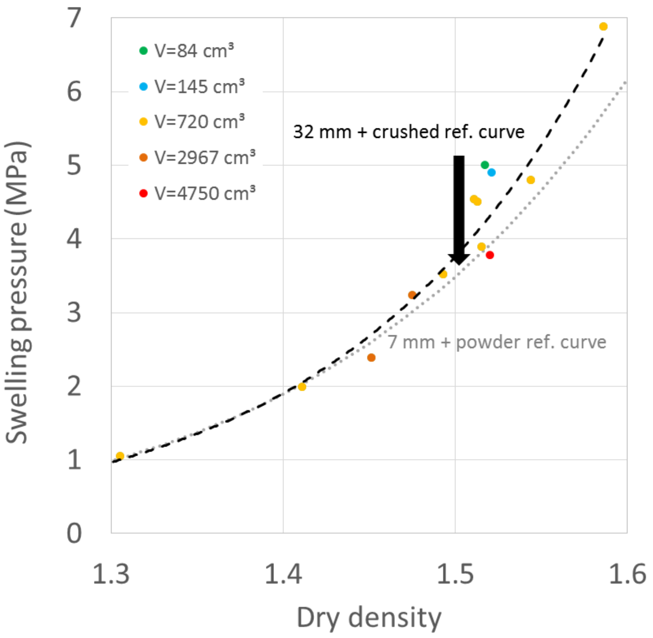


Figure 2: Final swelling pressure of FSS mix (ϕ 32 mm pellet) as a function of final dry density for various sample sizes, and its reference fit compared with PGZ mix (ϕ 7 mm pellet).

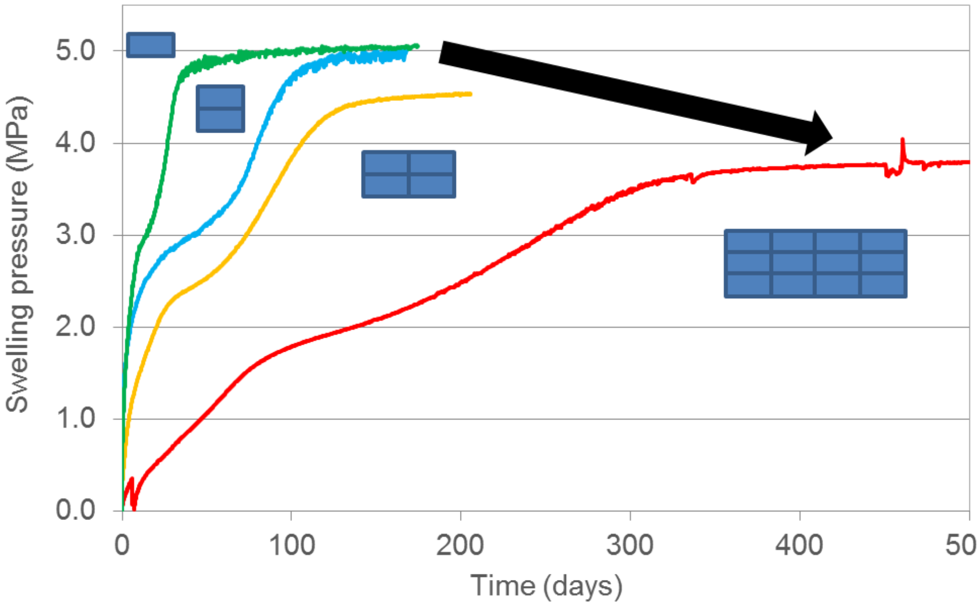


Figure 3: Swelling pressure kinetics for four samples around density 1.52 (same color code as for figure 2) of different volumes. The first two are diameter 57 mm, the other two are respectively 120 mm and 240 mm in diameter.

2. Local pressure measurements

Local pressure measurements were carried out for the ϕ240 mm test presented in Figure 3 as well as a ϕ120 mm test, both at approximately the same dry density. These pressure measurements are measured on a ϕ 7.6 mm disc (much smaller than a pellet) at several heights radially at the boundary of the cylindrical specimen. One can observe (Figure 4) than local pressures do not seem to converge at the "lab time scales" (>600 days here). Variability seems to be in the order of 20%.

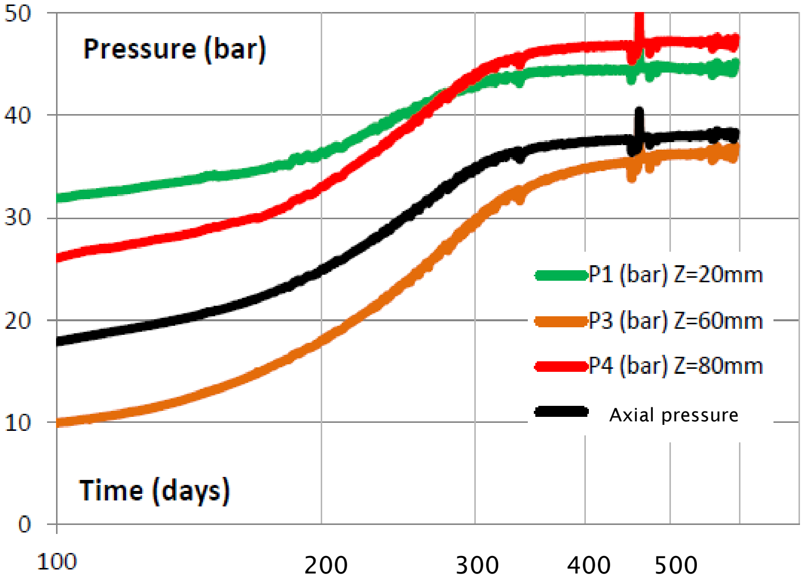


Figure 4: Local total pressure at several sample heights compared with the axial pressure for the ϕ240 mm test.

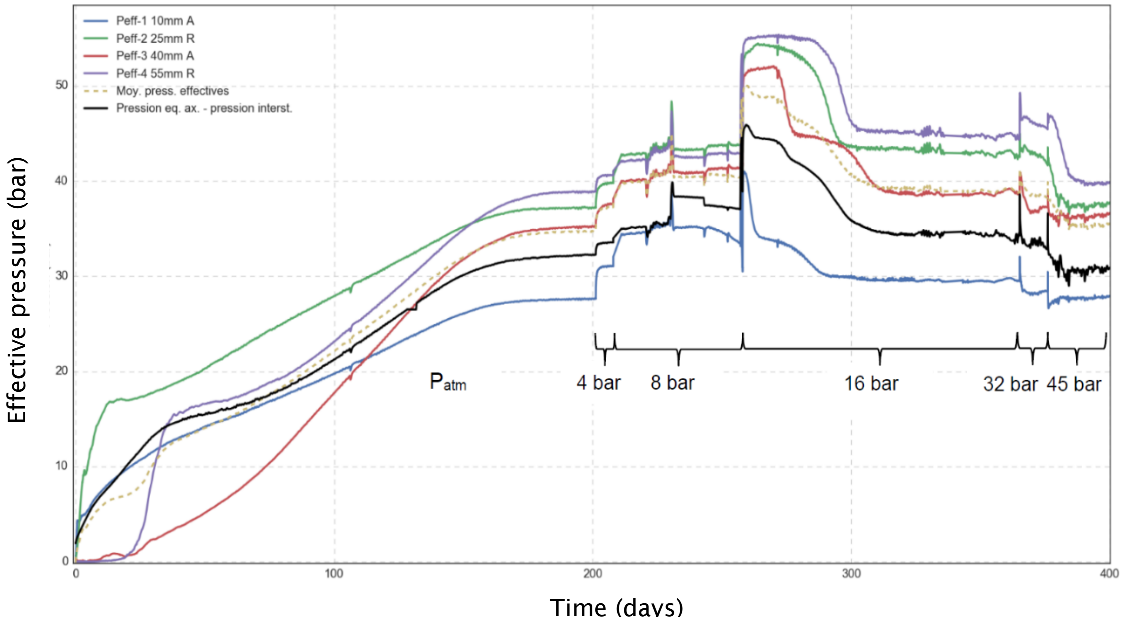


Figure 5: Local effective pressure at several sample heights (green, red, purple, blue) compared with the axial pressure (black) for the ϕ120 mm test (water injection pressures are reported).

In the second case (Figure 5), a ϕ120 mm sample was resaturated first at atmospheric pressure using the same method as described above, then water was injected at progressively increasing pressures from 4 to 45 bar (representative of the site pore pressure). Effective pressures are represented since porewater pressure sensors are placed close to the total pressure sensors. It can be observed that the pressure heterogeneities of 20-30% do not resorb after saturation is fully achieved and porewater pressures reach the expected values.

Main learning points concerning bentonite homogenization / mechanical evolution and relevance for the project

For bentonite under granular form :

- Extent of rehomogenization may be lower at high densities, small samples show abnormally high swelling pressure (maybe apparatus bias?)
- Stress field heterogeneities do not resorb at lab time scales, for the 1.52 density studied, and are of order 20-30%.

How could this work inform a new experimental or modelling study in BEACON?

This could inform studies of the rehomogenization of granular materials.

References (ideally with web links)

To be published.

Internal reports (in French)

F. Bernachy-Barbe, W. Dridi, W. Guillot, F.T. Caractérisation Bentonite - Rapport final FSS et essai de fluage, NT CEA/DEN, DPC/SECR/NT/2016/044 indice B, 2017

C. Gatabin, W. Guillot, F. Bernachy-Barbe, F.T. Caractérisation bentonite - REM : Essais de gonflement à l'échelle du laboratoire avec différentes eaux d'imbibition, DPC/SECR/RT/2015/050 indice B, 2016

Recommendations for BEACON project/ What would I do differently, were I to repeat my earlier study?

-

Project Acronym Gas release of bentonites	**Location** Grimsel rock laboratory / GRS lab	**Type** URL/lab-test
Lead organiser GRS	**Start date** 1996	**End date** 2007
Main partners involved in the project	**Characteristics of swelling clay** FEBEX bentonite	**Water Saturation** Artificial/natural
Instrumentation	**Main elements related to homogenization**	**Interfaces with other material**
Modelling Yes/no: Groups/Codes :	**Main processes studied** ☐T ☐H ☐M ☐Swelling pressure ☐Gas transfer ☐Other	**Reference concept if pertinent**

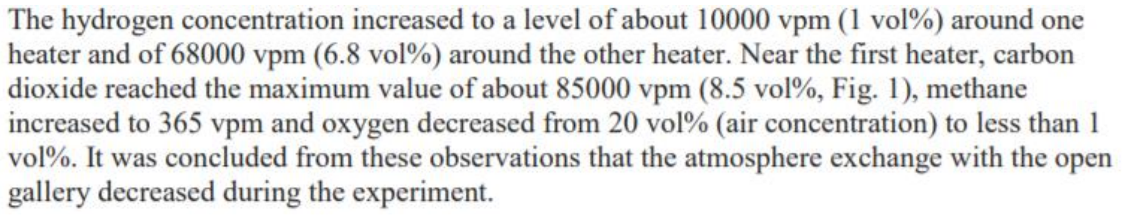
Main objectives of the experiment

To study the generation of gases from air-dry and hydrated FEBEX bentonite at the Grimsel rock laboratory and at the GRS lab [3].

General description

In the in-situ study, a buffer made up of highly compacted bentonite blocks was heated up to a maximum temperature of 100°C in two sections each containing a central heater. About 40-, 100- and 200-fold increases of, respectively, methane, hydrogen and carbon dioxide concentrations in draining pipes inside the bentonite buffer were observed.

Main learning points concerning bentonite homogenization / mechanical evolution and relevance for the project



The hydrogen concentration increased to a level of about 10000 vpm (1 vol%) around one heater and of 68000 vpm (6.8 vol%) around the other heater. Near the first heater, carbon dioxide reached the maximum value of about 85000 vpm (8.5 vol%, Fig. 1), methane increased to 365 vpm and oxygen decreased from 20 vol% (air concentration) to less than 1 vol%. It was concluded from these observations that the atmosphere exchange with the open gallery decreased during the experiment.

Still, though significant gas generation was observed, the gas pressure did not increase in excess of the atmospheric pressure around the second heater, and only in two draining pipes out of six around the first heater (see Fig. 2). Initially, no pressure increase was detected, and all released gases were concluded to migrate out of buffer through the gaps between the bentonite blocks and through the concrete seal separating the buffer from the open gallery. Then the gas pressure started to increase in two pipes, as accompanied by the detection of water in those. Apparently, formation water from the host rock reached the pipes and caused bentonite swelling to seal them.

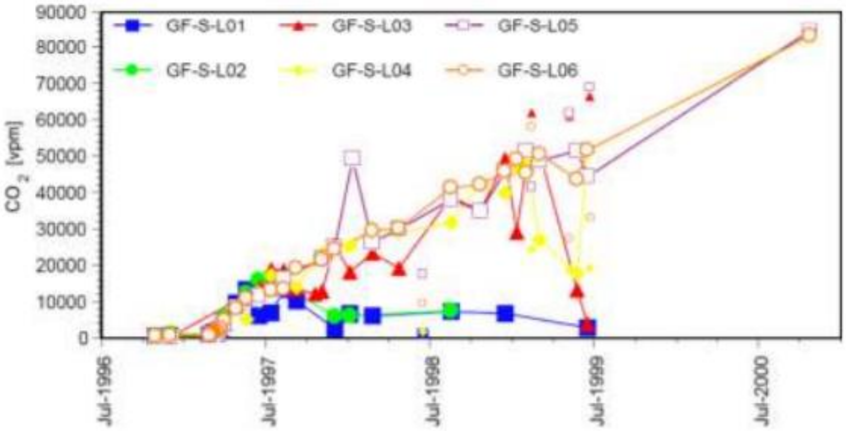


Fig. 1 Concentrations of carbon dioxide in draining pipes of the FEBEX in-situ experiment at Grimsel Test Site (vpm = 1 ml gas of a component in 1 m³ of the matrix gas) [3].

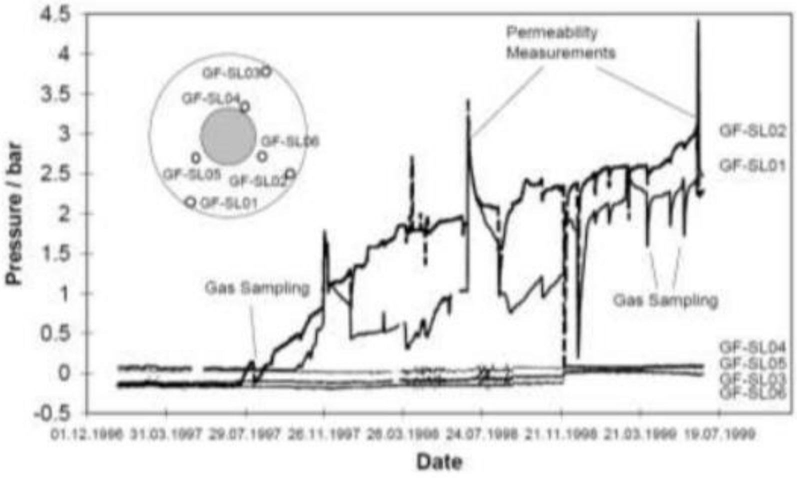


Fig. 2 Pressure evolution in the draining pipes of the FEBEX in-situ experiment at Grimsel Test Site [3].

In parallel to the in-situ test, laboratory experiments were carried out with dry and wet FEBEX bentonite exposed to temperatures of 20 °C, 50 °C and 95 °C in gas-tight welded glass vessels. To prepare wet samples, distilled water was added to bentonite at a weight ratio of 1:1. These experiments revealed that up to 0.35 m³ of carbon dioxide per one ton of hydrated bentonite were released for a reaction time of 100 days at 95 °C. With a reaction time of 10 years at 95 °C, 1 m³of carbon dioxide per one ton of hydrated bentonite was released. With decreasing temperature, the rate of gas generation decreased considerably. The generation of carbon dioxide did not depend on whether the residual volume of vessels was filled with air or nitrogen. The reason for this was supposed to be the oxygen adsorbed on bentonite or trapped in its pore space, which then presumably oxidized the organics to generate carbon dioxide. As an alternative source of carbon dioxide generation, a thermal decomposition of carbonates in the bentonite was suggested.

As can be seen in Fig. 3, an increase of the wet bentonite mass from 10 g to 100 g (plus 10 to 100 g water, respectively) in the 500-ml vessels resulted in a decrease of the carbon dioxide concentrations in the released gas by several times. This indicates that a back reaction occurred at higher partial pressures of carbon dioxide at the applied experimental conditions.

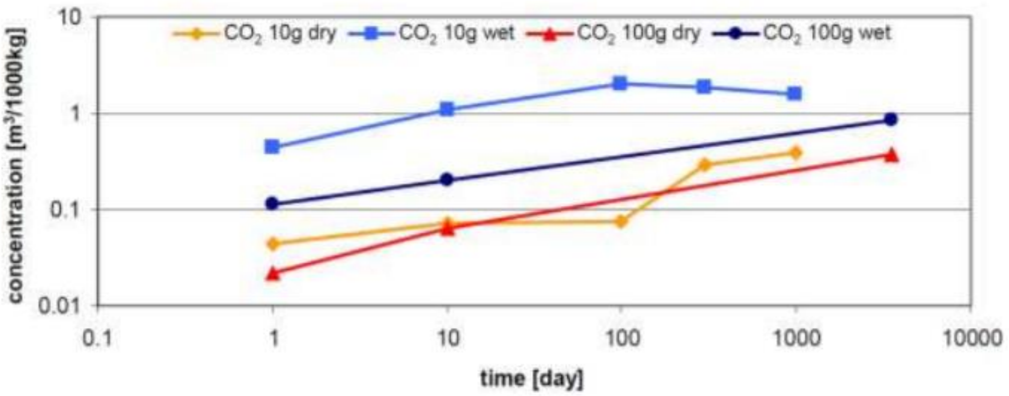


Fig. 3 Release of carbon dioxide from the dry and wet FEBEX bentonites at 95 °C as a function of time [3].

Since such a non-negligible gas release from bentonite may be of relevance for performance of a repository for high-level radioactive waste, a series of laboratory investigations with different bentonites is currently underway at the GRS laboratory. Fig. 4 shows the pressure evolution observed for three bentonites in contact with a cap rock solution diluted to a salinity of 150 g/l, which is used as a model solution for the clay pore water of Lower Cretaceous clays in the Northern Germany. At the applied temperature of 120 °C and solid/liquid ratio of 1/2, the gas pressure in excess of the vapor pressure of the solution varies between about 0.6 and 1.1 bar depending on the bentonite type (Fig. 4). Further experiments should provide data on fluid pressure and contribute to elucidation of the open questions identified in the previous study with the FEBEX bentonite [3].

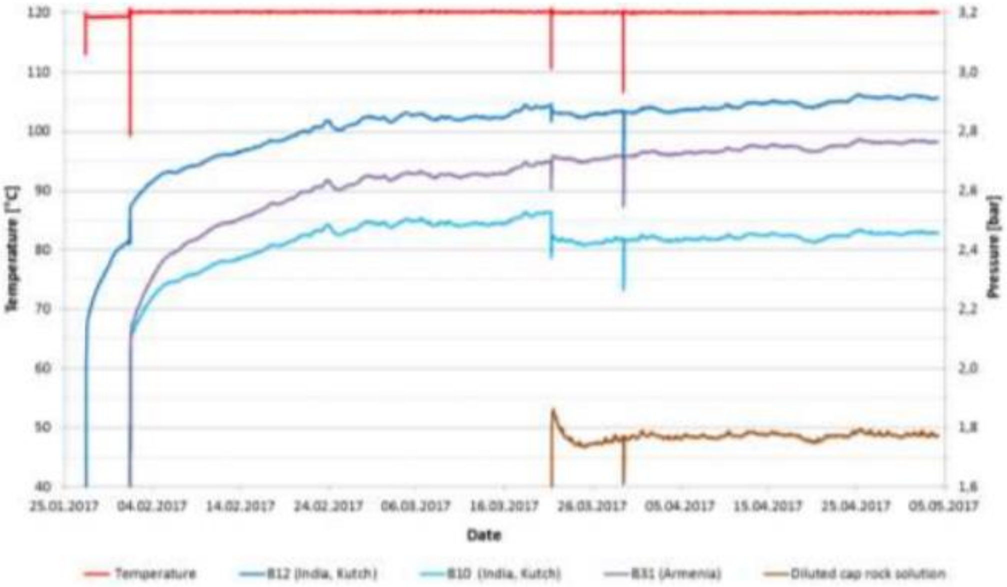


Fig. 4 Pressure evolution in bentonites B10, B12, and B31 as well as in the diluted cap rock solution at 120 °C as a function of time.

How could this work inform a new experimental or modelling study in BEACON?

References (ideally with web links)

[3] Jockwer, N., Wieczorek, K.: Investigations on gas generation, release, and migration in the frame of FEBEX. Report GRS-243, GRS, Braunschweig, 2008.

Recommendations for BEACON project

Project Acronym Microstructure and anisotropic swelling behaviour of compacted bentonite/sand mixture	**Location** -	**Type** lab-test
Lead organiser IRSN	**Start date** -	**End date** -
Main partners involved in the project Ecole des Ponts ParisTech	**Characteristics of swelling clay**	**Water Saturation** Artificial
Instrumentation	**Main elements related to homogenization**	**Interfaces with other material**
Modelling Yes/no: Groups/Codes :	**Main processes studied** ☐T ☐H ☐M ☐Swelling pressure ☐Gas transfer ☐Other	**Reference concept if pertinent**

Main objectives of the experiment

General description

In this work, the swelling pressure of a small scale compacted disk of bentonite and sand was experimentally studied in both radial and axial directions. Different swelling kinetics were identified for different dry densities and along different directions.

In parallel to the mechanical tests, microstructure investigation at the sample scale was conducted using microfocus X-ray computed tomography (μCT).

Main learning points concerning bentonite homogenization / mechanical evolution and relevance for the project

As a rule, the swelling pressure starts increasing quickly, reaches a peak value, decreases a little and finally stabilises. For some dry densities, higher peaks were observed in the radial direction than in the axial direction. The presence of peaks is related to the microstructure change and to the collapse of macropores.

Image observation showed a denser structure in the centre and a looser one in the border, which was also confirmed by image analysis. This structure heterogeneity in the radial direction and the occurrence of macro-pores close to the radial boundary of the sample can explain the large peaks observed in the radial swelling pressure evolution.

Another interesting result is the higher anisotropy found at lower bentonite dry densities, which was also analysed by means of µCT observation of a sample at low bentonite dry density after the end of test. It was found that the macro-pores, especially those between sand grains, were not filled by swelled bentonite, which preserved the anisotropic microstructure caused by uniaxial compression due to the absence of microstructure collapse.

How could this work inform a new experimental or modelling study in BEACON?

References (ideally with web links)

Saba S., Barnichon J-D., Cui Y. J., Tang A. M. and Delage P., "Microstructure and anisotropic swelling behaviour of compacted bentonite/sand mixture", Journal of Rock Mechanics and Geotechnical Engineering, Vol. 6, pp. 126-132, 2014

Saba S., Delage P., Lenoir N., Cui Y. J., Tang A. M. abd Barnichon J-D., "Further insight into 6 the microstructure of compacted bentoniteâA ¸Ssand mixture", Engineering Geology, Vol. 168, ˘ pp. 141-148, 2014

Saba S., "Hydro-mechanical behaviour of bentonite-sand mixture used as sealing materials in radioactive waste disposal galleries", PhD Thesis, 2013

Recommendations for BEACON project

Project Acronym Microstructure of saturated bentonites characterized by X-ray CT	**Location** -	**Type** lab-test
Lead organiser Hokkaido University	**Start date** -	**End date** -
Main partners involved in the project	**Characteristics of swelling clay** Wyoming bentonite	**Water Saturation** Artificial
Instrumentation	**Main elements related to homogenization**	**Interfaces with other material**
Modelling Yes/no: Groups/Codes :	**Main processes studied** ☐T ☐H ☐M ☐Swelling pressure ☐Gas transfer ☒Other	**Reference concept if pertinent**

Main objectives of the experiment

General description

Permeability tests and micro X-ray CT observations of Wyoming bentonite were performed to describe the relationship between microstructure and permeability of the bentonite used as a barrier material. Two types of samples, compacted bentonite-quartz sand mixtures and raw bentonite ores, were used in this study

Main learning points concerning bentonite homogenization / mechanical evolution and relevance for the project

The X-ray CT observations of the bentonite-quartz sand mixtures show that ’vacant pores’ and ’bentonite-water complexes’ of the bentonite samples after water permeation are distinguishable in X-ray CT images, and that the micro-structural differences are closely relating to the sample permeability, and depend on the mixing and saturation conditions. Permeability tests and X-ray CT observations of the bentonite ore samples show that the permeability and the microstructure are independent to the sedimentary texture developed within the ore samples. In addition, it is characteristic that the bentonite ore samples with micro-cracks show low hydraulic conductivity, comparable to the compacted powder bentonite, implying that cracks in the sample are filled with ’bentonite-water complexes’ formed after permeation.

How could this work inform a new experimental or modelling study in BEACON?
References (ideally with web links) Kawaragi C., Yoneda T., Sato T. and Kaneko K., "Microstructure of saturated bentonites characterized by X-ray CT observations", Engineering Geology, Vol. 106, pp. 51-57, 2009
Recommendations for BEACON project

Project Acronym Physicochemical controls on initiation and evolution of desiccation cracks	**Location** -	**Type** lab-test
Lead organiser University of California	**Start date** -	**End date** -
Main partners involved in the project University of Arizona	**Characteristics of swelling clay**	**Water Saturation** Artificial
Instrumentation X-ray CT imaging	**Main elements related to homogenization**	**Interfaces with other material**
Modelling Yes/no: Groups/Codes :	**Main processes studied** ☐T ☐H ☐M ☐Swelling pressure ☐Gas transfer ☐Other	**Reference concept if pertinent**

Main objectives of the experiment

Initiation and evolution of desiccation cracks in active clays are strongly dependent on physicochemical initial and boundary conditions. The objective is to investigate the effects of bentonite content, pore fluid chemistry and dry rates on cracking behavior.

General description

To investigate effects of bentonite content (20, 40, 60%), pore fluid chemistry (0.05 and 0.5 M NaCl) and drying rates (40 and 60˚C) on cracking behavior, well-controlled dehydration experiments were conducted and X-ray Computed Tomography (CT) was applied to visualize and quantify geometrical features of evolving crack networks. A stochastic model based on the Fokker-Plank equation was adopted to describe the evolution of crack aperture distributions (CAD) and to assess the impact of physicochemical factors on cracking behavior.

Main learning points concerning bentonite homogenization / mechanical evolution and relevance for the project

Analyses of crack porosity and crack specific surface area showed that both clay content and temperature had larger impact on cracking than pore fluid concentration. More cracks formed at high bentonite contents (40 and 60%) and at high drying rate (60˚C). The drift, diffusion and source terms derived from stochastic analysis indicated that evaporative demand had greater influence on the dynamics of the CAD than solution chemistry.

How could this work inform a new experimental or modelling study in BEACON?

References (ideally with web links)

Gebrenegus T. et al., « Physicochemical controls on initiation and evolution of desiccation cracks in sand-bentonite mixtures : X-ray CT imaging and stochastic modelling », Journal of Contaminant Hydrology, Vol. 126, pp. 100-112, 2011.

Recommendations for BEACON project

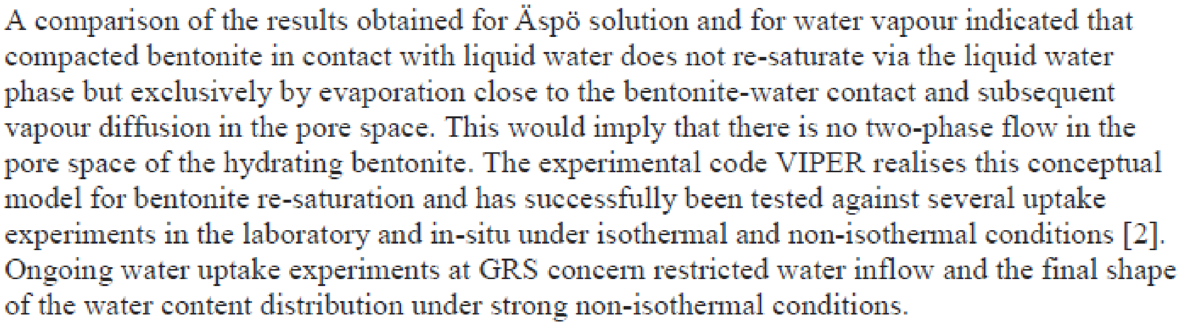
Project Acronym Re-saturation of bentonites	**Location** GRS laboratory	**Type** lab-test
Lead organiser GRS	**Start date**	**End date**
Main partners involved in the project	**Characteristics of swelling clay** MX-80	**Water Saturation** Artificial
Instrumentation	**Main elements related to homogenization**	**Interfaces with other material**
Modelling Yes/no: Groups/Codes :	**Main processes studied** ☐T ☐H ☐M ☐Swelling pressure ☐Gas transfer ☐Other	**Reference concept if pertinent**

Main objectives of the experiment

General description

Basically, re-saturation of compacted bentonite involves water migration inside the bentonite as well as hydration and subsequent swelling. To generate detailed data on the re-saturation dynamics under isothermal constrained conditions, the water content in a compacted bentonite as a function of the hydration duration and the distance from the water/bentonite interface was determined with high spatial resolution in a series of tests carried out at the GRS laboratory [1]. For this purpose, air-dry MX-80 bentonite samples were compacted within confining steel cylinders to a length of 10 cm, a diameter of 5 cm and a density of 1.5 g/cm^3, brought in contact with either Äspö solution or water vapour on one cylinder end and allowed to hydrate for different amounts of time between four days and six months. Afterwards, the hydrated samples were dismantled and cut into thin slices to determine water content distribution along the bentonite column.

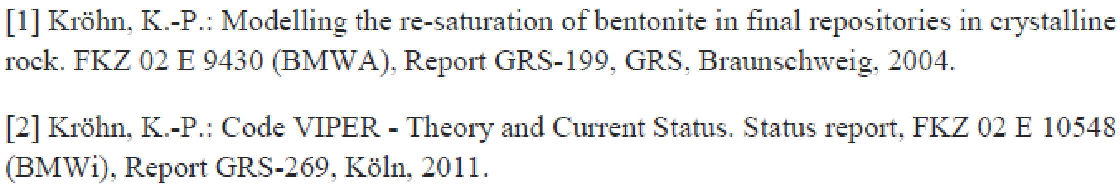
Main learning points concerning bentonite homogenization / mechanical evolution and relevance for the project



A comparison of the results obtained for Äspö solution and for water vapour indicated that compacted bentonite in contact with liquid water does not re-saturate via the liquid water phase but exclusively by evaporation close to the bentonite-water contact and subsequent vapour diffusion in the pore space. This would imply that there is no two-phase flow in the pore space of the hydrating bentonite. The experimental code VIPER realises this conceptual model for bentonite re-saturation and has successfully been tested against several uptake experiments in the laboratory and in-situ under isothermal and non-isothermal conditions [2]. Ongoing water uptake experiments at GRS concern restricted water inflow and the final shape of the water content distribution under strong non-isothermal conditions.

How could this work inform a new experimental or modelling study in BEACON?

References (ideally with web links)



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[2] Kröhn, K.-P.: Code VIPER - Theory and Current Status. Status report, FKZ 02 E 10548 (BMWi), Report GRS-269, Köln, 2011.

Recommendations for BEACON project

Project Acronym SB (preceding laboratory tests)	**Location** Mont Terri rock lab, CH	**Type** Lab tests
Lead organiser GRS	**Start date** January 1995	**End date** December 2007
Main partners involved in the project Nagra	**Characteristics of swelling clay** Sand/bentonite mixtures (calcigel)	**Water Saturation** artificial
Instrumentation Fluid and total pressure sensors	**Main elements related to homogenization**	**Interfaces with other material**
Modelling Yes Groups/Codes : GRS, Code_Bright	**Main processes studied** ☐T ☒H ☒M ☐Swelling pressure ☐Gas transfer ☐Other:	**Reference concept if pertinent**

Main objectives of the experiment or modelling study

Qualify sand/bentonite mixtures as material for engineered barriers with reduced cohesion and gas entry pressure to allow for discharge of corrosion gases while maintaining sufficiently low permeability to water and sufficiently high swelling pressure

General description

This text follows closely the respective section of a publication for the Mont Terri 20th anniversary (Wieczorek et al. 2017).

1 Preceding laboratory tests

Laboratory tests were performed on mixtures of sand and calcigel, with sand/bentonite ratios of 30/70, 50/50, and 65/35. Testing comprised the determination of grain and bulk density, permeability to gas (in the dry state) and to water (in the saturated state), gas entry pressure after re-saturation, swelling pressure, saturation time and water retention curves. Favourable results were obtained with mixtures of 65/35 and 50/50 sand/bentonite ratios. At dry densities above 1.8 g/cm^3 (65/35) or around 1.7 g/cm^3 (50/50), water permeabilities at full saturation in the range of 10^{-18} m^2 and swelling pressures above 0.2 MPa were reached. Gas entry pressure for these materials was 0.4 – 1.1 MPa (65/35) and 0.4 – 2.8 MPa (50/50), respectively (Rothfuchs et al. 2012).

Main learning points concerning bentonite homogenization / mechanical evolution and relevance for the project The focus of the experiment was on sand-bentonite mixtures.
How could this work inform a new experimental or modelling study in BEACON?
References (ideally with web links) Rothfuchs, T., Czaikowski, O., Hartwig, L., Hellwald, K., Komischke, M., Miehe, R., & Zhang, C.-L. (2012). Self-sealing Barriers of sand/bentonite mixtures in a clay repository - SB Experiment in the Mont Terri Rock **Laboratory**. *Final Report, Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) MbH, GRS-302*, 146 pp. Gesellschaft für Anlagen-und Reaktorsicherheit (GRS) mbH, Köln, Germany. **http://www.grs.de/german-publications** Wieczorek, K., I. Gaus, J.C. Mayor, K. Schuster, J.-L. García- Sineriz, T. Sakaki (2017). In-situ experiments on bentonite-based buffer and sealing materials at the Mont Terri rock laboratory (Switzerland). Swiss Journal of Geosciences, 110.
Recommendations for BEACON project/ What would I do differently, were I to repeat my earlier study?

Project Acronym SEALEX (supporting laboratory experiments)	**Location** Laboratoire Navier	**Type** Lab-tests
Lead organiser IRSN	**Start date**	**End date**
Main partners involved in the project Ecole des Ponts ParisTech, AFCN	**Characteristics of swelling clay** MX-80 80/20 powder/pellets	**Water Saturation** Artificial
Instrumentation	**Main elements related to homogenization** Heterogeneity was revealed in the internal structure of the pellet	**Interfaces with other material**
Modelling Yes/no: Groups/Codes :	**Main processes studied** ☐T ☐H ☐M ☐Swelling pressure ☐Gas transfer ☐Other	**Reference concept if pertinent**

Main objectives of the experiment

Mixtures made up of bentonite powder and pellets are a possible candidate for making sealing plugs used in deep radioactive waste disposal due to their low permeability, high swelling capacity, favourable properties with respect to radionuclide retention and operational advantages in terms of placement *in situ*, which is much easier than that of pre-compacted bricks of bentonite/sand mixture. It is therefore essential to better understand their hydro-mechanical behavior to optimize the design of the repository. In this context, the French Institute for Radiation Protection and Nuclear Safety (IRSN) has launched the SEALEX project (SEALing performance Experiments) in which this work has been conducted.

Once the initially heterogeneous unsaturated powder/pellet (80/20) MX80 bentonite mixture is put in place, these sealing materials will be subject to coupled hydro-mechanical loadings: hydration due to the infiltration of pore water from the natural barrier and mechanical confinement resulting from the engineered barriers. The present work focuses on the different scales of the material: at the macroscopic scale, it is characterized by a heterogeneous distribution of pellets and powder of bentonites; at the microscopic scale, it is studied by several techniques (MIP, µ-CT observations and SEM).

General description

This work focuses on the internal structure of MX80 bentonite pellets, powder and mixture of them with dry mass proportions of 80/20. The samples are studied in non-saturated conditions (<7.5% water content). The microscopic structure is studied by several techniques (MIP, µ-CT observations and SEM).

Main learning points concerning bentonite homogenization / mechanical evolution and relevance for the project

From μ-CT and SEM observations, a heterogeneity was revealed in the internal structure of the pellet : heterogeneous density distribution of the clay minerals and presence of several high density elements.

How could this work inform a new experimental or modelling study in BEACON?

References (ideally with web links)

Guerra A. M., Mokni N., Delage, P., Cui Y-J., Tang A. M., Aimedieu P., Bernier F. and Bornert M. “In-depth characterisation of a mixture composed of powder/pellets MX80 bentonite”, Applied Clay Science, Vol. 135, pp. 538-546, 2016.

Guerra A. M., Mokni N., Cui Y-J., Tang A. M., Delage, P., Aimedieu P., Bernier, F. and Bornert M., “Experimental and digital characterisations of the hydro-mechanical behaviour of a heterogeneous powder/pellet bentonite material”, 2nd Petrus-OPERA Conference on Radioactive Waste Management and Geological Disposal, 2016.

Guerra A. M., Mokni N., Cui Y-J., Tang A. M., Aimedieu, P., Delage, P., Bernier, F. and Bornert M., “Water retention properties and microstructure of bentonite pellets/powder mixture”, International Symposium on Energy Geotechnics, 2015.

Recommendations for BEACON project

Project Acronym Sealing Site Investigation Boreholes: Phase 2. Stage 2 laboratory programme	**Location** Clay Technology AB, Lund	**Type** Lab-test
Lead organiser Ola Karnland	**Start date** August 2015	**End date** February 2016
Main partners involved in the project Amec Foster Wheeler	**Characteristics of swelling clay** Wyoming Na dominated bentonite	**Water Saturation** Artificial
Instrumentation Force transducers Volume/pressure regulators	**Main elements related to homogenization**	**Interfaces with other material**
Modelling Yes/no: No Groups/Codes : -	**Main processes studied** ☐T ☒H ☒M ☒Swelling pressure ☐Gas transfer ☒Other	**Reference concept if pertinent**

Main objectives of the experiment or modelling study

The degree of homogenisation in bentonite is dependent on retarding and driving forces. The retarding forces are usually termed friction, and acts both between the bentonite and external surfaces in contact with the bentonite, and between particles within the bentonite. In dense heterogeneous bentonite, the dominating driving force stems from differences in swelling pressure. Neither the retarding nor the driving forces are straight forward material parameters, since they are dependent both on the bentonite and the boundary condition.

In this work, swelling pressure and hydraulic conductivity were determined for a commercial Wyoming Na-bentonite (AMCOL, Volclay MX-80) at various boundary conditions. Six different samples were prepared, ranging in density from 820 kg/m^3 to 1530 kg/m^3, all subsequently exposed to a range of water compositions.

General description

Small scale test samples (10 cm^3) were prepared from pellets by compaction into cylindrical test cells, and initially water saturated by de-ionized water (Figure 1). At equilibrium, i.e. at constant measured swelling pressure, a defined water pressure was applied on one side of the samples, and the introduced and percolated volumes were measured. The hydraulic conductivity was calculated from the percolated water volume according to Darcy´s law. The test solution was successively changed to 1.000 and 0.050 molal NaCl, 1.000 and 0.050 molal KCl, 1.000 and 0.016 molal $CaCl_2$. Constant boundary conditions was ensured by circulating the external solution over the confining filters at both sides. Swelling pressure and hydraulic conductivity was determined for all tests solution, respectively. The time period to reach near equilibrium conditions for each solution was calculated by use of a diffusion coefficient of 2E-11 m^2/s, and was experimentally indicated by the swelling pressures evolution.

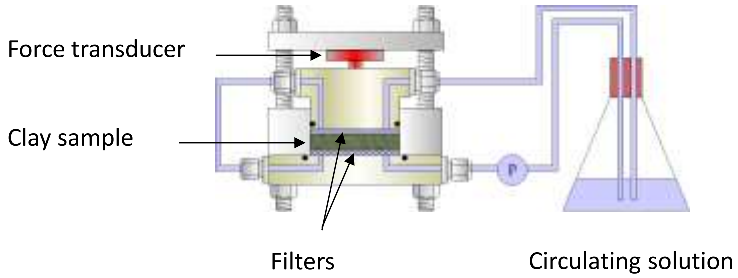

Figure 1. Principle test setup during water saturation and swelling pressure measurement. At subsequent hydraulic conductivity measurement, the upper and lower filters was disconnected, and test solution in the bottom filter was pressurized and the percolated volume was measure in the outlet tubes on the upper side.

Main learning points concerning bentonite homogenization / mechanical evolution and relevance for the project

Both swelling pressure and hydraulic conductivity results were in good agreement with previously published results for non-pelletized MX-80 bentonite in equilibrium with sodium and calcium solutions. The potassium exchanged bentonite had in general significantly lower swelling pressure, and higher hydraulic conductivity, compared to the sodium and calcium exchanged bentonite (Figure 2).

The most interesting result from this study concerns the coupling between swelling pressure and hydraulic conductivity at densities above 1000 kg/m^3. The product between the two properties is almost constant at a given condition, regardless of salinity and ion type, although the properties individually varies several orders of magnitude. The coupling has implications on the conceptual view of bentonite.

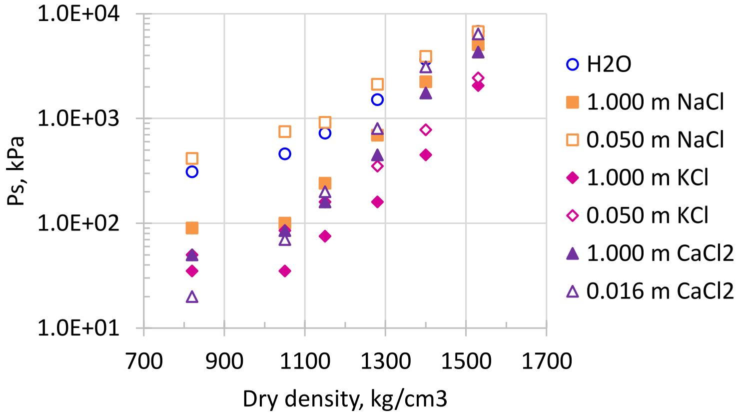

Figure 2. Measured swelling pressures as a function of density for different boundary solution with respect to ion types and concentrations.

How could this work inform a new experimental or modelling study in BEACON?

To take boundary conditions into account.

References (ideally with web links)

RWM project : Sealing Site Investigation Boreholes: Phase 2. Stage 2 laboratory programme

Recommendations for BEACON project/ What would I do differently, were I to repeat my earlier study?

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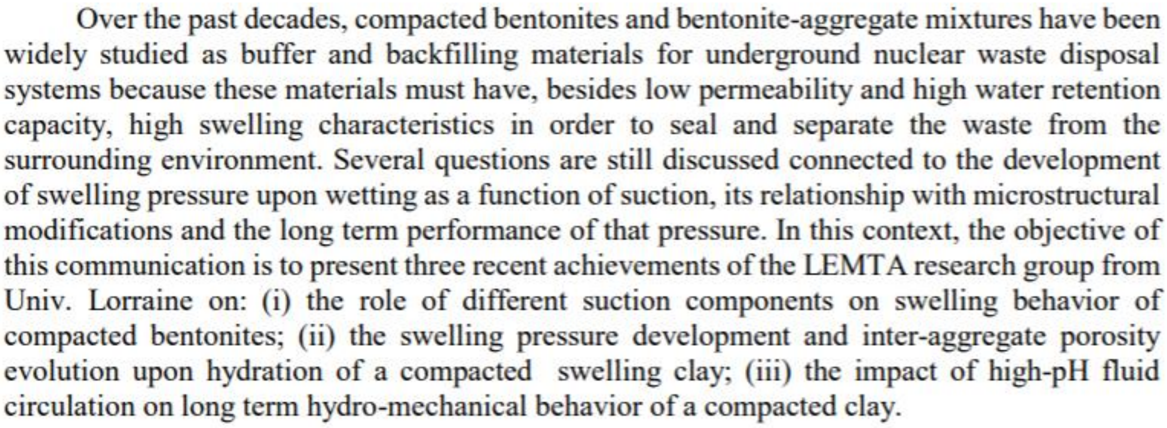
Project Acronym Swelling pressure development of compacted bentonite	**Location**	**Type** lab-test
Lead organiser LEMTA	**Start date**	**End date**
Main partners involved in the project CNRS, BGRM, LIEC	**Characteristics of swelling clay**	**Water Saturation** Artificial
Instrumentation	**Main elements related to homogenization**	**Interfaces with other material**
Modelling Yes/no: Groups/Codes :	**Main processes studied** ☐T ☐H ☐M ☒Swelling pressure ☐Gas transfer ☐Other	**Reference concept if pertinent**

Main objectives of the experiment



Over the past decades, compacted bentonites and bentonite-aggregate mixtures have been widely studied as buffer and backfilling materials for underground nuclear waste disposal systems because these materials must have, besides low permeability and high water retention capacity, high swelling characteristics in order to seal and separate the waste from the surrounding environment. Several questions are still discussed connected to the development of swelling pressure upon wetting as a function of suction, its relationship with microstructural modifications and the long term performance of that pressure. In this context, the objective of this communication is to present three recent achievements of the LEMTA research group from Univ. Lorraine on: (i) the role of different suction components on swelling behavior of compacted bentonites; (ii) the swelling pressure development and inter-aggregate porosity evolution upon hydration of a compacted swelling clay; (iii) the impact of high-pH fluid circulation on long term hydro-mechanical behavior of a compacted clay.

General description

The swelling pressure has been generally studied in relation to the initial sample conditions and the measured final swelling pressure. A monotonic or a non-monotonic swelling pressure development is observed depending on density and initial water content of the tested soils. However, the transient swelling pressure behavior, which corresponds to the moisture range between the initial water content and full saturation, has not often been investigated. This point has been addressed by developing experimental systems with suction control. Yigzaw et al. (2016) combined different suction-controlled devices, with the osmotic method or the vapor equilibrium technique (VET), to investigate the respective impact of the matric and osmotic components of suction on the development of the swelling pressure upon wetting (Figure 1).

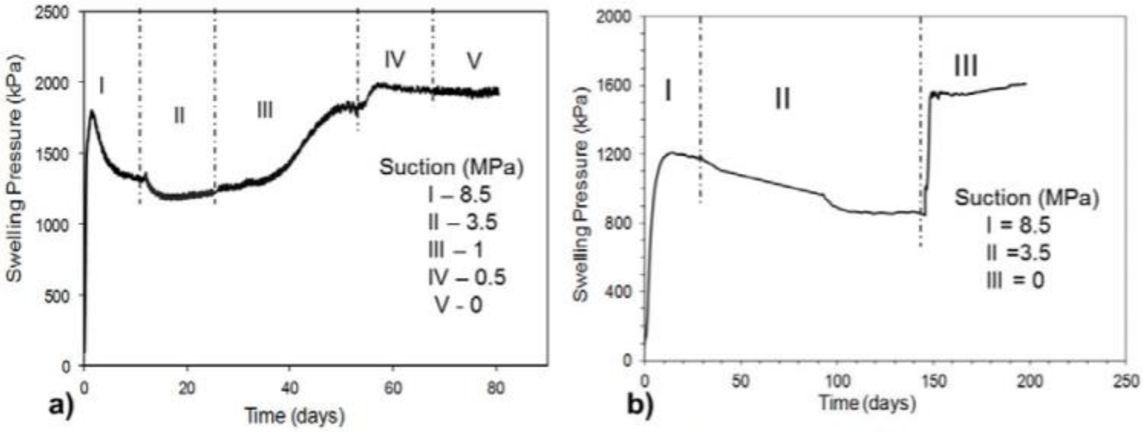


Figure 1. Evolution of swelling pressure of compacted MX-80 during decreasing suction at constant volume using (a) osmotic, or (b) vapor equilibrium techniques.

The swelling pressure values measured at each suction reduction stage using the osmotic suction control method were higher than those obtained by vapor equilibrium technique. This was interpreted to be related to differences in the suction control methods, the osmotic method imposes only matric suction while VET imposes total suction, and to differences related to the hydration mode. In addition, it is found that different hydration modes resulted different swelling pressure values, indicating the hydration path dependence of swelling pressure behavior under the constant-volume condition.

3- Swelling pressure development and inter-aggregate porosity evolution

Moreover, hydration modifies clay microstructure, and consequently it also impacts materials' mechanical properties. Most of the microstructural available studies were conducted either on samples submitted to a specific preparation procedure (freeze drying, etc.) that may have altered their fabric or without any concomitant determination of materials' macroscopic mechanical properties. In this context, a new oedometer cell, transparent to X-ray (Figure 2), was designed both to monitor swelling pressure over time and to visualize inter-aggregate porosity changes through X-ray micro-computed tomography (µCT), and at lower scale with BET, MEB and SEM analysis, on a unique specimen [2], [3].

The results combined both swelling pressure measurements and quantification of microstructure evolution upon hydration. Two types of wetting fluids were employed: aqueous solutions and an organic solvent (methyl methacrylate so called MMA). The saturation with NaCl solutions was done to evaluate the coupled development of crystalline and osmotic swelling. MMA molecule was a good mean to assess the swelling pressure and the porosity evolution mostly controlled by the influence of crystalline swelling component, the osmotic pressure being hindered. This material used was a highly pure montmorillonite (Kunipia-G).

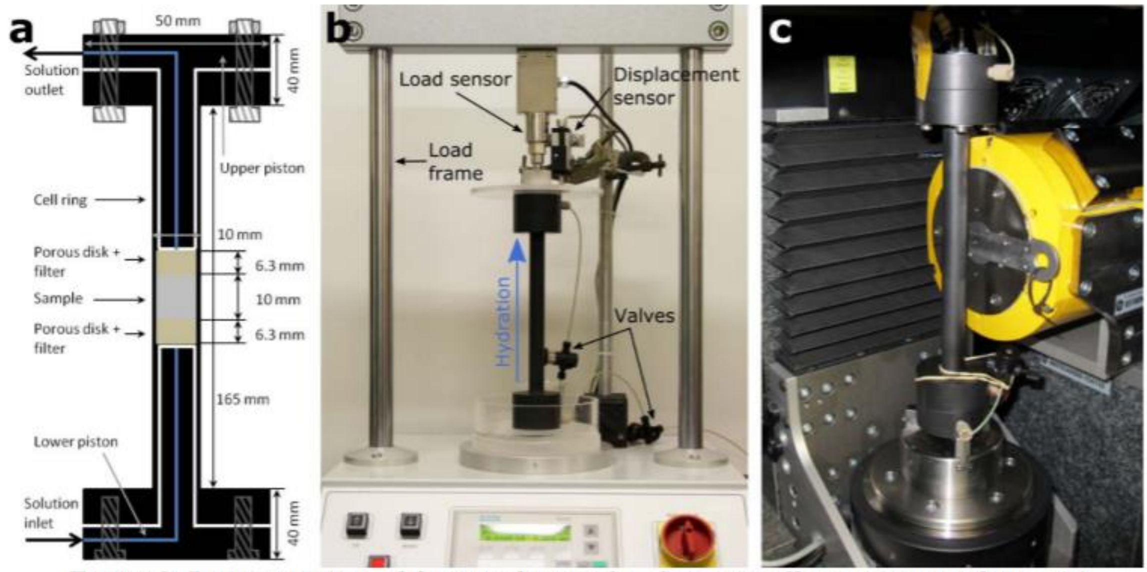


Figure 2. Representation of the new designed oedometer cell at constant volume: (a) schematic layout, (b) cell into load frame and (c) cell installed into X-ray tomograph.

The set of results obtained permitted to identify key differences in the combined evolution of swelling pressure and macroporosity of the compacted smectite employed upon hydration (Figure 2). Two behaviours of swelling pressure developments were observed according to the different solvents with non-monotonic and monotonic evolutions according to saline solutions and MMA inlets, respectively. Because this non-monotonic behaviour is not seen with MMA, where calculation has shown that the osmotic pressure is negligible (crystalline contribution), the non-monotonic swelling pressure development was found to be due to the osmotic pressure under the hydration front of the compacted sample, leading to reorganisation of the microstructure with filling of part of the inter-aggregate porosity; combined phenomena could be both responsible for the drop in swelling pressure.

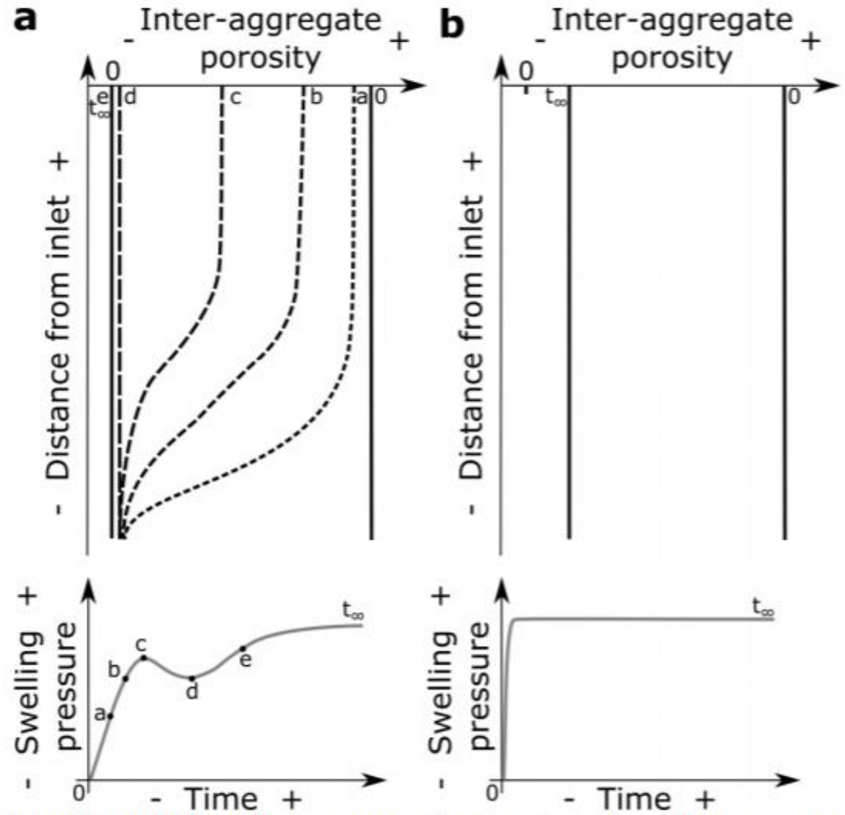


Figure 3. Schematic evolution of inter-aggregate porosity and swelling pressure upon sample hydration with (a) aqueous solution and (b) MMA.

Numerous studies have demonstrated that the pore fluid properties can alter the behavior of clays, including the swelling pressure. Among all phenomena that are likely to occur in a deep repository, one aspect is connected to the degradation of the galleries' concrete linings, which will generate alkali-rich and high-pH solutions that will diffuse into the backfill and give rise to a phenomenon called the hyper-alkaline plume. Cuisinier et al. ([4]–[6]) assessed the impact of high-pH water circulation on compacted clay samples. These samples were a mixture of remolded argillite mixed with 20% of MX-80 bentonite. After the circulation of high-pH water (higher than 12), a strong reduction of the swelling properties associated to an increase in friction angle was evidenced, whereas the hydrodynamic properties remained stable. These modifications were associated with an alteration of the fabric of the samples, i.e., the dissolution of the initial clay minerals (Figure 3) and the precipitation of neoformed illite, which is a non-swelling mineral [6].

These transformations modified some aspects of the hydromechanical behaviour of the compacted MHM-clay and included a dramatic reduction in the swelling strain and increase in the friction angle. Thus, these processes will likely alter the sealing characteristics of a backfill made of compacted MHM-clay in the very long term, and should be taken into account in the design of such structures.

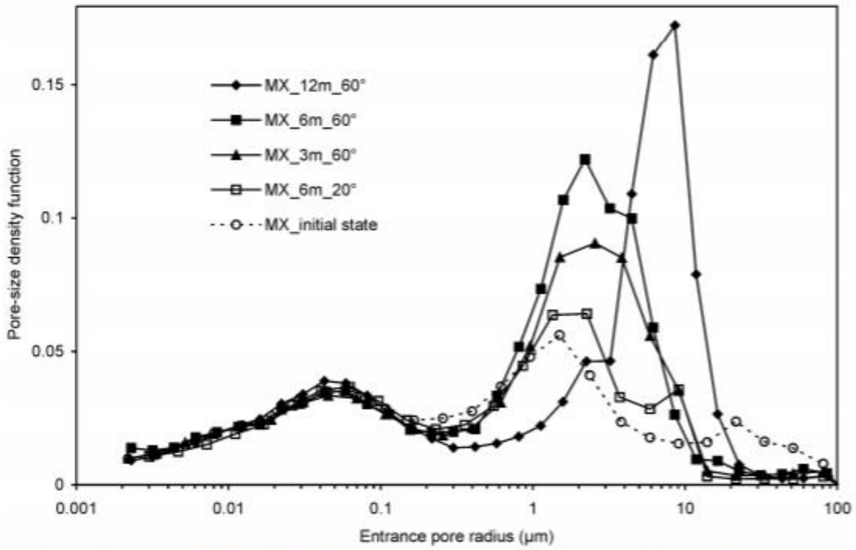


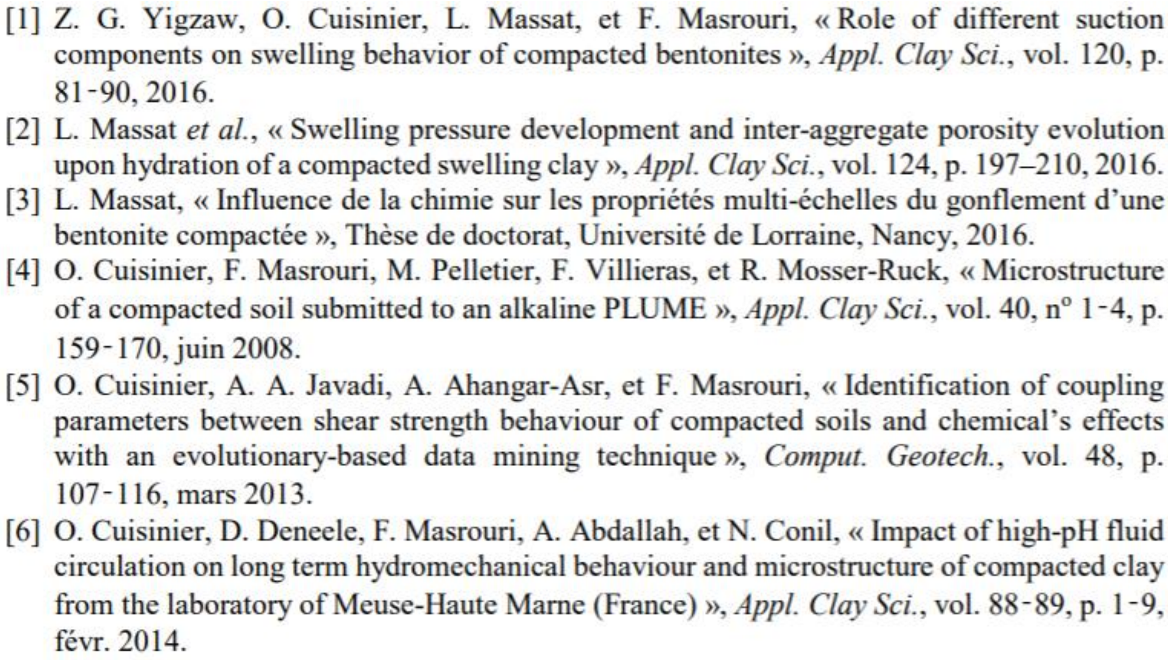
Figure 4. Impact of high pH fluid circulation on pore size distribution of compacted mixture of remolded argilite and 20% of MX-80 [4].

Main learning points concerning bentonite homogenization / mechanical evolution and relevance for the project

The work carried out by LEMTA deals with the development of swelling pressure under wetting. The results of these studies, using different suction-controlled experimental methods and several wetting fluids, highlighted the relative importance of osmotic and crystalline swelling. These investigations were associated to a joint investigation of microstructure at several scale, from the clay platelet level up to sample scale. Additional studies demonstrated the detrimental impact of high-pH water circulation on the sealing properties (i.e. swelling potential, hydraulic conductivity, etc.) of compacted expansive clays. The role of additives mixed with the expansive clay (sand, lime, etc.) appeared to be determinant on the extent of the alteration.

How could this work inform a new experimental or modelling study in BEACON?

References (ideally with web links)



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[4] O. Cuisinier, F. Masrouri, M. Pelletier, F. Villieras, et R. Mosser-Ruck, « Microstructure of a compacted soil submitted to an alkaline PLUME », *Appl. Clay Sci.*, vol. 40, n° 1‑4, p. 159‑170, juin 2008.

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[6] O. Cuisinier, D. Deneele, F. Masrouri, A. Abdallah, et N. Conil, « Impact of high-pH fluid circulation on long term hydromechanical behaviour and microstructure of compacted clay from the laboratory of Meuse-Haute Marne (France) », *Appl. Clay Sci.*, vol. 88‑89, p. 1‑9, févr. 2014.

Recommendations for BEACON project

SWELLING PRESSURE ACTING TO THE CONSTRAINING MATERIAL WITH SLIGHT DEFORMABILITY

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Introduction

Bentonite-based material will be used to prevent nuclide migration in radioactive waste disposal facilities. Mechanical behaviour of the bentonite over a long period, including a saturation process, needs to be evaluated for the safety assessment of the disposal. In the saturation process of the bentonite, increase in the degree of saturation causes the evolution of the swelling pressure.

The swelling pressure of the bentonite can be measured by laboratory tests. Stiffness of the experimental system is usually required to secure counterforce of swelling. In practice, the bentonite will be confined by a host rock or backfill materials, which might show fracture or flexibility. It has not been solved enough how much swelling pressure acts to the constraining materials with slight deformability. It is difficult to measure the changeable swelling pressure under controlling confining conditions during saturation of the bentonite.

This study developed the swelling pressure test apparatus equipped with small strain control, and investigated the swelling pressure acting to the constraining material with slight deformability, supposing elastic strain of rocks.

Experimental procedure

The swelling pressure apparatus consists of a stiff four-columned load frame with a stepping motor and a strain wave gearing, a stainless vessel and a load cell. A noncontact type displacement gage was directly inserted into the specimen in order to measure the height of the specimen in 0.1 μm precision.

To simulate elastic deformation of rock-like materials contacted to the bentonite, the height of the specimen was continuously adjusted by the stepping motor. First, the elastic modulus of the deformable material, 750 MPa to 37000 MPa, was set. Increment of the swelling pressure was measured by the load cell. The elastic strain of the constraining material was calculated complying with the Hooke's law, and the height of the specimen was mechanically controlled by the stepping motor. Time step of the adjustment was 1.0 second. After the swelling pressure converged to a steady value, the confining pressure applied to the specimen unloaded step by step, and the swelling deformation was observed. The specimen, 20 mm in height and 60 mm in diameter, was produced by using Na-type and Ca-type bentonite.

Results and discussion

For Na-type bentonite at 1.6 $\text{Mg/m}^3$of dry density, the elastic modulus corresponding to a hard rock, 37000 MPa, showed that the displacement of the specimen was only 1 μm during the swelling pressure increased up to 1.9 MPa. In the case of the smallest elastic modulus corresponding to a soft rock, 750 MPa, 40—50 μm of the displacement occurred and 1.5 MPa of the swelling pressure was measured. Ca-type bentonite also represented that the swelling pressure became lower in the case of smaller elastic modulus of the constraining material. Although the dry density of the specimen was not almost changed by the displacement, the swelling pressure decreased with slight deformation of the bentonite in saturation process.

Project Acronym	**Location**	**Type** Lab-test
Lead organiser CRIEPI	**Start date** 2013	**End date** In progress
Main partners involved in the project	**Characteristics of swelling clay** Compacted Na-bentonite (Dry density: 1.4 - 1.8 Mg/m^3) and Ca-bentonite (Dry density: 1.2 Mg/m^3)	**Water Saturation** Artificial
Instrumentation ● Total pressure ● Strain ● Pore water pressure	**Main elements related to homogenization** Zone filled by compacted bentonite	**Interfaces with other material** Bentonite/Constraining material (ex. Rock)
Modelling Yes/no: No Groups/Codes : None	**Main processes studied** ☐T ☐H [✓ ☐M] [✓ ☐Swelling pressure] ☐Gas transfer ☐Other	**Reference concept if pertinent**

Main objectives of the experiment or modelling study

Bentonite-based materials will be used to prevent nuclide migration in radioactive waste disposal facilities. Mechanical behaviour of the bentonite over a long period, including a saturation process, needs to be evaluated for the safety assessment of the disposal. In the saturation process of the bentonite, increase in the degree of saturation causes the evolution of the swelling pressure.

The swelling pressure of the bentonite can be measured by laboratory tests (Johannesson and Nilsson, 2006; Tanaka, 2011). Stiffness of the experimental system is usually required to secure counterforce of swelling. In the facilities, the bentonite will be confined by a host rock or a backfill material, which might show fracture or flexibility. It has not been solved enough how much swelling pressure acts to the constraining material with slight deformability. It is difficult to measure the changeable swelling pressure under controlling confining conditions during saturation of the bentonite.

This study developed the swelling pressure test apparatus equipped with small strain control, and investigated the change of the swelling pressure acting to the constraining material with slight deformability, supposing elastic strain of rocks.

General description

Specimen procedure: The specimen, 20 mm in height and 60 mm in diameter, was produced by using a Na-type and a Ca-type bentonite (Kunigel-V1 and Kunibond/ Kunimine Industries Co. Ltd.).

The methylene blue adsorbed of the Na-type and Ca-type bentonite was 70 mmol/100g and 118 mmol/100g, respectively. The specimen was produced by axial loading. The dry density of the specimen was 1.4 to 1.8 Mg/m^3 for Na-bentonite and 1.2 Mg/m^3 for Ca-bentonite.

Swelling pressure test apparatus: The swelling pressure apparatus consists of a stiff four-columned load frame with a stepping motor and a strain wave gearing, a stainless vessel and a load cell (see Fig. 1). A noncontact type displacement gage was directly inserted into the specimen in order to measure the height of the specimen in 0.1 μm precision.

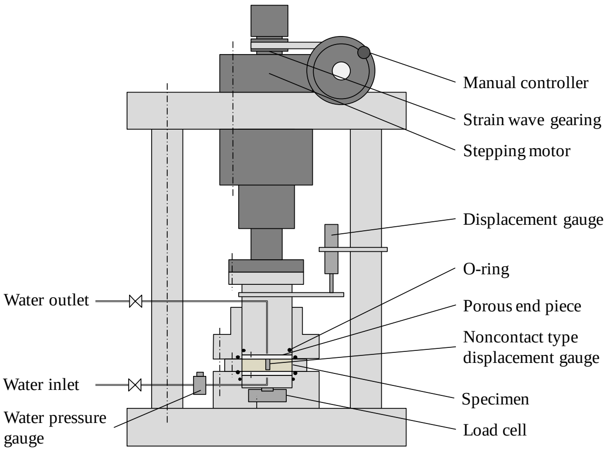


Figure 1. Swelling pressure apparatus equipped with small strain control.

Simulation of elastic micro-deformation: To simulate elastic deformation of rock-like materials contacted to the bentonite, the height of the specimen was continuously adjusted by the stepping motor (see Fig. 2). The top porous end piece contacted to the specimen at beginning. First, the elastic modulus of the deformable material, 750 MPa to 37000 MPa, was set. Increment of the swelling pressure was measured by the load cell. The elastic deformation which caused in the constraining material was calculated complying with the Hooke's law as presented in Eq. 1, and the height of the specimen was mechanically controlled by the stepping motor. Time step of the adjustment was 1.0 second.

$$\Delta H = \frac{\Delta P_s}{E} H_0 \quad \text{(Eq. 1)}$$

where ΔH [m] denotes the incremental elastic deformation of the constraining material caused by the incremental swelling pressure ΔP_s [MPa]. H_0 [m] is the initial height of the specimen. E [MPa] represents the elastic modulus of the constraining material.

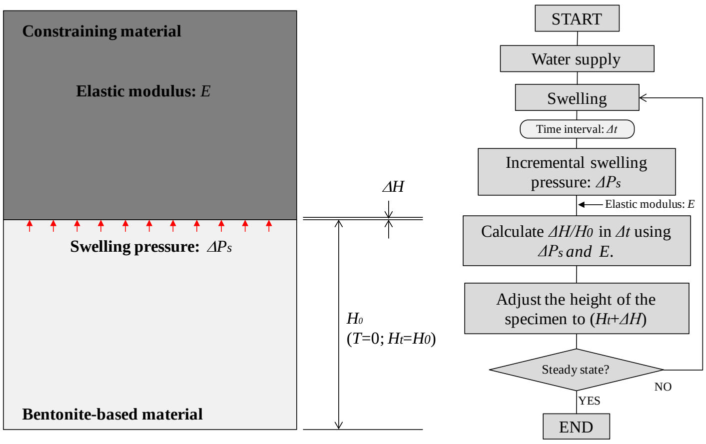


Figure 2. Control procedure of the swelling test.

Swelling deformation by unloading: After the swelling pressure converged to a steady value, the confining pressure applied to the specimen unloaded step by step, and the swelling deformation was observed.

Main learning points concerning bentonite homogenization / mechanical evolution and relevance for the project

Swelling pressure: Experimental results of the swelling pressure test with controlling small strain are shown in Fig. 3. For Na-type bentonite at 1.6 Mg/m^3 of dry density, the setting of the elastic modulus corresponding to a hard rock, 37000 MPa, showed that the displacement of the specimen was only 1 μm during the swelling pressure increased up to 1.9 MPa. In the case of the smallest elastic modulus corresponding to a soft rock, 750 MPa, 40—50 μm of the displacement occurred, and 1.5 MPa of the swelling pressure was measured. Figure 4 shows the relation between the relative swelling pressure and the deformation ratio of the bentonite. The relative swelling pressure is defined as it is normalized by the swelling pressure at 37000 MPa of the elastic modulus at steady state. The displacement of the bentonite in each condition was less than 0.2 % of the deformation ratio. Although the dry density of the specimen was not almost changed by the displacement, the swelling pressure decreased with slight deformation of the bentonite in saturation process.

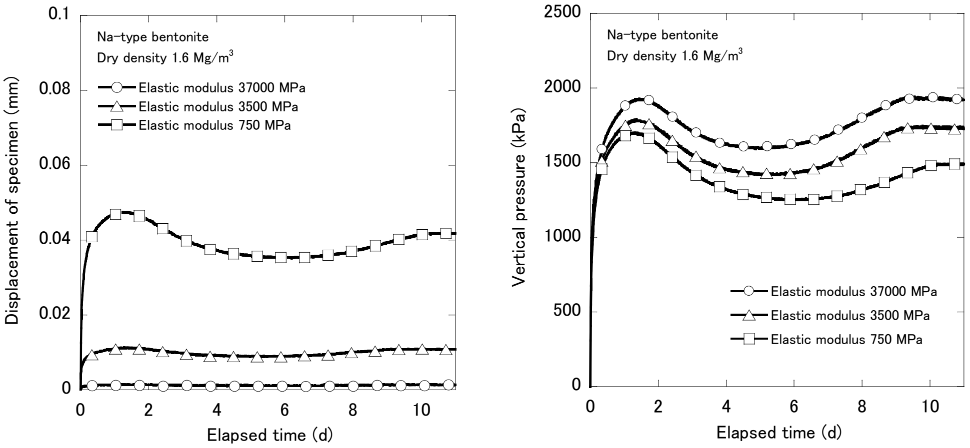


Figure 3. Experimental results of the swelling pressure test with controlling small strain.

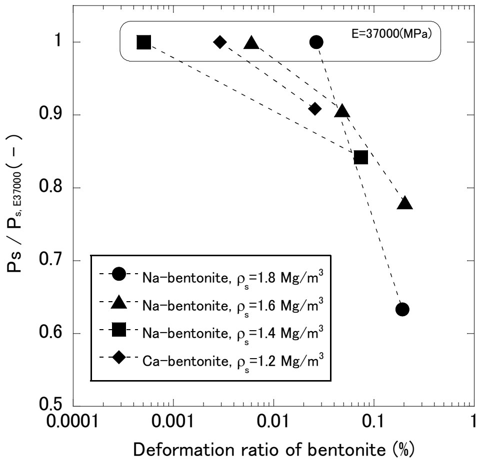


Figure 4. Relation between the relative swelling pressure ($P_s/P_{s,\,E=37000}$) and the deformation ratio of the bentonite.

Swelling deformation in unloading process after saturation: The relation between the vertical confining pressure and the deformation ratio of the bentonite is represented in Fig. 5. In the unloading process after saturation, smaller vertical confining pressure showed larger deformation ratio of the bentonite in each initial dry density. The vertical confining pressure at the steady state depended on the setting of the elastic modulus. Under the same dry density, **the difference of the vertical confining pressure between each elastic modulus decreased with the increase in the deformation ratio of the bentonite**. For the bentonites of the initial dry density from 1.2 to 1.6 Mg/m³, the difference of the vertical confining pressure decreased more than approximately 1 % of the deformation ratio. While, for the bentonite of 1.8 Mg/m³, more than 20 % of the deformation ratio was required for reduction of the difference of the vertical confining pressure.

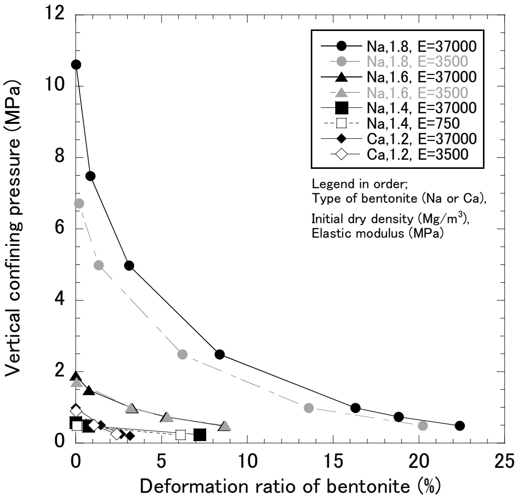


Figure 5. Relation between the vertical confining pressure and the deformation ratio of the bentonite.

How could this work inform a new experimental or modelling study in BEACON?

This study investigated the swelling pressure of the bentonite acting to the constraining material with slight deformability, supposing elastic strain of rocks, by the laboratory test. This approach leads estimation of the swelling pressure and the swelling deformation of the bentonite, considering boundary conditions in terms of the bentonite-rock interaction.

Furthermore, standardization of the mechanical tests for the compacted bentonite is important to promote the radioactive waste disposal. In the laboratory test, the deformability of the apparatuses also may influence to the measured swelling pressure (Tanaka, 2011). The new experiment is useful to discuss the experimental method for measuring swelling pressure of the compacted bentonite.

References (ideally with web links)

Johannesson, L. E. and Nilsson, U. (2006) Deep repository – engineered barrier systems. SKB Report, R-06-73.

Tanaka, Y. (2011) Numerical simulation on effects of test conditions on measured swelling pressure of compacted bentonite by swelling model. Journal of Japan Society of Civil Engineering, 67, 4, 513-531. (in Japanese)

Recommendations for BEACON project/ What would I do differently, were I to repeat my earlier study?

By measuring the realistic swelling pressure in the bentonite-rock interaction through the swelling test in this study, the result will be a parameter to design the facility or useful information for various numerical simulations. It is important to understand the difference of swelling properties observed in laboratory tests and full scale experiments.

Project Acronym THEBES/JyU	**Location** University of Jyväskylä (JyU), Finland	**Type** laboratory scale experiment
Lead organiser Aalto University, JyU	**Start date** 1.2.2015	**End date** 31.1.2018
Main partners involved in the project Aalto University, VTT, Numerola Oy, JyU	**Characteristics of swelling clay** Pre-compacted cylindrical samples of purified bentonite (MP Biomedicals bentonite) and of MX-80. Dry density: 1.2-1.9 g/cm3 Initial water content : 7-24%	**Water Saturation** Artificial. Salinity 0.1 M
Instrumentation · X-ray tomographic scanners. · Sample chambers with ~~a~~ force sensors and wetting and venting channels · In-house image analysis algorithms	**Main elements related to homogenization** Free and constrained swelling monitored in a '4D' non-intrusive measurement utilizing X-ray tomography and X-ray imaging. Data useful for model validation purposes	**Interfaces with other material**
Modelling Yes: Collaboration with Numerola, VTT and Aalto	**Main processes studied** ☐T ☒H ☒M ☒Swelling pressure ☐Gas transfer ☒Other Deformation of the bentonite sample (direct non-intrusive measurement of 3D or 1D displacement field)	**Reference concept if pertinent**

Main objectives of the experiment or modelling study

The objective is to produce accurate and detailed experimental data on wetting and swelling behaviour of bentonite, thereby supporting development and validation of hydromechanical models developed for assessing the functional ability of bentonite barrier.

General description

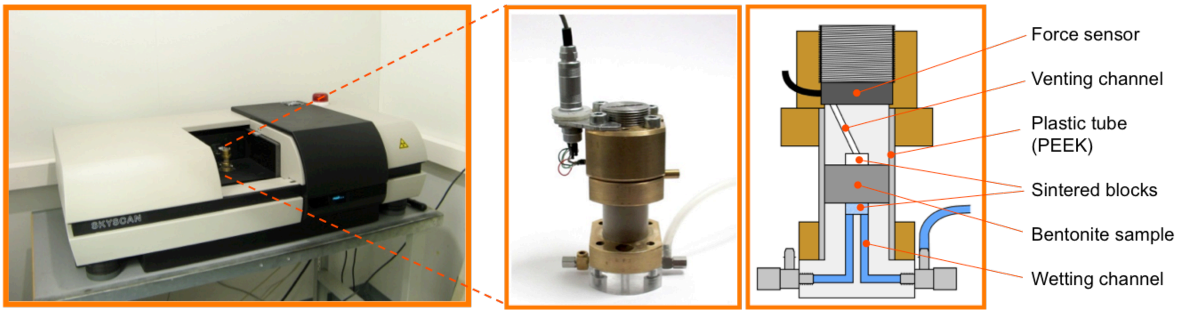
Non-invasive methods for measuring time evolution of the displacement field and water content distribution in wetting/swelling bentonite material have been developed. The methods are based on X-ray tomography (3D wetting geometry) or X-ray imaging (1D wetting geometry). The tomographic method is applicable on relatively slow processes while the X-ray imaging method is useful also for measuring rather fast processes.

A microtomographic device is used to take sequential X-ray tomographic images (3D case) or of individual X-ray images (1D case) of the samples during the wetting/swelling process. The X-ray images, corrected for various imaging artifacts, are used to calculate the linear X-ray attenuation coefficient, and calibrated to yield the local (total) density of wetted bentonite. The deformation of the sample is measured by tracking the motion of natural or added tracer particles between consecutive X-ray images. The measured displacement field and the initial density of the sample are used to calculate the local partial density of the (dry) bentonite material. Finally, the local water content is found based on total density and dry density.

3D wetting and swelling in a closed volume [1]

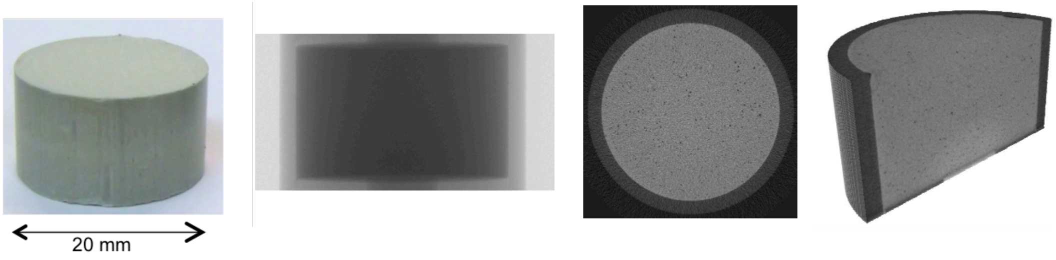
Bentonite samples were studied in approximately constant volume conditions in a plastic (PEEK) tube between cylindrical end-pieces. The end-pieces include wetting and venting channels, and glass sintered plates that allow water flow in the sample through the lower end surface, and escape of air through the upper surface (see Fig. 1).

The local displacement of the solid phase caused by swelling was monitored by comparing the tomographic images of the reference state and each of the partially wetted states of the bentonite sample. This was made possible by doping the quite homogenous purified bentonite sample with small amounts of tracer particles. A refined box matching image analysis algorithm was then used to extract the local 3D displacements from the tomographic images taken at various times during the wetting process. The displacement field together with the known initial dry density distribution allows calculating the dry density distribution at later times. This, together with calibrated gray scale values of the tomographic images then lead to 3D distribution of also water content at different times of wetting process.



(a) (b) (c)

Figure 1: Experimental set-up in 3D experiment based on X-ray tomographic images. (a) Tomographic scanner. (b) Sample holder with force axial measurement. (c) Schematic illustration of the sample holder structure.



(a) (b) (c) (d)

Figure 2: (a) Compacted cylindrical purified bentonite sample doped with small marker particles (hollow glass spheres), (b) a single X-ray image of the sample inside the sample holder, (c) a single reconstructed horizontal slice of the sample, (d) 3D rendered tomographic image showing one half of the sample and a segment of sample holder tube wall.

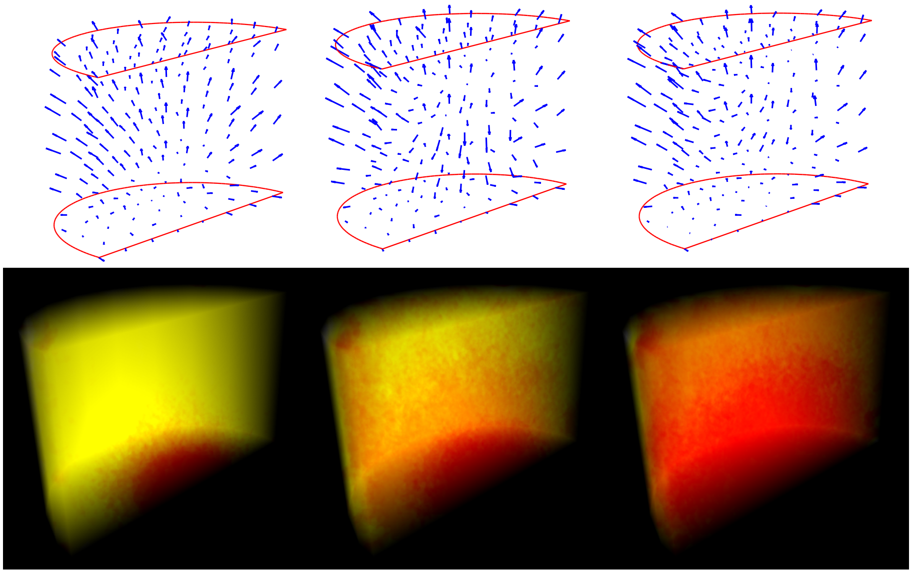


Figure 3: Three-dimensional visualization of displacement field (upper images) and water content distributions (lower images) at wetting times of 7 h, 25 h and 71 h, for half a sample (see Fig. 2(d)). The displacement vectors are shown scaled by a factor of 10. The color code for water content corresponds to that shown in Fig. 4 [1].

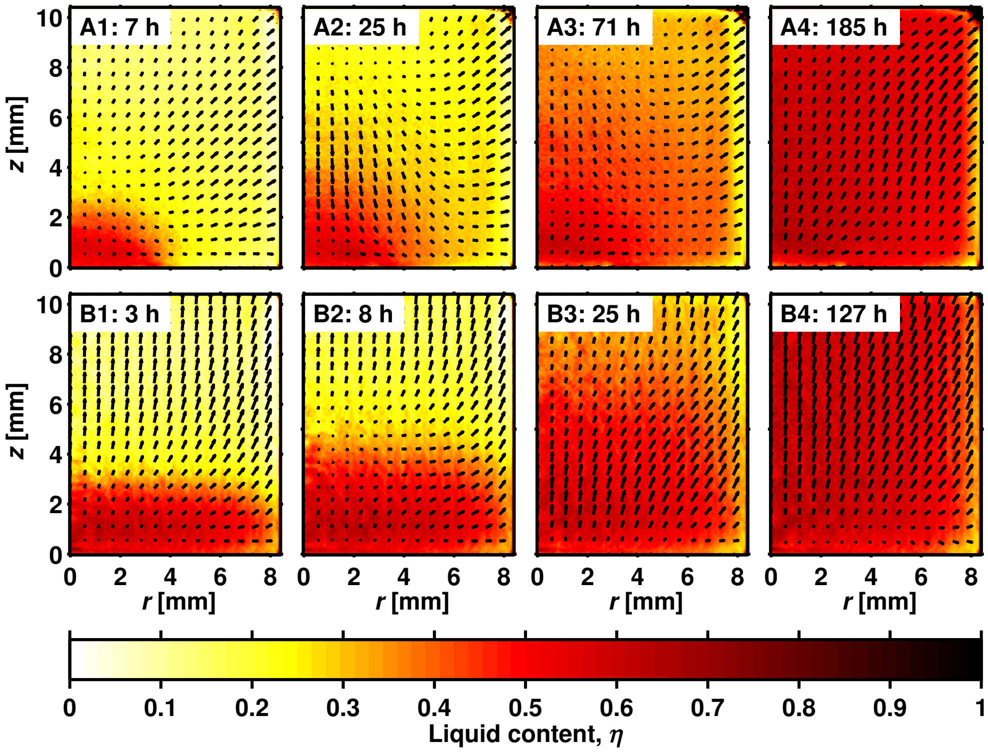


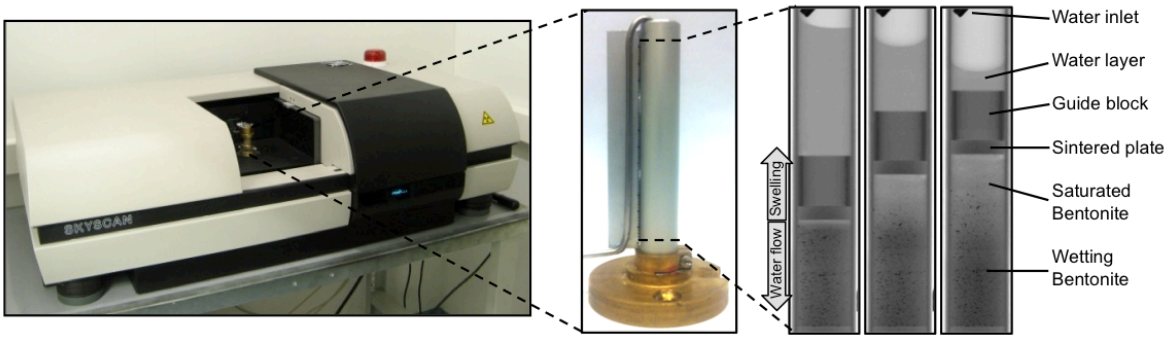
Figure 4: Water content and displacement vector fields averaged azimuthally for two different wetting geometries with 6 mm and 15 mm diameter sintered plates, labeled as A and B, respectively. The smaller and larger sintered plate dimensions correspond to 3D cylindrically symmetric and an approximately 1D axial wetting/swelling set-ups, respectively. The displacement vectors are drawn scaled by a factor of 5. The wetting times are indicated in the image labels. The liquid content η is defined as the mass ratio between water and dry bentonite [1].

1D Free swelling in a narrow channel [2].

A method based on X-ray imaging was developed and used to study free swelling of compacted bentonite in a tube. The process mimics erosion of bentonite buffer that may happen in narrow channels/cracks of rock surrounding the buffer. In this case the process is virtually one-dimensional but the initial swelling rate and the total degree of swelling can be very high. Instead of full (and slow) tomographic scans, the present method is based on fast X-ray imaging (no 3D reconstructions). This allows monitoring also the initial stages of the process which is essential for successful deformation analysis (which, in turn, is the crux of the method).

The sample holder consisted of a vertical aluminum tube (h = 95 mm, inner diameter 10 mm) mounted on a base plate (Fig. 5). A compacted bentonite sample (h = 20 mm, d = 10 mm) was placed inside the tube with bottom end against a porous filter disc. A guiding block that consists of a permeable sintered disc and a short piece of aluminum tube with outer diameter ~10 mm is placed on top of the sample. Water is thus able to flow through the guiding block and wet the sample from the top. The guiding block is allowed to move freely upwards with swelling bentonite.

The measuring process and the method of analysis are similar to that used in the 3D tomographic technique discussed above [1], and thus yield the local displacement, dry density and water content of the bentonite as functions of vertical position and time (see Fig. 6).



(a) (b)

Figure 5: Experimental set-up for 1D axial free swelling experiment in a narrow channel, based on X-ray imaging. (a) Tomographic scanner, (b) sample holder tube (c) a set of X-ray image taken at various states of wetting. The images show the wetting bentonite sample, the (freely moving) tubular guide block with permeable bottom, and the water layer wetting the bentonite sample from above.

Table 1: 1D free swelling experiments completed. The numbers show the amount of repetition experiments for each case.

Initial dry density	**Initial water content**		
	w_0 = 12%	**w_0 = 17%**	**w_0 = 24%**
ρ_b = 1.90 g/cm^3	2	2	-
ρ_b = 1.65 g/cm^3	2	2	2
ρ_b = 1.40 g/cm^3	2	2	2

Examples of results are shown in Figures 6 and 7.

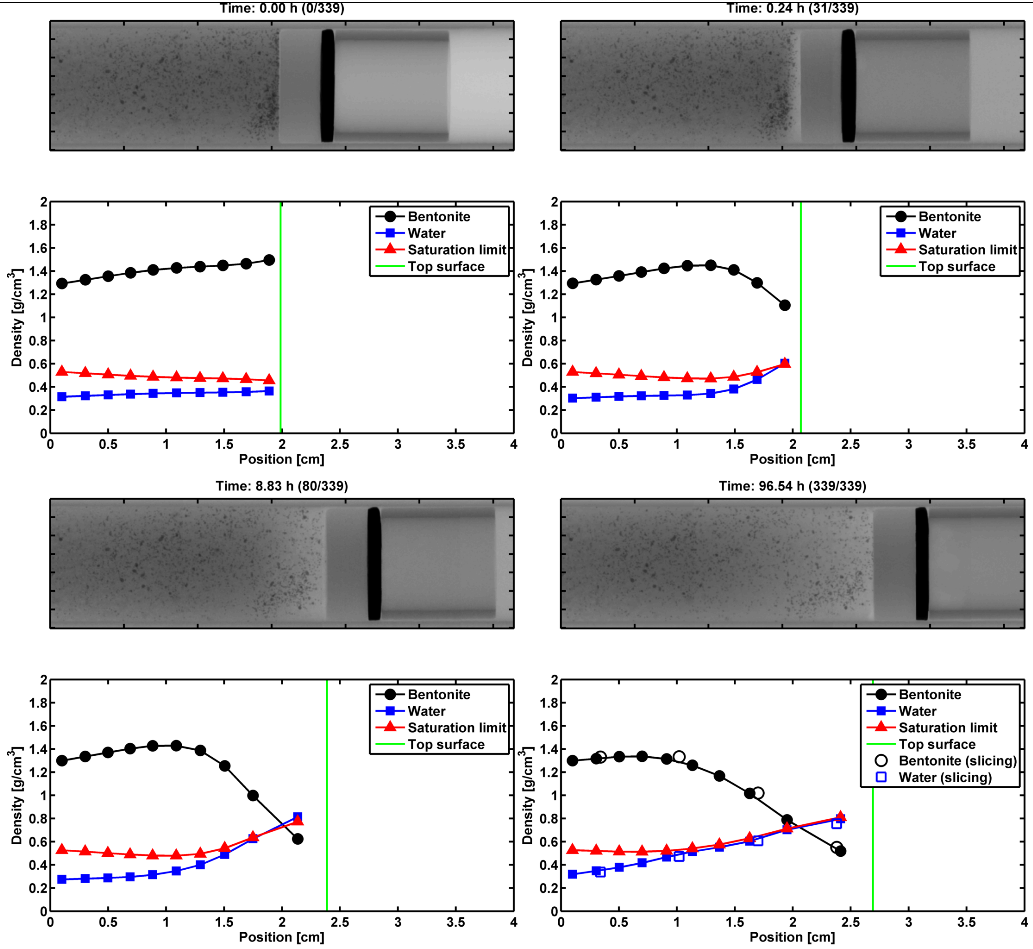


Figure 6: The time development of the axial bentonite and water content during free swelling at four instants of time. The last image also shows the validation data measured gravimetrically from the sliced sample at final state. Also shown are the original X-ray images used for the analysis. [2]

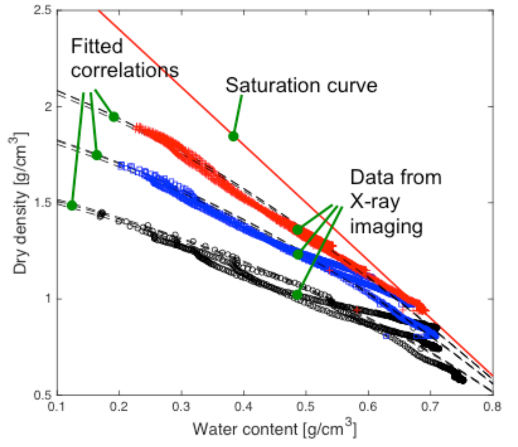


Figure 7: Behaviour of dry density and water content of bentonite samples in free swelling. The theoretical saturation curve is calculated assuming grain density of 2.75 g/cm^3. [2]

Similar experiments but for 1D wetting and swelling of bentonite in a closed volume are ongoing.

Main learning points concerning bentonite homogenization / mechanical evolution and relevance for the project

The hydromechanical behaviour of bentonite is complex indeed. More detailed experiments probing the basic material properties and transport mechanisms, devoted to serve phenomenological modelling efforts, are called for.

How could this work inform a new experimental or modelling study in BEACON?

The methods can be used to non-destructively measure the local dry density and water content of the sample as a function of time (see e.g. Fig.8 [1]). The method is thus well suited to study both the homogenization process and the homogeneity of the final state. The data is best suited for model validation. The drawback with the current tomographic devices is the rather small sample size. Development of techniques that would allow larger samples are ongoing.

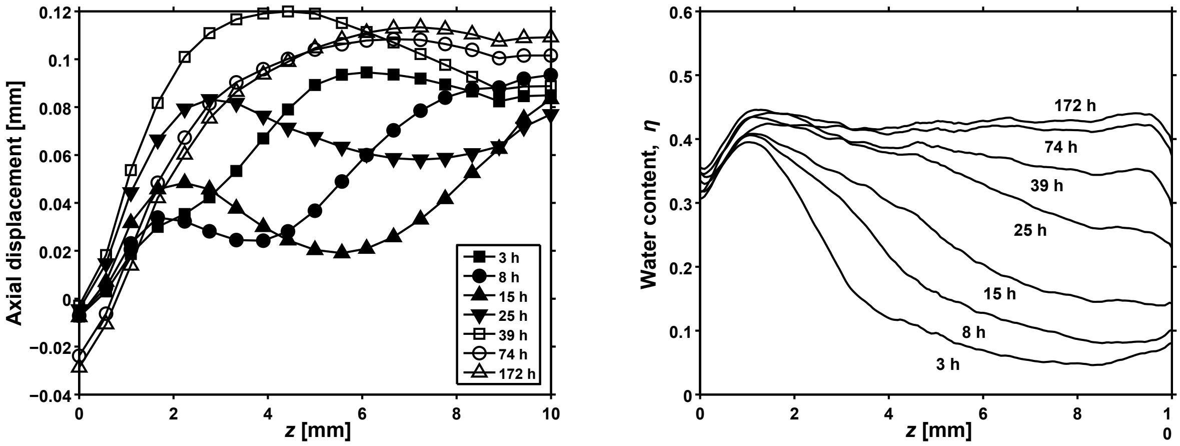


Figure 8: Evolution of the averaged axial displacement (a) and water content profiles (b) for a bentonite sample wetted in the sample holder with 15 mm sintered plate (approximatley 1D axial wetting/swelling set-up. See Fig. 4)

References (ideally with web links)

[1] Tero Harjupatana, Jarno Alaraudanjoki and Markku Kataja, "X-ray tomographic method for measuring three-dimensional deformation and water content distribution in swelling clays", Applied Clay Sciences Vol. 114, pp. 386-394, 2015.
doi:10.1016/j.clay.2015.06.016
https://jyx.jyu.fi/dspace/handle/123456789/48232

[2] Tero Harjupatana, Joni Lämsä, Jarno Alaraudanjoki and Markku Kataja, "A method for measuring swelling of bentonite in a narrow channel using X-ray imaging", In preparation.

Recommendations for BEACON project/ What would I do differently, were I to repeat my earlier study?

Project Acronym Transu	**Location** Lab facilities of Saanio & Riekkola Oy	**Type** Lab-test
Lead organiser Posiva Oy	**Start date** Transu 1: 8.4.11 Transu 2: 27.7.11 Transu 3: 27.7.11 Transu 4: 14.9.11 Transu 8: duration 133 days	**End date** Transu 1: 22.8.11 Transu 2: 18.10.11 Transu 3: 21.10.11 Transu 4: 16.10.11 Transu 8: duration 133 days
Main partners involved in the project Saanio & Riekkola Oy (earlier B+Tech)	**Characteristics of swelling clay** Transu 1 and 2: Compacted MX-80 bentonite blocks: • Block diameter 210 mm • Block height 200 mm • Dry density ~1800 kg/m^3 • Water content 16.7 % Non-filled gap: • Width 30 mm Transu 3 and 4: Compacted MX-80 bentonite blocks: • Block diameter 210 mm • Block height 200 mm • Dry density 1790 kg/m^3 • Water content 16.7 % Extruded Cebogel QSE bentonite pellets: • Pellet dimensions: L = 4 – 16 mm, d = 6 – 6.5 • Width of pellet-filled gap 30 mm • Dry density of individual pellets ~ 1740 kg/m^3 • Dry density of pellet fill 920 kg/m^3 • Water content 18.8 % Transu 8: Compacted MX-80 bentonite blocks: • Block diameter 210 mm • Block height 200 mm • Dry density 1810 kg/m^3 • Water content 16.3 % SKB pillow-shaped bentonite pellets • Width of pellet-filled gap 30 mm	**Water Saturation** Artificial

	- Dry density of pellet fill 920 kg/m^3 - Water content 14.5 %	
Instrumentation Monitoring of: - Inlet water pressure - Inlet and outlet flow rates - Outlet effluent solids concentration - Axial swelling pressure Transu tests 2 – 4 and 8: 1 load cell per test - Radial swelling pressure Transu 1, 2 and 4: 9, 5 and 15 strain gauges, respectively; Transu 3: 5 strain gauges, 1 total pressure transducer; Transu 8: 3 strain gauges - Suction Transu 8: 2 capacitive hygrometers	**Main elements related to homogenization** Initial heterogeneity of density: - zone filled by compacted block - zone filled with pellets	**Interfaces with other material** Bentonite/uPVC (un-plasticised polyvinyl-chloride) cell
Modelling Yes Groups/Codes : CODE_BRIGHT	**Main processes studied** ☐T ☒H ☒M ☒Swelling pressure ☐Gas transfer ☐Other	**Reference concept if pertinent** KBS-3V repository design

Main objectives of the experiment or modelling study

The purpose of these tests was to study early saturation behavior of buffer at mock-up scale. Swelling pressure development, piping and erosion due to groundwater inflow and the extent of homogenization as determined from post-mortem analysis were followed.

General description

The Transu test cell is comprised of a PVC cylinder fitted with plastic pistons at the top and bottom. The cell can accommodate sample systems up to 269 mm in diameter and 800 mm in height (Figure 1). The cylinder wall is 5.5 mm thick. Some Transutype tests include axial load cell measurement as well as total pressure transducers in radial positions. Flow inlet and outlet ports (6 mm ID) are found at the bottom and top of the device, respectively. In some cases single inlet and outlet ports were used while in others multiple inlet and outlet were employed. Given their transparent main cylinders, Transu tests also allow direct visualization of saturation evolution and formation of piping and erosion channels.

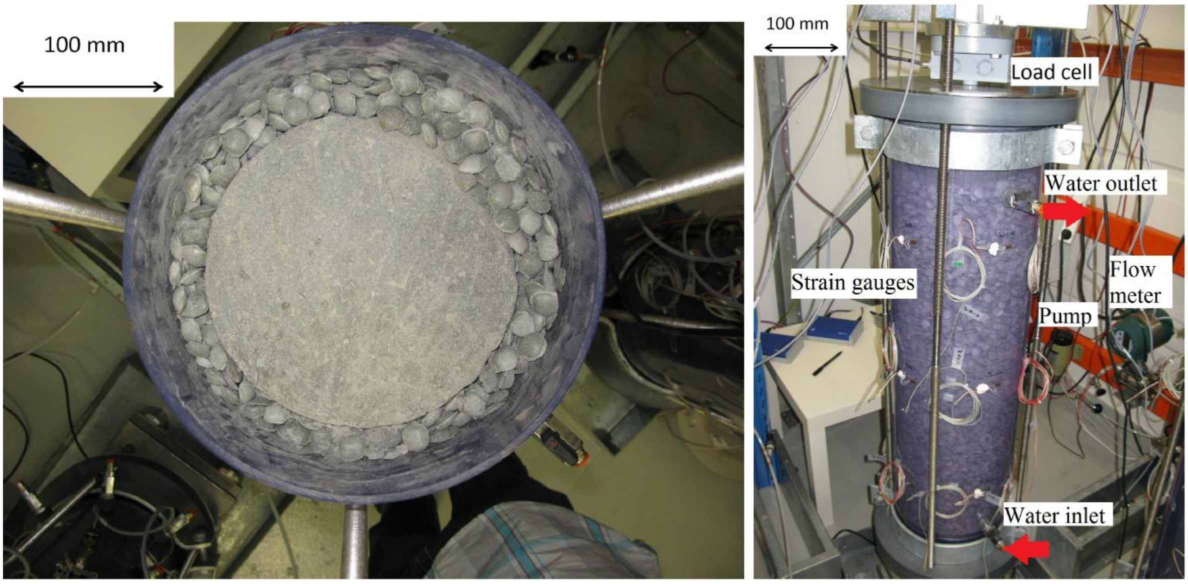


Figure 1. Overhead view of open test assembly showing sample bentonite block and gap filled with bentonite pellets (left). Complete test assembly (right).

In Transu tests 1 – 4, the envisaged constant water inflow rate was 0.1 L/min. In Transu test 1, a single flow inlet and outlet were used similar to the X-boy tests. For Transu tests 2 – 4, a series of eight, sequentially connected, flow inlets and outlets were utilized in order to simulate a larger inflow intersection. Unfortunately constant inflow and outflow could not be maintained over all of the connected ports throughout any of tests 2 – 4. For Transu test 1 tap water was used while the salinity of the water used in tests 2 – 3 was 35 g/l and 10 g/l in test 4. Transu test 8 had a constant water pressure of 25 kPa (corresponding to a static head of 2.5 m) at the inlet and the valve of water outlet was closed. The water used in test 8 had a salinity of 1 g/l.

Transu tests were performed on sets of stacked, compacted, bentonite blocks. The diameter of each block was 210 mm and height of each block was 200 mm. The initial dry density of the blocks were 1800 kg/m^3 and 1790 kg/m^3 for Transu tests 1 and tests 2 – 4, respectively. Four such blocks were stacked on top of one another on the bottom piston and the main cylinder was placed over them (see Figure 5-7 and 5-8) and the top piston installed. In Transu tests 1 and 2 the gap (30 mm) between the stacked blocks and interior cylinder wall was left empty while in tests 3 and 4 the gap was filled with Cebogel pellets (dry density of pellet fill 920 kg/m^3).

Throughout the course of a Transu test numerous sensors are used to measure axial and radial swelling pressure, inlet water pressure and inlet and outlet flow rates. In Transu test 8 the suction was measured by means of capacitive hygrometers. Periodically, the amount of effluent solids concentration is determined by gravimetric analysis. After the test, samples are taken in order to measure water content and density distribution over the sample volume. The swelling pressure evolution in axial and radial direction was monitored with a load cell and a varying quantity of strain gauges at different positions and/or total pressure transducers, respectively.

The axial and radial pressure evolution are exemplarily depicted for Transu test 4 in Figures 2 and 3, respectively. With regard to Transu test 4, the maximum axial pressure was 750 kPa and the radial pressure varied between 260 – 880 kPa.

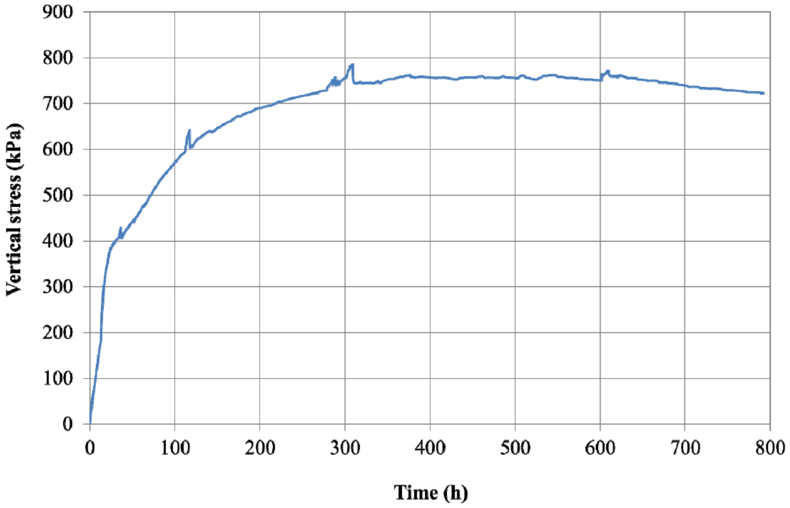


Figure 2. Axial swelling pressure development over the course of Transu test 4.

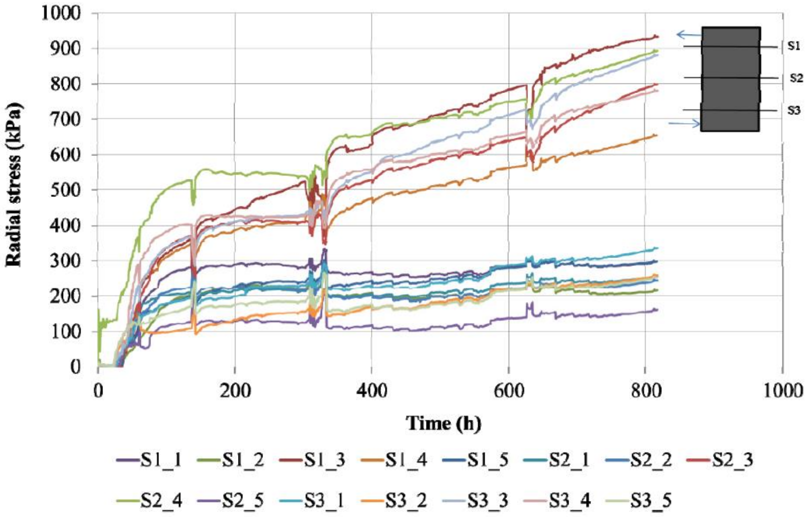


Figure 3. Radial swelling pressure development, corresponding to strain gauge position, over the course of Transu test 4.

Upon completion of the tests, samples were extracted from different positions in the Transu test volume for post-mortem analyses. The sampling scheme for the Transu tests are shown in Figure 4 and 5.

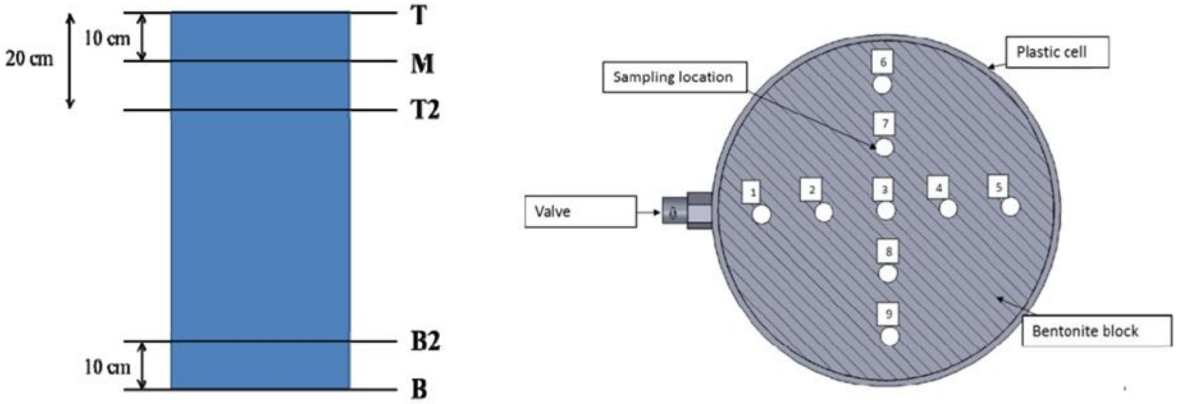


Figure 4. Post-mortem sample height sections (left) and sample locations per section (right). Note that for Transu test 4 the T2 section was not sampled.

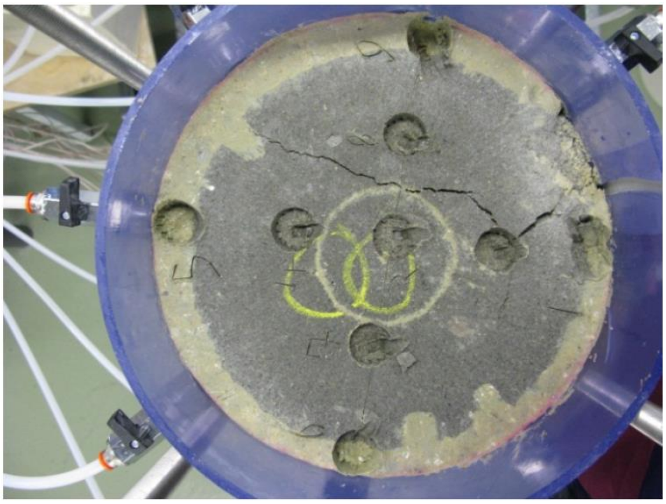


Figure 5. Overhead view of section T after sampling (Transu test 4)

Upon opening the cell at the completion of the test, clear visual distinction could be made between the pellet and block materials which indicates that no material homogenization occurred over the course of the test (see Figure 5). Cracks on the sample surface were also evident.

Water content, bulk density and suction were measured for each sample. Figure 6 displays dry density distribution, water content distribution and degree of saturation distribution, respectively, by sample position averaged over the five sampling sections. The samples at nearest the cylinder wall (positions 1, 5, 6, and 9) have the highest water contents and correspondingly lowest dry densities.

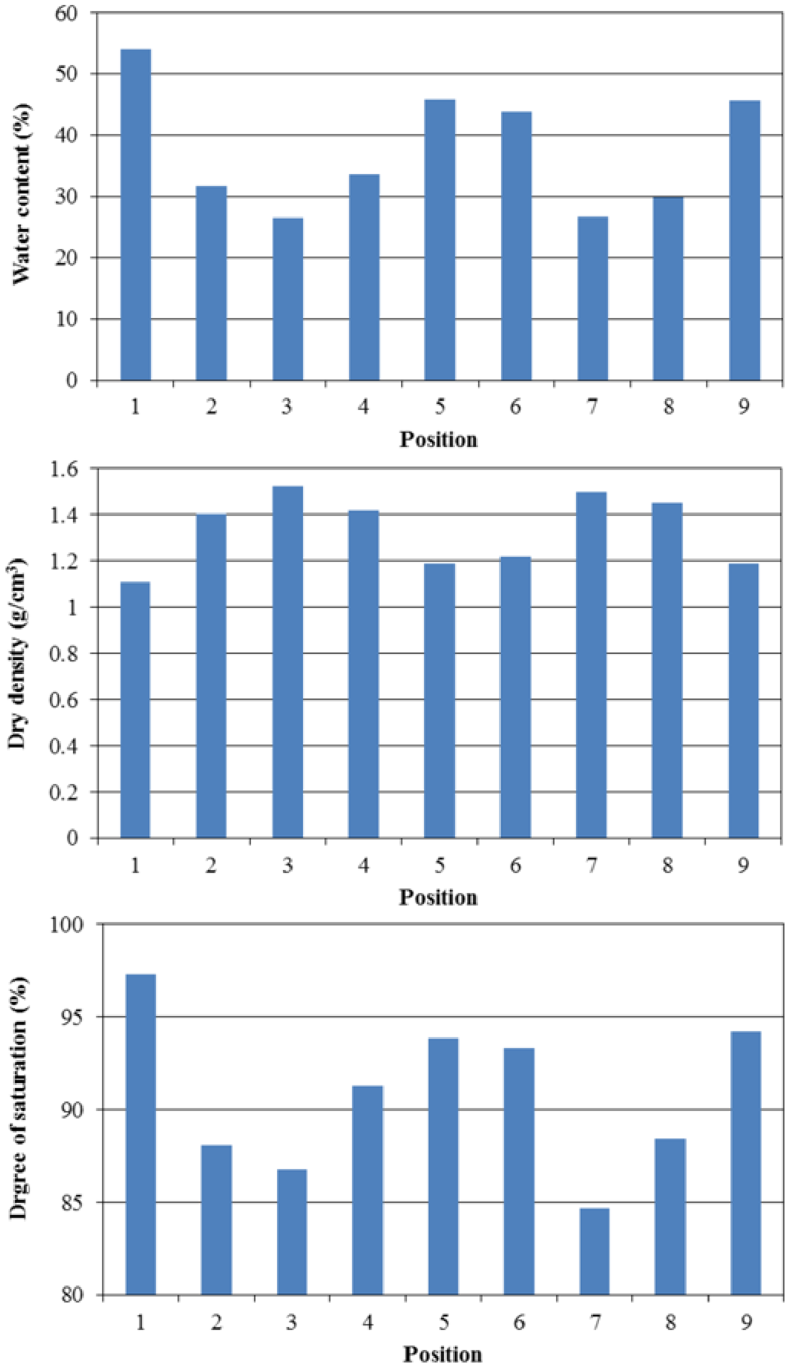


Figure 6. Dry density (top), water content (middle) and saturation degrees (bottom) by sample location averaged over the five sample sections T, M, M2, B2 and B. The water inlet was close to position 1.

The modelling work (CODE_BRIGHT) shows material saturation will evolve drastically differently depending on whether it is able to saturate across its full surface or only from a discrete channel (Figure 7). These results are in basic agreement with observations from the Transu tests.

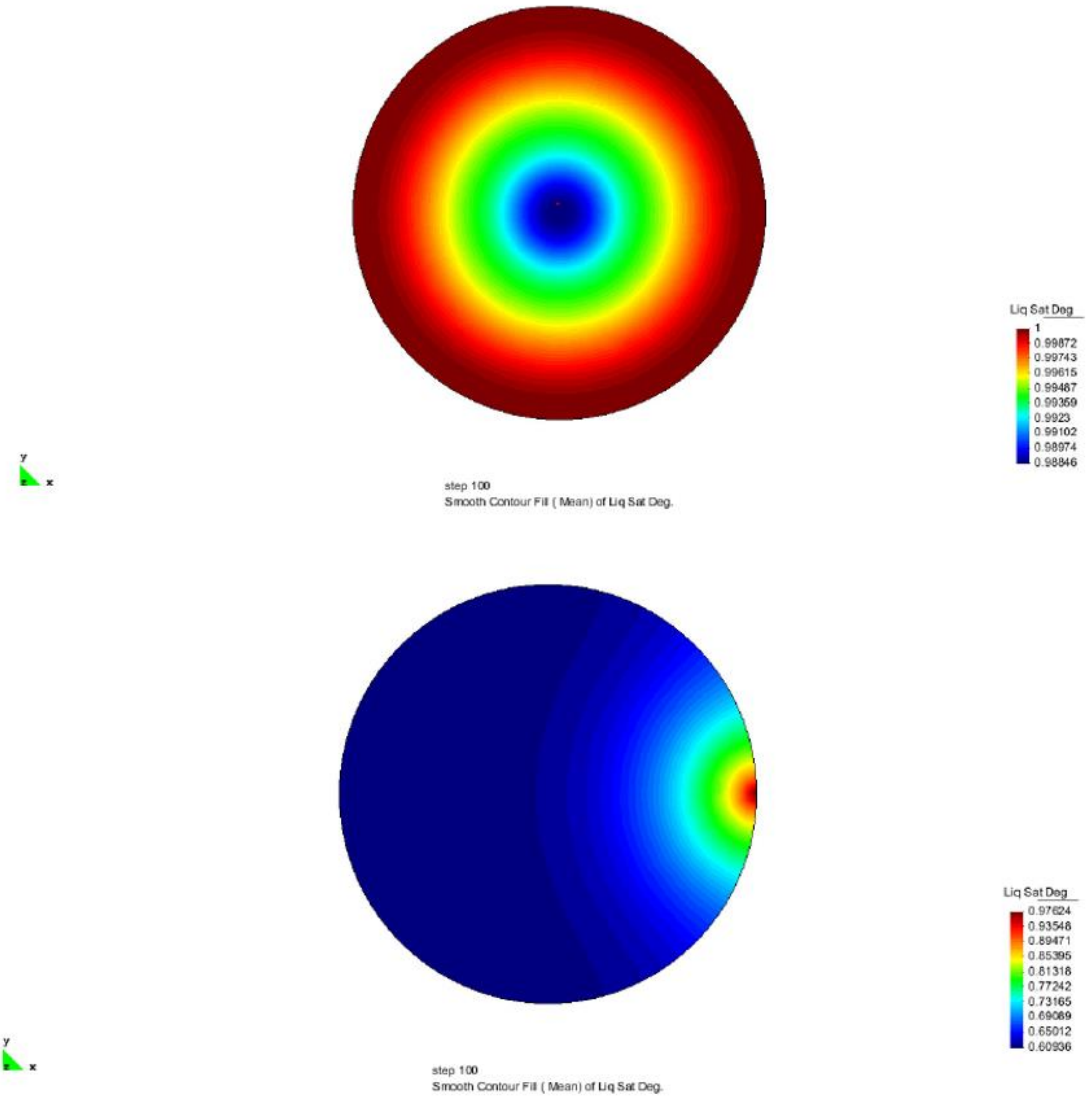


Figure 7. Degree of saturation modelling result after 100 days for the total circumference case (top) and for discrete channel case (bottom).

In deviation from this, the laboratory tests had a single water inlet and yet the post-mortem analysis showed that also parts not directly adjacent to the water inlet were considerably wetted, albeit to a lesser extent. A likely reason for this is the permeability of the pellet fill which is initially higher and provides for a wider water distribution and decreases with progressing swelling and closure of voids between the pellets. Most likely, the time available for water flowing in from single points to be significantly distributed through over the pellet fill is scale-dependent. However, modelling of the pellet fill is challenging and needs to be addressed more extensively.

Another modelling exercise was related to the axial and radial swelling pressure development of Transu test 8 (Figures 8 and 9, respectively).

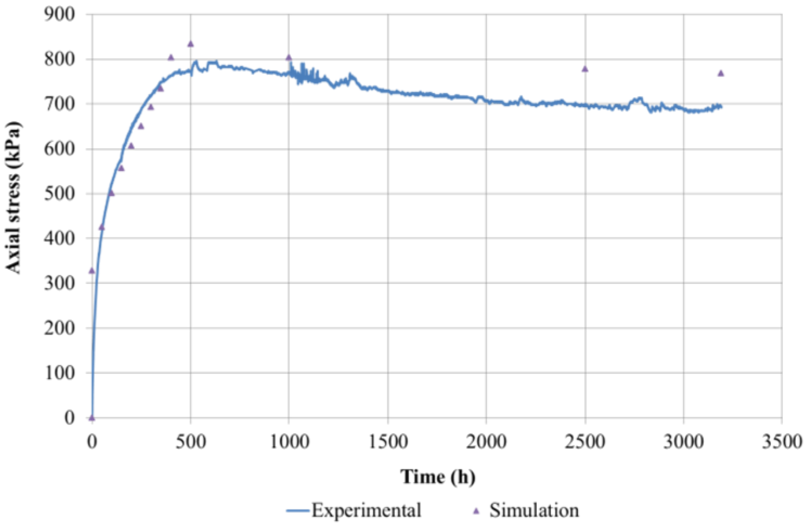


Figure 8. Axial swelling pressure development, corresponding to load cell measurement (blue line) and to the simulation results (purple trianlges), over the course of Transu test 8.

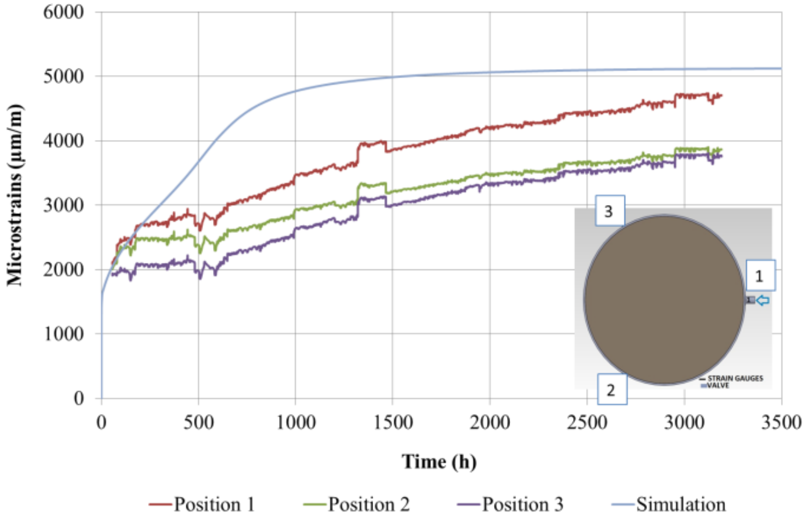


Figure 9. Radial swelling pressure development, corresponding to strain gauge positions (purple, green and red lines) and to the simulation results (blue line), over the course of Transu test 8.

The evolution of axial swelling pressure as the average swelling pressure of the system consisting a of a pellet filled gap and compacted cylindrical blocks in the center can be reproduced quite well although the behavior in maximum shows small differences under the qualitatively point of view.

The radial strains measured and simulated presents also differences under the qualitatively point of view. The initial increase in radial strains is clear but the strains increase more continuously in the experiment than in the simulation. This could be because of the pellets reach the steady state conditions in the simulation relatively fast because of the high intrinsic permeability considered, which could not be realistic after the pellets swell and the large porous disappear.

The suction evolution in Transu test 8 was also measured and simulated (Figure 10). It is possible to see that although the water inflow was through a single inlet, the measures of both hygrometers installed apart from each other (see in the right top corner in Figure 10) evolve in a similar way. Hence, although the test is clearly three-dimensional, the one-dimensional simulation is able to follow-up quite well the suction evolution.

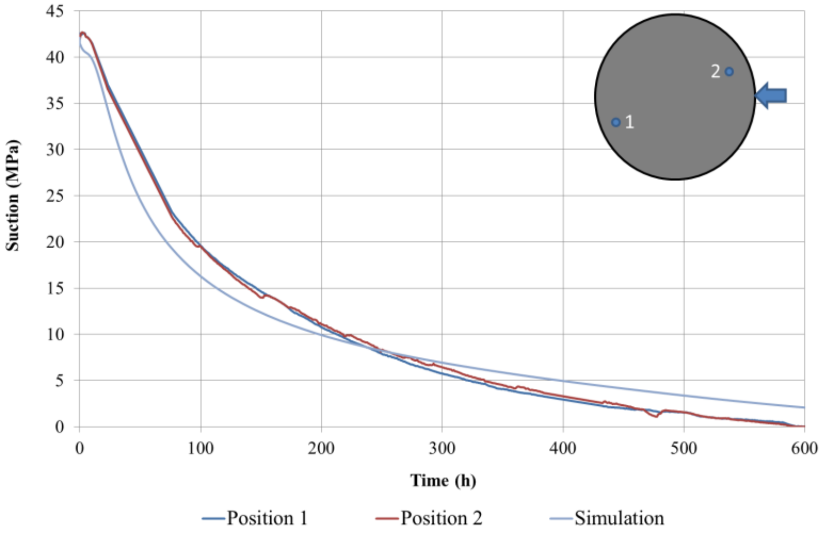


Figure 10. Suction evolution of Transu test 8 measured with with two hygrometers (dark blue and red lines) positioned as depicted in the right top corner and simulated (light blue line).

Main learning points concerning bentonite homogenization / mechanical evolution and relevance for the project

- No significant resistance to inlet water pressure was observed for any of tests 1 – 4., due to developments occurring within the test cylinders, indicating that flow pathways through the buffer system remained open.
- Effluent solids concentrations above background levels were observed over the course of all of the tests with outflow (tests 1 – 4) indicating continuous erosion.
- In general, higher levels of erosion were observed against increased solution salinity.
- The strain gauge measurements allow the evolution of swelling pressure during the hydration process to be monitored from a qualitative viewpoint and allow the magnitude of the swelling pressure developed to be quantified.
- In tests under constant water flow, the evolution of measurements in the five strain gauges differed substantially, while in tests with constant water head, differences in the evolution of measured strain values obtained from the three strain gauges are less marked.
- Relatively low swelling pressures (both axial and radial) were observed during all of tests 1 – 4.
- Non-uniform radial swelling pressure development and saturation (from post-mortem sampling) were observed for tests 1 – 4.
- Flow channels were continuously observed at the sample/test cylinder interface during all of tests 1 – 4.
- Modelling showed material saturation will evolve drastically differently depending on whether it is able to saturate across its full surface or only from a discrete channel.
- The evolution of the axial and radial swelling pressures in a down-scaled test can be simulated although there are some differences under qualitatively point of view.
- The suction evolution is quite well simulated.
- It is possible to use one-dimension meshes for simulating complex 3-D tests taking into account the geometry and process symmetries.

How could this work inform a new experimental or modelling study in BEACON?

- The modelling of different inflow and wetting situations could be extended.
- Especially modelling of the pellet fill needs to be further developed.
- Creep in the plastic cell material could affect the strain gauge measurements. In tests over very long periods where the swelling pressure is high, creep could result in the radial swelling pressure being overestimated.

References (ideally with web links)

Pintado, X., Adesola, F. & Turtiainen, M., 2013. Downscaled tests on buffer behaviour. WR 2012-100, Posiva Oy, Eurajoki, Finnland

Bendito, E., Pintado, X., 2016. Monitoring of swelling pressure in bentonite. Environmental Geotechnics,, Volume 3, Issue 5, pp. 334-345.

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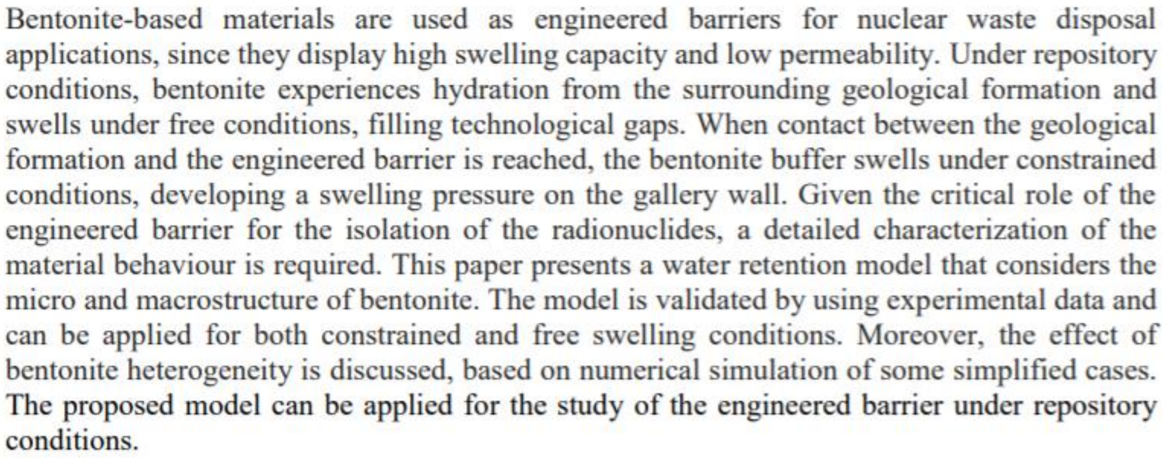
Recommendations for BEACON project

Project Acronym Water retention behaviour of compacted bentonites	**Location**	**Type**
Lead organiser University of Liege	**Start date**	**End date**
Main partners involved in the project CEA, ANDRA	**Characteristics of swelling clay**	**Water Saturation** Artificial/natural
Instrumentation	**Main elements related to homogenization**	**Interfaces with other material**
Modelling Yes/no: Groups/Codes :	**Main processes studied** ☐T ☐H ☐M ☐Swelling pressure ☐Gas transfer ☐Other	**Reference concept if pertinent**

Main objectives of the experiment



Bentonite-based materials are used as engineered barriers for nuclear waste disposal applications, since they display high swelling capacity and low permeability. Under repository conditions, bentonite experiences hydration from the surrounding geological formation and swells under free conditions, filling technological gaps. When contact between the geological formation and the engineered barrier is reached, the bentonite buffer swells under constrained conditions, developing a swelling pressure on the gallery wall. Given the critical role of the engineered barrier for the isolation of the radionuclides, a detailed characterization of the material behaviour is required. This paper presents a water retention model that considers the micro and macrostructure of bentonite. The model is validated by using experimental data and can be applied for both constrained and free swelling conditions. Moreover, the effect of bentonite heterogeneity is discussed, based on numerical simulation of some simplified cases. The proposed model can be applied for the study of the engineered barrier under repository conditions.

General description

The model was validated based on experimental data under free swelling conditions. As observed in Fig. 1 (left), the model can reproduce the measured data for the following calibration parameters: $C_{ads} = 0.0053$ MPa^{-1}, $n_{ads} = 0.79$, $A = 0.2$, $n = 3$ and $m = 0.15$. The proposed formulation can also capture the micro and macro structure behaviour under confined conditions, where the total volume remains constant (Fig. 1, right). The progressive expansion of clay particles during hydration, illustrated by the increases of the microstructural void ratio, results in a progressive decrease of the macropores volume.

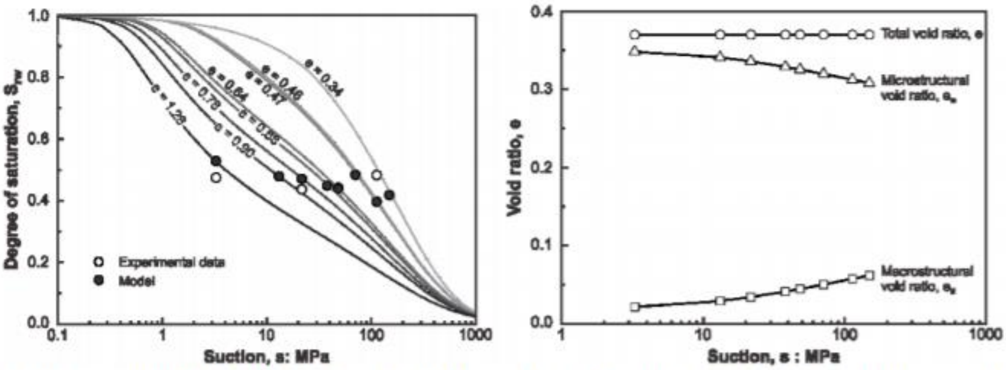


Fig. 1. Experimental data (Gatabin et al. 2016) and model predictions for free swelling conditions (left) and void ratios evolution based on model predictions for confined conditions (right) (Dieudonne et al. 2017).

Bentonite heterogeneity effect

Bernachy-Barbe et al. (2016) studied the behaviour of heterogeneous bentonite admixtures (blocks and powder) by conducting hydration tests at laboratory samples. They concluded that the non-uniform initial dry density does not affect the developed swelling pressure under confined conditions. However, heterogeneity seems to be critical for the radial and axial stresses evolution along the sample. To further understand this effect, hydration tests were simulated numerically by using the finite element code LAGAMINE (Charlier et al., 2001; Collin et al., 2002). The applied hydromechanical constitutive law was based on the water retention model, presented above, and on a modified version of the Barcelona Basic Model (Dieudonne, 2016). The parameters of the model were calibrated based on the experimental data. Two simplified axisymmetric cases (axial and radial heterogeneity) were studied. Fig. 2 shows numerical results of the axial heterogeneity case. As expected, water pressure evolves faster along the more permeable layers. The observed radial stresses evolution is the result of the varying distance to the wetting end and of the different applied properties at the layers. However, the axial stresses evolution is constant with height. Fig. 3 shows results for the axial heterogeneity case. In this case, the water pressure evolution is not uniform along the radial direction and axial and radial stresses vary along the sample. Moreover, for both cases the swelling pressure (3.9 MPa) is equal to the one of an equivalent homogenous sample. This is also the case for the height-average radial and axial stress evolution. These results are in good agreement with the laboratory observations and validate the developed constitutive law.

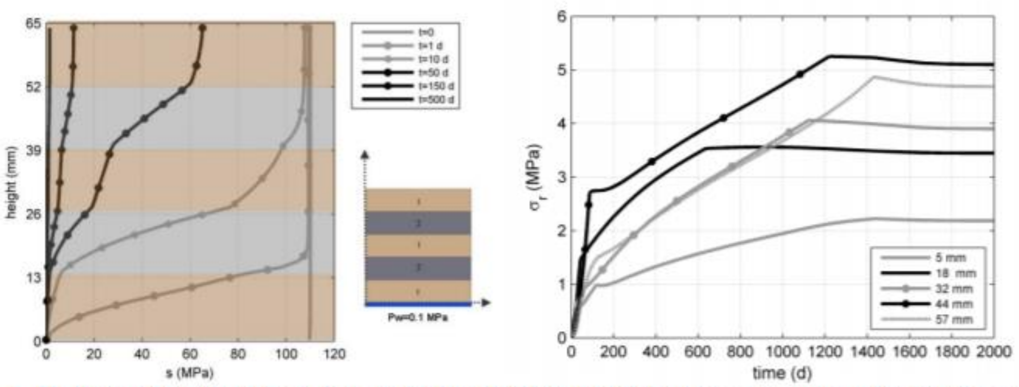


Fig. 2. Numerical results of suction evolution (left) and radial stresses evolution (right) for varying distance to the wetting end (axial heterogeneity case, layer 1: ρ_d=1.43 g/cm³, K_w=4.0·10^{-20} m², layer 2: ρ_d=1.60 g/cm³, K_w=1.5·10^{-20} m²)

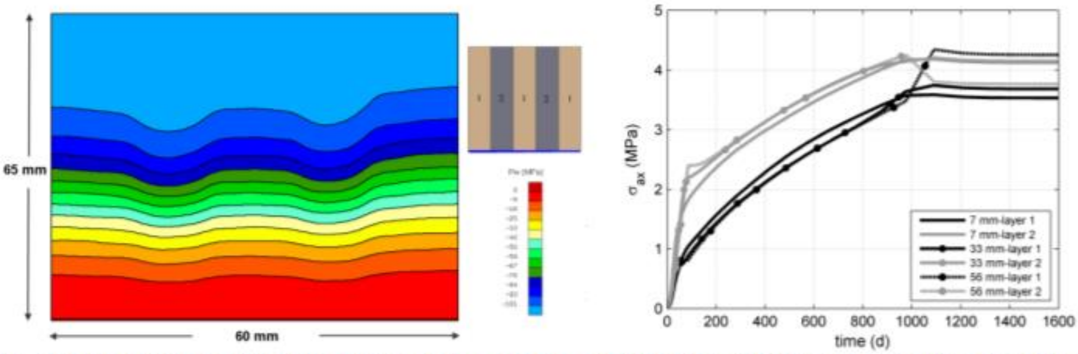


Fig. 3. Numerical results of water pressure evolution (left) and axial stresses evolution for varying distance to the wetting end (right) (radial heterogeneity case, layer 1: ρ_d=1.43 g/cm³, K_w=4.0·10^{-20} m², layer 2: ρ_d=1.60 g/cm³, K_w=1.5·10^{-20} m²)

Main learning points concerning bentonite homogenization / mechanical evolution and relevance for the project

A water retention model is presented that satisfactory reproduces the observed laboratory behaviour of bentonite-based materials. The model was calibrated and validated against experimental data and was coupled with a modified version of the Barcelona Basic Model, to study numerically the effect of heterogeneity on the behaviour of bentonite admixtures. Based on the numerical results, bentonite heterogeneity does not affect the developed swelling pressure or the height-average radial and axial stress evolution. However, it is critical for the evolution of radial and axial stresses along the sample. These results are in good agreement with laboratory observations and put in evidence the applicability of the proposed model for the study of bentonite-based materials. Moreover, contrary to classical water retention models, the proposed model considers the double-structure of compacted bentonite materials (micro and macrostructures) and can be applied for both confined and free swelling conditions. This makes it suitable for the study of the engineered barrier under repository conditions.

How could this work inform a new experimental or modelling study in BEACON?

References (ideally with web links)

Bernachy-Barbe, F., Dridi, W. & Guillot, W. (2016). F.T. Caractérisation Bentonite-Rapport Final FSS. *Technical report*, Commissariat à l'énergie atomique et aux énergies alternatives (CEA)

Charlier, R., Radu, J.-P. & Collin, F. (2001). Numerical modelling of coupled transient phenomena. *Revue Française de Génie Civil*, 5(6), 719-741

Collin, F., Li, X.L., Radu, J.-P. & Charlier, R. (2002). Thermo-hydro-mechanical coupling in clay barriers. *Engineering Geology*, 64, 179-193

Della Vecchia, G., Dieudonne, A.C., Jommi, C. & Charlier, R. (2015) Accounting for evolving pore size distribution in water retention models for compacted clays. *International Journal for Numerical and Analytical Methods in Geomechanics,* 39(7): 702-723

Dieudonné, A.C. (2016). *Hydromechanical behaviour of compacted bentonite: from micro-scale analysis to macro-scale modelling*. PhD thesis, University of Liege, Belgium

Dieudonné, A.C., Della Vecchia, G. & Charlier, R. (2017). Water retention model for compacted bentonites. *Canadian Geotechnical Journal*, 10.1139/cgj-2016-0297

Dubinin, M. M. & Radushkevich, L. V. (1947). Equation of the characteristic curve of activated charcoal. *Proceedings of the Academy of Sciences*, Physical Chemistry Section, USSR 55, 331–333

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Van Genuchten, M. T. (1980). A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. *Soil Science Society of America Journal*, 44, No. 5, 892–898

Recommendations for BEACON project

BEACON
Bentonite Mechanical Evolution

Project Acronym X-Boy	**Location** Lab facilities of Saanio & Riekkola Oy	**Type** Lab-test
Lead organiser Posiva Oy	**Start date** X-Boy 1: 20.10.10 X-Boy 2: 2.5.11	**End date** X-Boy 1: 28.12.10 X-Boy 2: 1.9.11
Main partners involved in the project Saanio & Riekkola Oy (earlier B+Tech)	**Characteristics of swelling clay** X-Boy 1: Compacted MX-80 bentonite blocks: • Block diameter 290 mm • Block height ~205 mm • Dry density ~1935 kg/m^3 • Water content 12.9 % Non-filled gap: • Width 30 mm X-Boy 2: Compacted MX-80 bentonite blocks: • Block diameter 290 mm • Block height ~205 mm • Dry density ~1860 kg/m^3 • Water content 12.7 % Extruded Cebogel QSE bentonite pellets: • Pellet dimensions: L = 4 – 16 mm, d = 6 – 6.5 • Width of pellet-filled gap 30 mm • Dry density of individual pellets ~ 1740 kg/m^3 • Dry density of pellet fill 930 kg/m^3 • Water content 18.8 %	**Water Saturation** Artificial
Instrumentation • Monitoring of: • Inlet water pressure • Inlet and outlet flow rates • Outlet effluent solids concentration • Outlet effluent turbidity	**Main elements related to homogenization** Initial heterogeneity of density: • zone filled by compacted block • non-filled zone or zone filled with pellets	**Interfaces with other material** Bentonite/steel cell

- Temperature (two thermocouples) - Axial swelling pressure (1 load cell per test) - Radial swelling pressure (X-Boy 1: 12 sensors; X-Boy 2: 24 load cells)		
Modelling Yes Groups/Codes : CODE_BRIGHT	**Main processes studied** ☐T ☒H ☒M ☒Swelling pressure ☐Gas transfer ☐Other	**Reference concept if pertinent** KBS-3V repository design

Main objectives of the experiment or modelling study

The purpose of these tests was to study early saturation behavior of buffer at mock-up scale. Swelling pressure development, piping and erosion due to groundwater inflow and the extent of homogenization as determined from post-mortem analysis were followed.

General description

The X-Boy test setup is essentially a steel cylinder with top and bottom piston inserts that can be rigidly fixed in place. Sample sizes up to 350 mm in diameter and approximately 800 mm total height can be accommodated in this device (Figure 1). The X-Boy setup is able to withstand pressures up to 4 MPa. Flow inlet and outlet ports (6 mm ID) are found at the bottom and top of the device, respectively. The tests were performed under ambient laboratory conditions. Water inflow rates were maintained at approximately 0.1 L/min. Tap water was used for artificial wetting.

X-Boy tests were performed on sets of stacked, compacted, bentonite blocks. The diameter of each block was 290 mm and height of each block was about 200 mm. The initial dry density of the blocks were ~1935 kg/m^3 and ~1860 kg/m^3 for X-Boy tests 1 and 2, respectively. Four such blocks were stacked on top of one another in the test device. After block emplacement the remaining gap between the radial block surfaces and interior test device (main cylinder) surface was 30 mm, which was left empty in X-Boy test 1 and filled with Cebogel pellets in X-Boy test 2 (dry density of pellet fill 930 kg/m^3). The duration of X-Boy test 1 and X-Boy test 2 was 69 and 122 days, respectively.

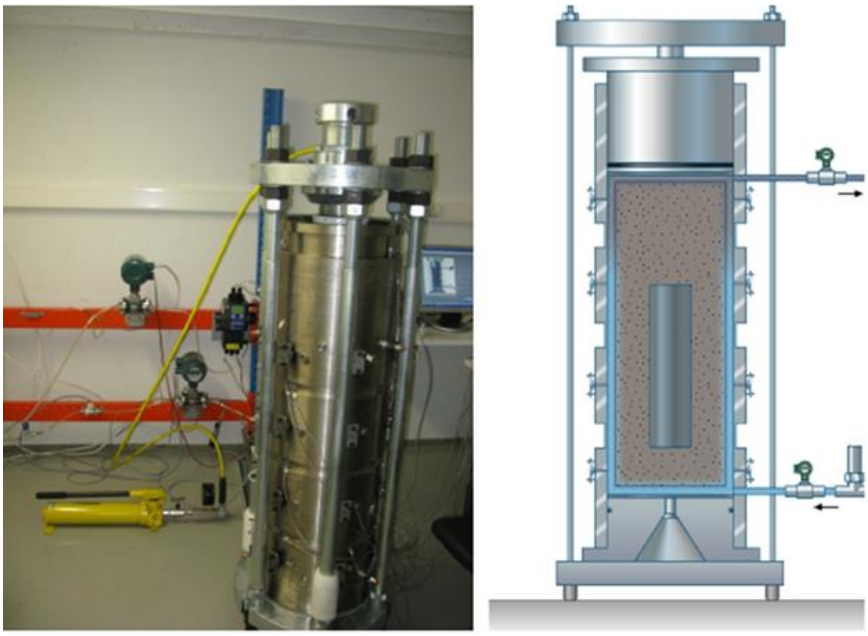


Figure 1. Photographic (left) and schematic (right) image of X-Boy test setup.

Manual, effluent sample collection is performed at regular intervals. Eroding solids concentrations were determined by drying the samples and determining the residual mass. In-line turbidity and collected filtrate mass measurements were performed as well. The turbidity of effluent samples was also measured manually. Temperature is measured with two K-type thermocouples. The axial pressure was measured with an axial load cell. For X-Boy 1, the radial pressure evolution was followed with 12 sensors located at four different height levels and three different positions per height level. For X-Boy 2, the instrumentation for measuring radial pressure evolution was similar to X-Boy 1,except for that six sensors per height level were installed (24 sensors in total). The axial and radial pressure evolution are exemplarily depicted for X-Boy test 2 in Figures 2 and 3, respectively. With regard to X-Boy test 2, the maximum axial pressure was 1120 kPa and the radial pressure varied between 200 – 1260 kPa.

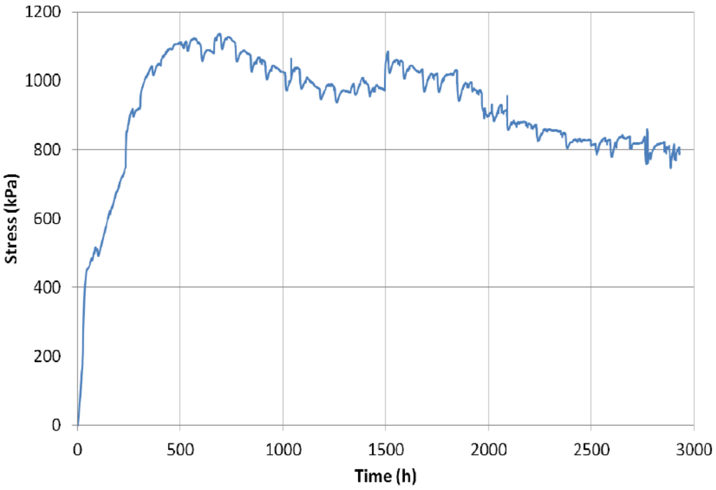


Figure 2. Axial swelling pressure development over the course of X-Boy test 2.

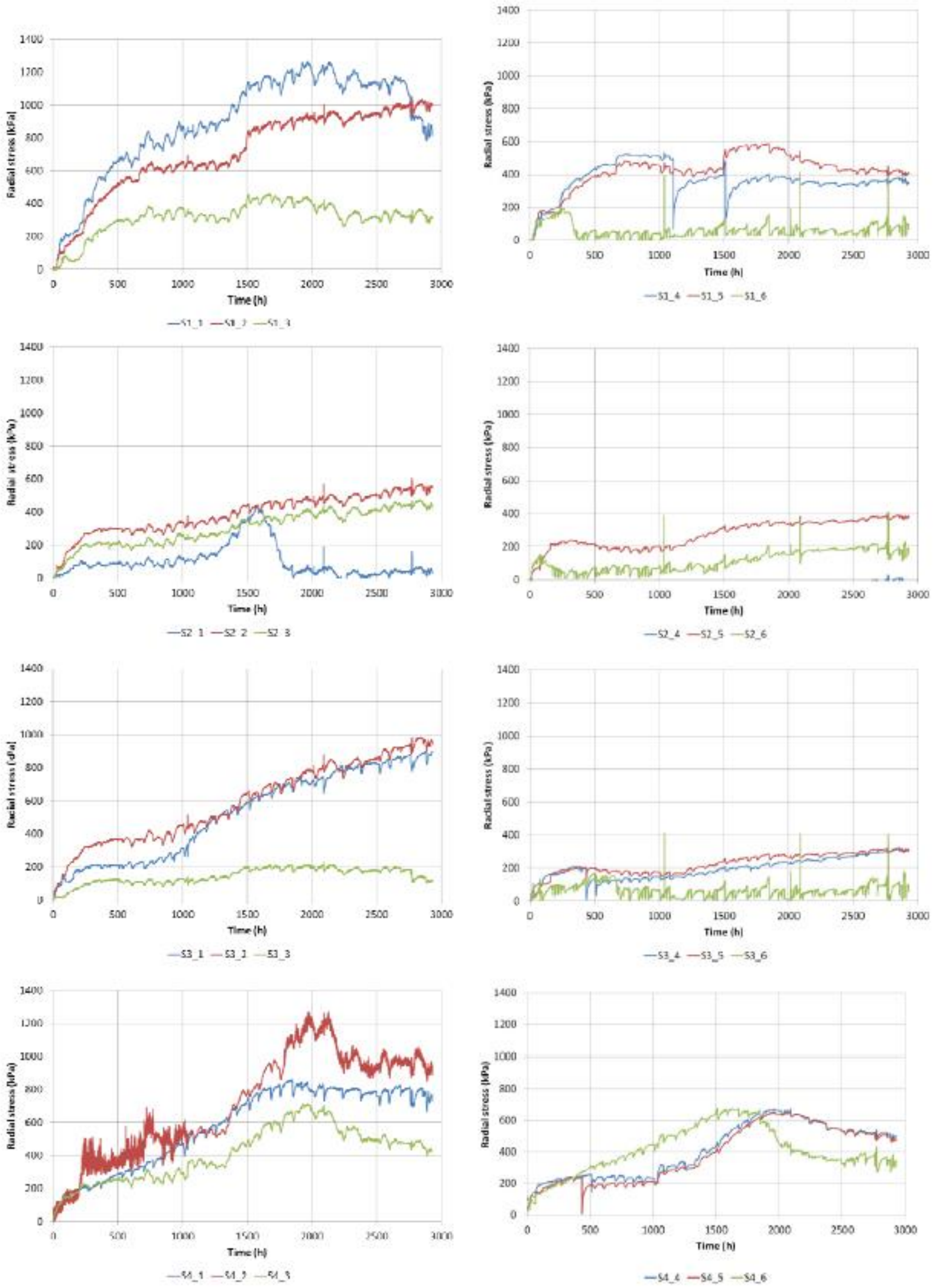


Figure 3. Radial swelling pressure development, corresponding to load cell position, over the course of X-Boy test 2.

The test was dismantled after stopping the flow and post-mortem analyses were performed. In the following, the post-mortem analysis of X-Boy test 2 is summarized, since the test setup included both compacted blocks and pellets made from bentonite. Numerous samples were extracted from three sections at different depths (Figure 4).

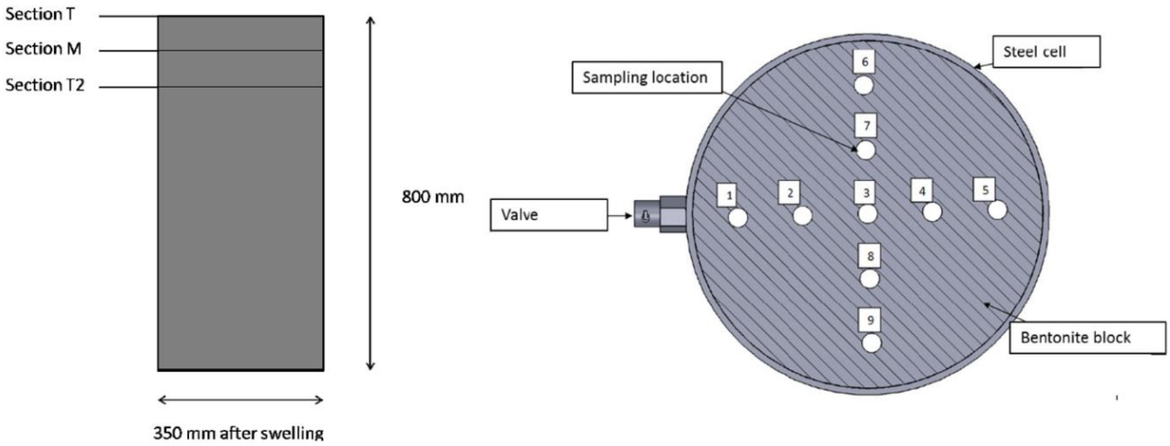


Figure 4. Post-mortem sample height sections (left) and sample locations per section (right) (X-Boy test 2).

Water content, bulk density and suction were measured for each sample. Upon opening the cell at the completion of the test, clear visual distinction could be made between the pellet and block materials which indicates that no material homogenization occurred over the course of the test (see Figure 5). Cracks on the sample surface were also evident.

Figure 5. Overhead view of section T after sampling (X-boy test 2).

Figure 6 (top) displays the calculated dry density distribution by sample location averaged over the three sampling sections. The dry density is distributed rather evenly over positions 2 - 9 but is much lower in position 1. Figure 6 (middle) displays the water content distribution by sample location averaged over the three sampling sections which is similarly distributed rather evenly over positions 2 - 9 but is much higher in position 1. It is clear that the samples in line between the inflow and outflow ports are significantly higher in water content than the other samples closest to the cell wall. Figure 6 (bottom) displays the calculated degree of saturation distribution by sample location averaged over the three sampling sections which indicates that the samples closest to the cell wall are more saturated than the interior samples and the samples inline between the inlet and outlet flow ports are the most saturated.

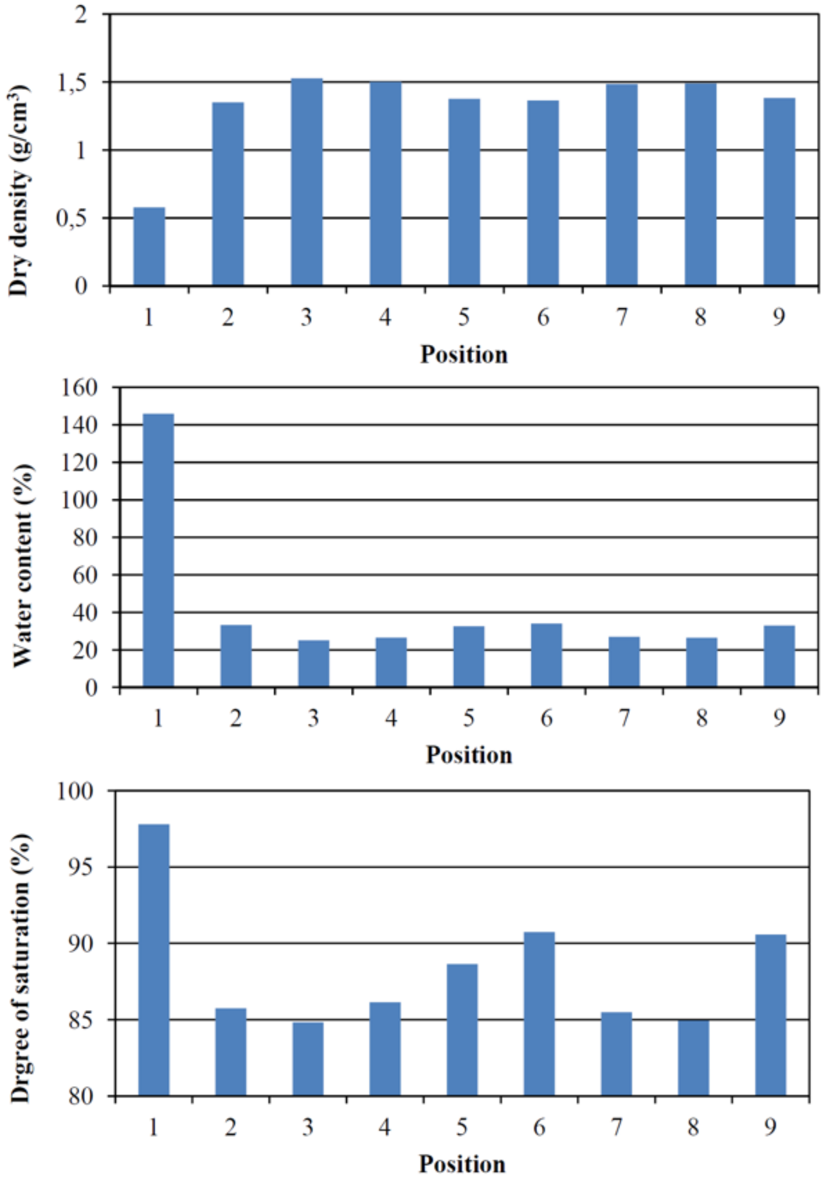


Figure 6. Dry density (top), water content (middle) and saturation degrees (bottom) by sample location averaged over sections T, M and T2. The water inlet was close to position 1.

Assuming complete homogenization and zero mass loss, the final dry density of the buffer material in this test would be 1570 kg/^{3}. The accumulated mass loss was 15.37 kg, which is equivalent to a density reduction of 200 kg/m^3. On the basis of these values, a final dry density of 1370 kg/m^3 can be calculated. This value is in good agreement with the average sample dry density (1340 kg/m^3, calculated as a weighted mean taking into account the influence area of each sample measurement).

The modelling work (CODE_BRIGHT) shows material saturation will evolve drastically differently depending on whether it is able to saturate across its full surface or only from a discrete channel (Figure 7). These results are in basic agreement with observations from the X-Boy tests.

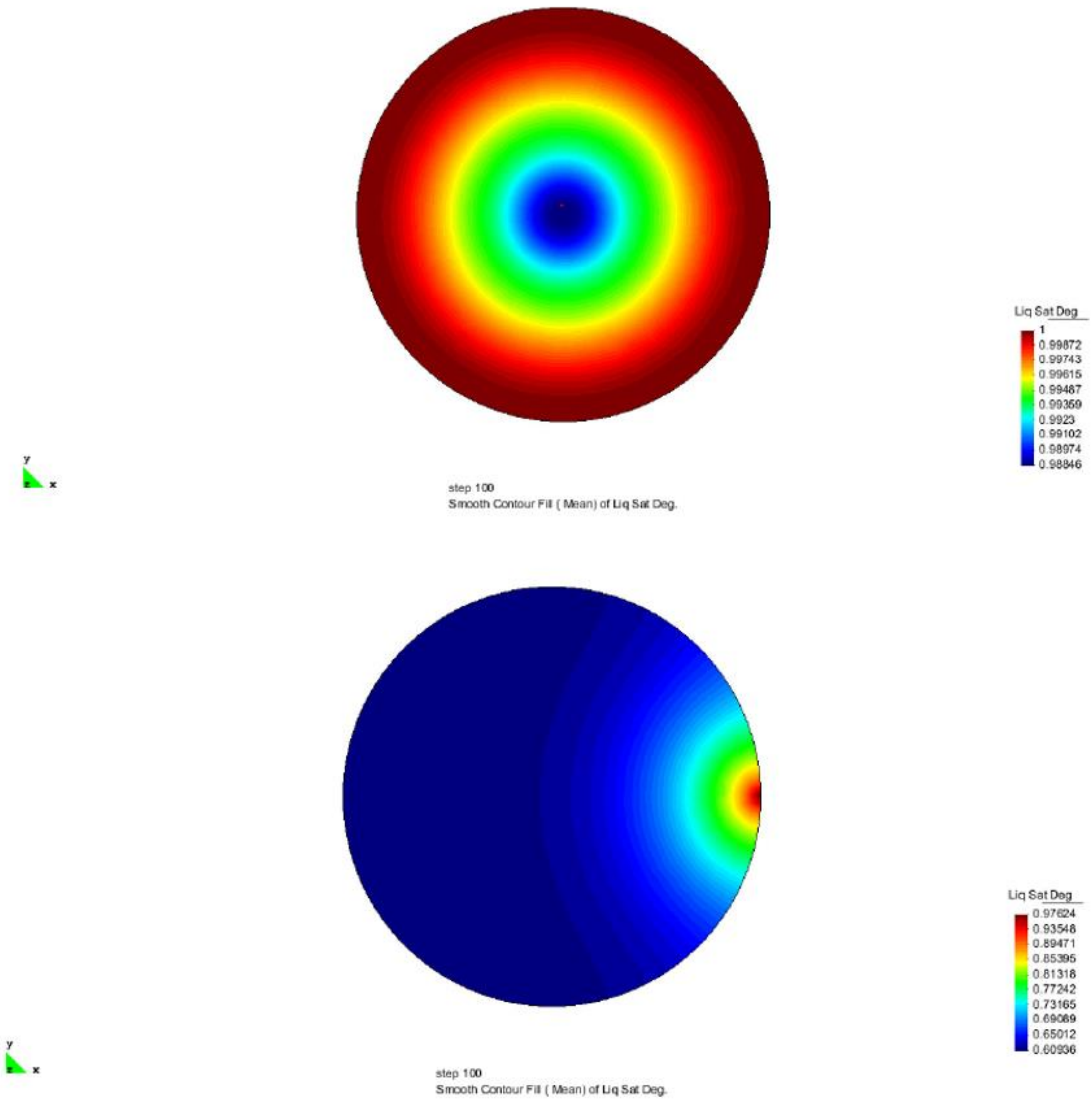


Figure 7. Degree of saturation modelling result after 100 days for the total circumference case (top) and for discrete channel case (bottom).

In deviation from this, the laboratory tests had a single water inlet and yet the post-mortem analysis showed that also parts not directly adjacent to the water inlet were considerably wetted, albeit to a lesser extent. A likely reason for this is the permeability of the pellet fill which is initially higher and provides for a wider water distribution and decreases with progressing swelling and closure of voids between the pellets. Most likely, the time available for water flowing in from single points to be significantly distributed through over the pellet fill is scale-dependent. However, modelling of the pellet fill is challenging and needs to be addressed more extensively.

Main learning points concerning bentonite homogenization / mechanical evolution and relevance for the project

- No significant resistance to inlet water pressure was observed for either test, due to developments occurring within the test cylinders, indicating that flow pathways through the buffer system remained open.

- Effluent solids concentrations above background levels were observed over the course of both tests indicating continuous erosion.
- Relatively low swelling pressures (both axial and radial) were observed during both tests.
- Non-uniform radial swelling pressure development and saturation (from post-mortem sampling) were observed for both tests.
- Modelling showed material saturation will evolve drastically differently depending on whether it is able to saturate across its full surface or only from a discrete channel.

How could this work inform a new experimental or modelling study in BEACON?

- The modelling of different inflow and wetting situations could be extended.
- Especially modelling of the pellet fill needs to be further developed.

References (ideally with web links)

Pintado, X., Adesola, F. & Turtiainen, M., 2013. Downscaled tests on buffer behaviour. WR 2012-100, Posiva Oy, Eurajoki, Finnland

Recommendations for BEACON project

Project Acronym X-ray computed tomography visualization of a clay liner	**Location** -	**Type** lab-test
Lead organiser Kumamoto University	**Start date** -	**End date** -
Main partners involved in the project Queen's University	**Characteristics of swelling clay** Layer of granular sodium bentonite Thickness 6.0 mm Mass per unit area 6.4 kg/m^2 Initial moisture content 12%	**Water Saturation** Artificial
Instrumentation External humidity sensor Scanned using a micro-focused X-ray CT scanner	**Main elements related to homogenization** Investigated crack generation due to dehumidification and subsequent desiccation Investigated both one-sided and two-sided dehumidification conditions	**Interfaces with other material** Bentonite interfaces with: non-woven cover geotextile; woven carrier geotextile; base soil
Modelling Yes/no: no Groups/Codes :	**Main processes studied** ☒T ☒H ☐M ☐Swelling pressure ☐Gas transfer ☐Other	**Reference concept if pertinent**

Main objectives of the experiment

The objective of this study was to evaluate the change in the barrier performance of a geosynthetic clay liner (GCL) as a result of desiccation due to dehumidification at 55°C.

General description

Specimens of GCL that were damaged by desiccation were scanned using a micro-focused X-ray computed tomography (CT) scanner, and crack generation under two different dehumidification conditions was examined using the results of image analysis. Permeability tests were performed to estimate the hydraulic conductivity of GCL damaged by desiccation with respect to a calcium chloride solution.

Main learning points concerning bentonite homogenization / mechanical evolution and relevance for the project

The results obtained indicate that dehumidification and a space between a GCL and a membrane sheet are key factors in the generation of cracks in the bentonite layer of a GCL at 55°C. This study is of relevance to the final repository context because dehumidification may occur also in those surroundings and lead to decrease of bentonite buffer performance.

How could this work inform a new experimental or modelling study in BEACON?

References (ideally with web links)

T. Mukunoki and A. Take (2016). Visualization of a desiccated geosynthetic clay liner due to dehumidification using micro-focused X-ray computed tomography. Japanese Geotechnical Society Special Publications, The 15th Asian Regional Conference on Soil Mechanics and Geotechnical Engineering. https://www.jstage.jst.go.jp/article/jgssp/2/53/2_JPN-050/_pdf

Recommendations for BEACON project

Appendix B 2: Mock-up experiments

BEACON
Bentonite Mechanical Evolution

Project Acronym BBI (Buffer-Backfill Interaction) Test	**Location**	**Type** 1/6 scale mock-up lab test
Lead organiser VTT	**Start date** 2014	**End date** After 62 days
Main partners involved in the project Posiva Oy	**Characteristics of swelling clay**	**Water Saturation** Artificial (0.1 litres/minute)
Instrumentation	**Main elements related to homogenization**	**Interfaces with other material**
Modelling Yes/no: Groups/Codes :	**Main processes studied** ☐T ☐H ☐M ☐Swelling pressure ☐Gas transfer ☐Other	**Reference concept if pertinent** KBS-3V (1/6 scale)

Main objectives of the experiment

The Buffer-Backfill Interaction (BBI) test was an example of a large scale investigation to demonstrate repository safety. The BBI test was a laboratory test which simulated the KBS-3V nuclear waste disposal concept with swelling bentonite clay. The BBI test was a unique test set-up consisting of both the buffer and the backfill parts which also enabled to study the interaction between the buffer and the backfill. The results of the BBI test are being used to support Posiva's next phase of repository licensing and safety analyses.

General description

The BBI equipment was commissioned in 2014 between Posiva Oy and VTT. The test equipment consisted of a horizontal tunnel (backfill) and a vertical tube (buffer) which represented the deposition tunnel and the deposition hole of the KBS-3V concept at about 1/6 scale (Figure 1). The tunnel and the buffer were filled with bentonite blocks and pellets. The focus of the BBI test was on understanding the effects of flowing water on the bentonite clay products regarding swelling, formation of water channels and erosion. Homogenization of different material types of bentonite blocks and the surrounding bentonite pellets was also investigated. Duration of the BBI test was 62 days. During the test the bentonite was exposed to a water inflow (0.1 litres/minute) with a salinity of 1 % of the water. The location of inflow was in the buffer. There were open outlets in the tunnel for the water to flow out and the outflowing water was analysed for bentonite content indicating erosion. Swelling of the bentonite was monitored during the test from various locations in the buffer and the backfill. After the test, bentonite samples were taken for water content and density analyses.

Figure 1. The BBI test equipment simulated the tunnel (left) and the buffer (right) of the KBS-3V concept. The buffer was attached to the bottom of the tunnel.

Main learning points concerning bentonite homogenization / mechanical evolution and relevance for the project

It was found that the water used the same flow paths in the test system with a continuous inflow from the same location. Most of the pellet layers in both the buffer and the tunnel were wetted. However, water distributed more to the other side of the tunnel. The tunnel backfill blocks were mostly dry after the test (Figure 2). Some dry pellets were also found after the test which indicated inhomogeneous wetting of the system. During the test there was a pause in the inflow after which the water flow directed towards dry areas of bentonite. Also, high increases of swelling pressure were registered due to pauses of the water inflow. Swelling pressure varied in different parts of the test system due to uneven wetting. Some rapid changes in the swelling pressure occurred especially during the first days of the test.

Figure 2. Cross sections from the tunnel during the dismantling. There were 6 backfill blocks in the tunnel surrounded by a backfill pellet layer.

The pellet layer in the tunnel was more saturated close to the tunnel walls than close to the backfill blocks. This indicated that the water channels were located close to the tunnel walls. Highest water contents of the tunnel pellet layers were found from above the buffer. The water content of the tunnel pellet layer ranged between 25 and 126 %. In the buffer, highest water contents were found from the pellet part having a maximum of 55 % (Figure 3). Lowest water contents in the buffer were in the middle of the block part where the minimum water content value was 27 %. The dry densities of the tunnel pellet layer ranged between 601 and 1159 kg/m^3. The dry densities in the buffer including both the pellet and the block part ranged between 1050 and 1420 kg/m^3. Vertical upheave of the buffer due to swelling was 40 mm during the test.

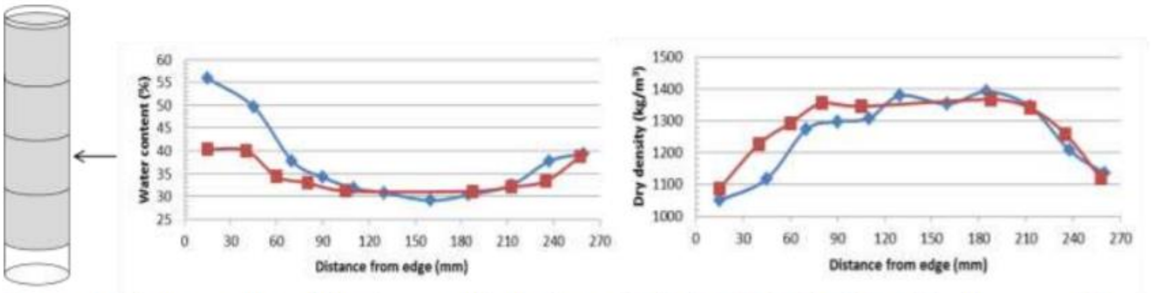


Figure 3. Water content and dry density of the buffer from the height level indicated by the arrow. The blue and red lines represent two different directions, perpendicular to each other. Diameter of the buffer was 269 mm. There were four buffer blocks in the buffer surrounded by a 50 mm thick buffer pellet layer.

How could this work inform a new experimental or modelling study in BEACON?

References (ideally with web links)

Recommendations for BEACON project

Project Acronym FEBEX mock up	**Location** CIEMAT, Madrid	**Type** Large-scale mock up (lab)
Lead organiser ENRESA	**Start date** 04/02/1997	**End date** -
Main partners involved in the project	**Characteristics of swelling clay** FEBEX bentonite (Serrata)	**Water Saturation** Artificial
Instrumentation Temperature, total pressure, axial/radial/tangential stress, relative humidity	**Main elements related to homogenization**	**Interfaces with other material**
Modelling Yes/no: Yes Groups/Codes :	**Main processes studied** ☒T ☒H ☒M ☐Swelling pressure ☐Gas transfer ☐Other	**Reference concept if pertinent** Spanish

Main objectives of the experiment

To gain knowledge and understanding of the long-term behavior of a clay barrier under well controlled thermal and hydraulic gradients.

To validate and verify the near field THM models under controlled boundary conditions.

General description

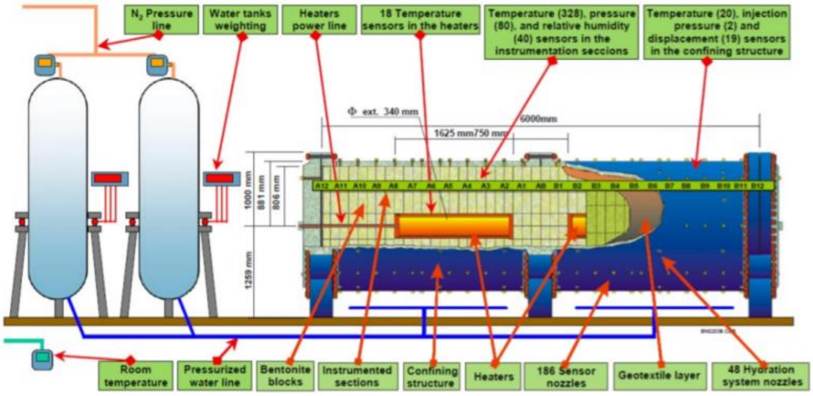


Fig. 1.7: Layout of Mock-Up test at CIEMAT (Madrid) (from Cañamón et al., 2004)

The FEBEX Mock-Up experiment is a near full-scale laboratory experiment performed at the CIEMAT in Madrid. The heater and buffer layout is similar to the In Situ Test at a slightly reduced scale and without liner. The heaters are arranged symmetrically within a steel confining structure. Water is provided through inlets in the confining structure and with a geotextile layer as interface to assure homogeneous water distribution. The Mock-Up Test is highly instrumented with a high density of temperature and total pressure cells.

The FEBEX bentonite used was fully characterized (mineralogical and chemical composition, mechanical properties, pore size distribution, density etc.)

Water is supplied at constant pressure to the buffer via the geotextile.

Main learning points concerning bentonite homogenization / mechanical evolution and relevance for the project

After a very short initial transient related to heating, temperature throughout the buffer remains steady with strong symmetry and high reliability. Axial stresses have risen quickly over the first 500 days before stabilizing. An overall

How could this work inform a new experimental or modelling study in BEACON?

Not dismantled so probably unsuitable for modelling study

References (ideally with web links)

Lanyon G. W., Gaus I., 2013. Main outcomes and review of the FEBEX In Situ Test (GTS) and Mock-Up after 15 years of operation. Nagra Arbeitsbericht NAB 13-96.

Recommendations for BEACON project

Mock-Up CZ

Jiří Svoboda[1], Radek Vašíček[2], Irena Hanusová[3]
[12] Czech Technical University, Thákurova 6, 166 29 Prague 6, Czech Republic
[3] SÚRAO, Dlážděná 6, Prague 1, 110 00 Czech Republic

Project Acronym Mock-Up-CZ	**Location** Prague, CZ	**Type** mock up (lab-test)
Lead organiser CTU in Prague	**Start date** May 2002	**End date** January 2006
Main partners involved in the project CTU, SURAO	**Characteristics of swelling clay** Mixture of: - Ca-Mg bentonite (85%), - quartz sand (10%) - graphite (5%) Initial state: - compacted blocks ρ_d=1800kg/m^3 - powder material ρ_d=1000kg/m^3	**Water Saturation** Artificial Synthetic granitic water
Instrumentation - 52 thermometers, - 50 hydraulic pressure cells, - humidity sensors of varying construction (due to poor performance replaced by sampling) - 20 resistive tensometers (on vessel) Sampling in regular intervals (water content and others)	**Main elements related to homogenization** Material redistribution and homogenization within the experiment. Highly compacted blocks expanded into voids and compressed powder material.	**Interfaces with other material** Steel heater and vessel Corrosion samples of various metals
Modelling Yes/no: Limited modelling only (no fully coupled analysis done). Groups/Codes :	**Main processes studied** ☒T ☒H ☒M ☒Swelling pressure ☐Gas transfer ☐Other – Mineralogicall changes, corrosion	**Reference concept if pertinent** KBS3 - V

Main objectives of the experiment or modelling study

The Mock-Up-CZ experiment was designed to study EBS evolution (bentonite) behavior in the disposal well. It was initially conceived as an introductory geotechnical (monodisciplinary) experiment. Its original purpose was to provide experience in solving the various problems connected with research into bentonite-based engineered barriers. However during the run of the experiments the scope was broadened and multidisciplinary research has been carried out. Especially during the dismantling, a comprehensive multidisciplinary post mortem analysis has been performed.

General description

The Mock-Up-CZ experiment simulated the vertical placement of a container with radioactive waste, an approach that is in line with the Swedish KBS-3 system. The physical model consisted of a barrier made up of bentonite blocks, powdered bentonite backfill, a heater and hydration and monitoring systems (Figure 1). The whole experiment was enclosed in a cylindrical box, whose construction was able to withstand high pressure due to bentonite swelling. A number of sensors (monitoring changes in temperature, pressure and moisture) were placed inside the bentonite barrier (Figure 5). Moreover sampling has been performed at regular intervals. The basic material used in the experiment consisted of a mixture of Czech bentonite from the Rokle deposit (85%), quartz sand (10%) and graphite (5%). To study corrosion samples of varius metals were embedded into bentonite.

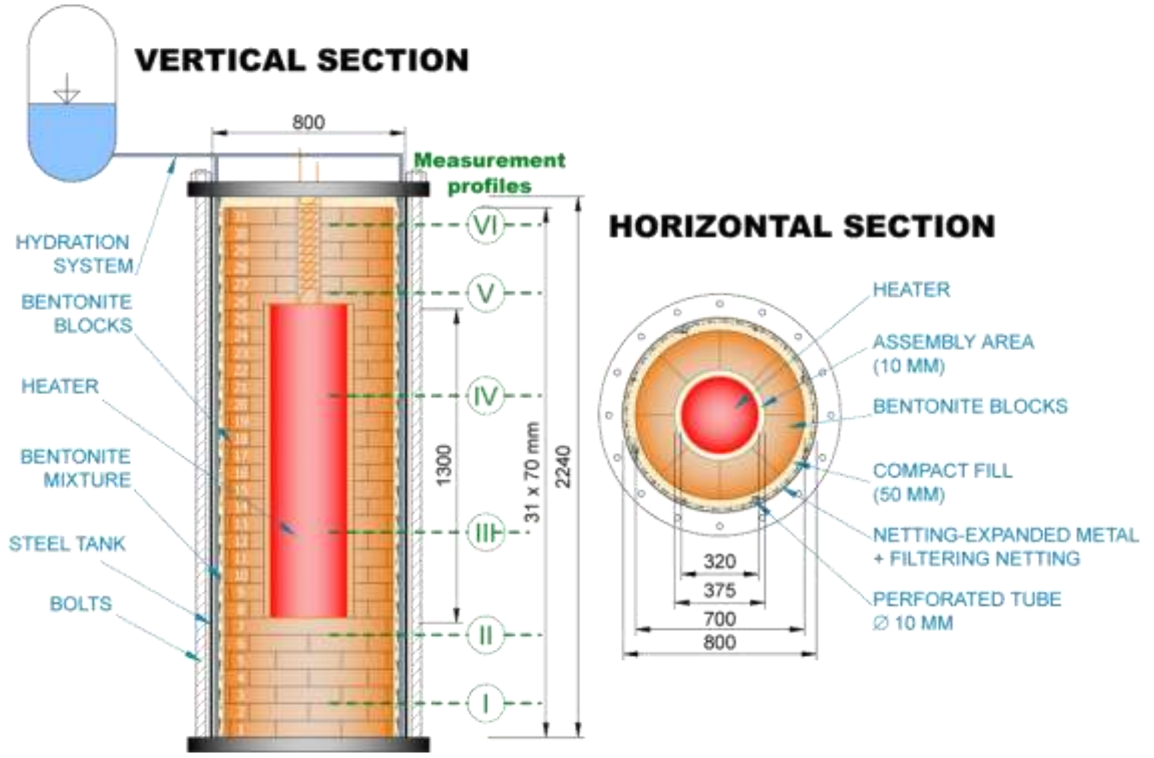


Figure 1 Mock-Up-CZ Cross-section

The first phase of the experiment commenced on 7th May 2002, during which the heater was switched on, with no water input. After 6 months the second phase commenced in which water was introduced through the hydration system (Pacovský et. al., 2007). This phase ended on 2nd January 2006 when the heater was switched off. After allowing time for cooling, the dismantling phase commenced (30th January 2006). After a further one and a half months (17th March 2006) the dismantling of the experimental vessel was completed. Post-decommissioning analysis continued until the end of 2007 (Svoboda, Vašíček 2010). This analysis included geotechnical, geochemical, mineralogical, corrosion and bacteriological research.

The experiment was monitored using (Figure 2): 52 thermometers, 50 hydraulic pressure cells, humidity sensors of varying construction (due to poor performance replaced by sampling), 20 resistive tensometers (on vessel). Sampling was performed in regular intervals by core drilling (water content and others, Figure 4).

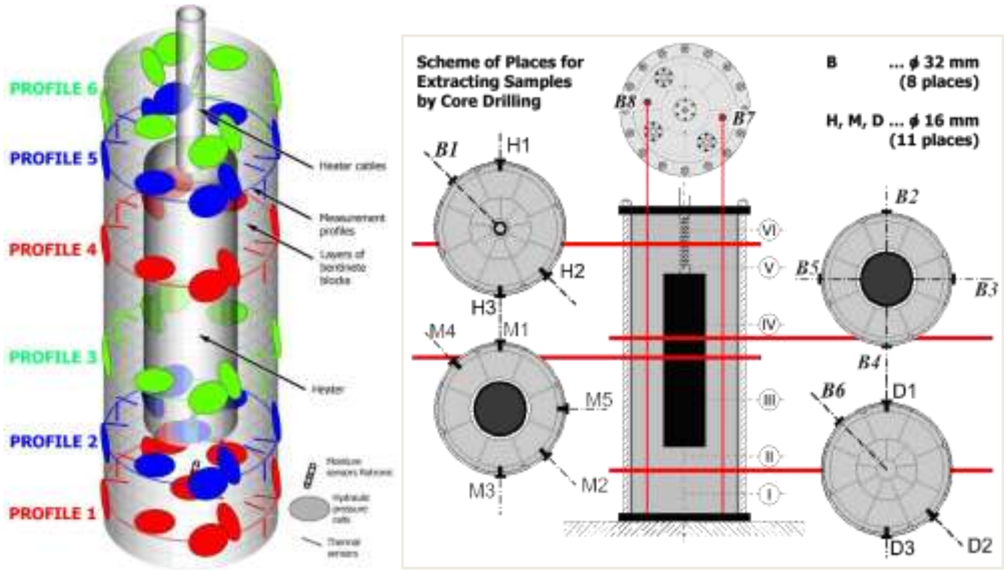


Figure 2 Instrumentation and sampling points

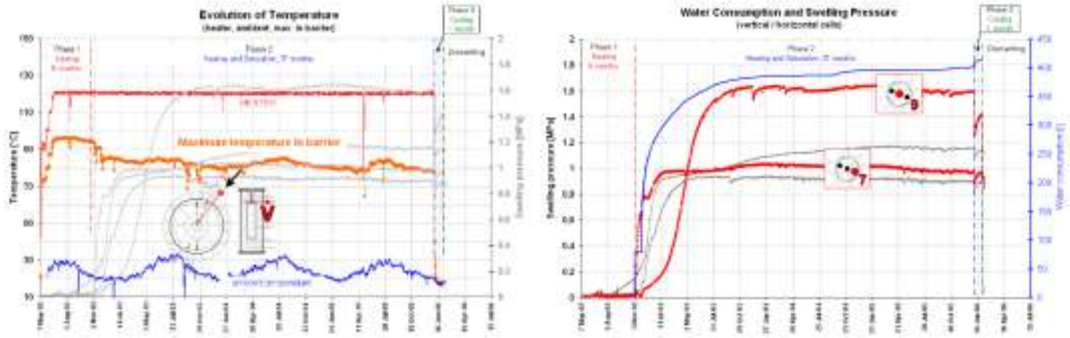


Figure 3 Temperature, swelling pressure and water consuption

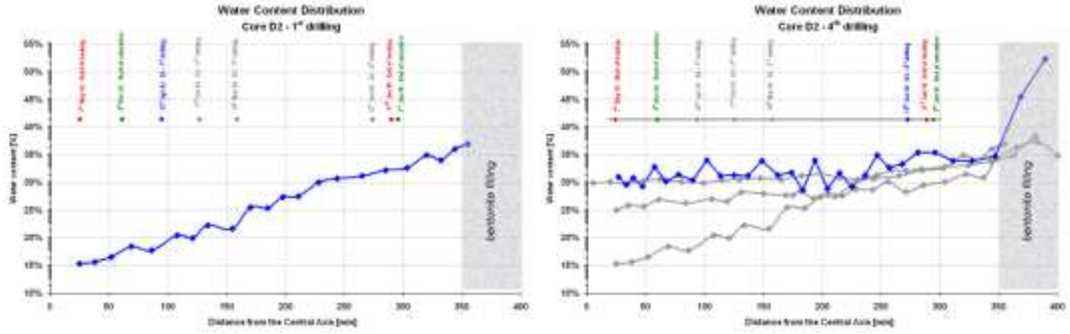


Figure 4 Water content distrubition in core drill (from core drills)

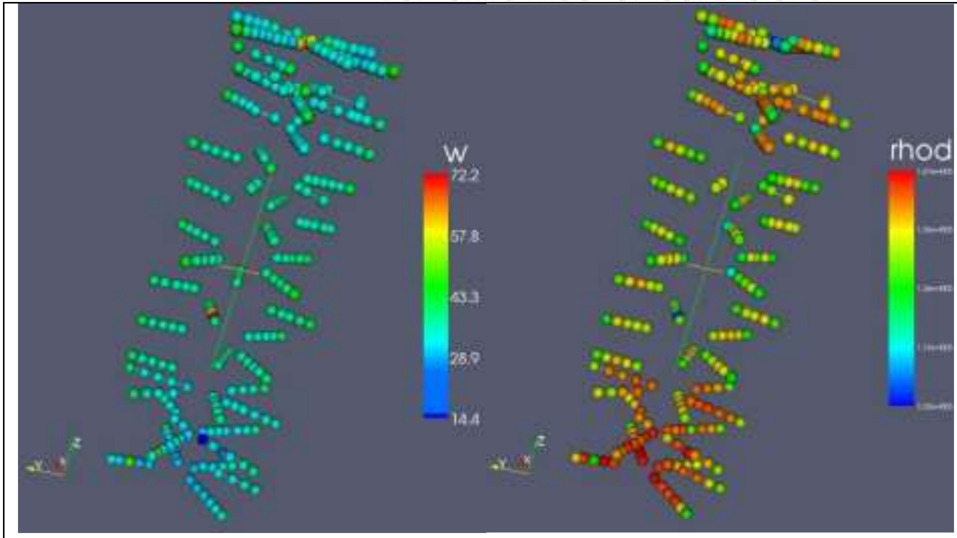


Figure 5 Water content and dry density density distribution (dismantling)

Main learning points concerning bentonite homogenization / mechanical evolution and relevance for the project

The experiment used bentonite in two main forms – highly compacted blocks and powder material. During the experiment run, a material redistribution has been observed. The highly compacted block expanded, compressed the loose materials and voids were filled. The detail data from post mortem analysis documents this process. Some shear has been observed.

The first two phases of experiment run give insight into system behavior without and with additional water available. This allows to study both humidity migration due to the temperature gradient only (first phase – water moving into outer parts) and saturation phase when bentonite got fully saturated despite the temperature gradiens.

The big advantage of the experiment is data from the material sampling during the experiment runt. This gives very precise info about water content development during the experiment run.

How could this work inform a new experimental or modelling study in BEACON?

The experiment can serve as benchmarking tool and verification tool for mathematical models.

The experiment is already finished and dismantled/decommissioned. Both the data from the experiment run and from comprehensive analysis of final state is available. The geometry and boundary conditions are clearly defined. This gives a rich dataset, which can serve as input and validation for the modelling teams.

References (ideally with web links)

Svoboda, J.; Vašíček, R. 2010: "Preliminary geotechnical results from the Mock-Up-CZ experiment", *Applied Clay Science*. 2010, 47(1-2), 139-146. ISSN 0169-1317. https://doi.org/10.1016/j.clay.2008.12.012 , http://www.sciencedirect.com/science/article/pii/S0169131708002949

Pacovský, J., Svoboda, J., Zapletal, L. 2007: "Saturation development in the bentonite barrier of the Mock-Up-CZ geotechnical experiment", *Physics and Chemistry of the Earth*, Parts A/B/C, Volume 32, Issues 8-14, 2007, Pages 767-779, https://doi.org/10.1016/j.pce.2006.03.005, http://www.sciencedirect.com/science/article/pii/S1474706506002038

Pacovský, J., Svoboda, J., Vašíček, R., 2008. Testing Possible Czech Waste Disposal Concept and Clay Material through Real Scale Mock-Up (Dismantling and Preliminary Geotechnical Results), *Science & Technology Series,* no 334 (2008), Andra, France

Svoboda, J.; Vašíček, R., 2006, Some Results After 3 Years of Mock-Up-CZ Experiment Operation, In: Proceedings of the 2006 International High-Level Radioactive Waste Management Conference "Global Progress Towards Safe Disposal", April 30 - May 4, 2006, Las Vegas, NV, USA. I. Rotterdam: CIB Proceedings, 2006, pp. 17-22. ISBN 0-89448-691-8.

Kolarikova, Irena; Svandova, Jana; Prikryl, Richard; et al., 2007, Mineralogical changes in bentonite barrier within Mock-Up-CZ experiment, Conference: Workshop on Long-term Performance of Smectitic Clays Embedding Canisters with Highly Radioactice Waste Location: IDEON Sci Pk, Lund, SWEDEN Date: NOV 26-28, 2007, APPLIED CLAY SCIENCE Volume: 47 Issue: 1-2 Special Issue: SI Pages: 10-15 Published: JAN 2010, https://doi.org/10.1016/j.clay.2009.11.011, http://www.sciencedirect.com/science/article/pii/S016913170900307X

Recommendations for BEACON project

Project Acronym OPHELIE mock-up	**Location** Belgium	**Type** mock up
Lead organiser EURIDICE	**Start date** 02/12/1997	**End date** 02/10/2002
Main partners involved in the project ONDRAF/NIRAS	**Characteristics of swelling clay** M2: A mixture of FoCa clay (60 wt.%), sand (35 wt.%) and graphite (5 wt.%) M14: A mixture of FoCa clay (85 wt.%), sand (10 wt.%) and graphite (5 wt.%)	**Water Saturation** Artificial (1 MPa fixed hydration pressure, hydrated from pipes installed at the buffer's periphery)
Instrumentation 147 sensors within the mock-up, 42 on the outside. Majority (100) thermocouples, plus 54 strain gauges, 9 pressure cells, 9 relative humidity cells, 6 piezometers. 78 type K thermocouples within mock-up, 6 within heater, 16 on outside. Hydration monitored by external hydration system (injected volume, pressure), relative humidity cells, pore pressure transducers, thermal pulses method. Swelling monitored through deformation of steel, total pressure cells and load cells on the bolted cover	**Main elements related to homogenization** Unexpected heterogeneity of temperature and temperature gradient was observed.	**Interfaces with other material** Stainless steel casing
Modelling Yes/no: Yes (coupled THM, 1D) Groups/Codes: LAGAMINE (University of Liège)	**Main processes studied** ☒T ☒H ☒M ☐Swelling pressure ☐Gas transfer ☐Other	**Reference concept if pertinent** SAFIR-2 (horizontal)
Main objectives of the experiment The initial objective of the mock-up was to prepare for the PRACLAY Experiment. The PRACLAY Project was aimed at demonstrating the technical and economic feasibility of the repository design		

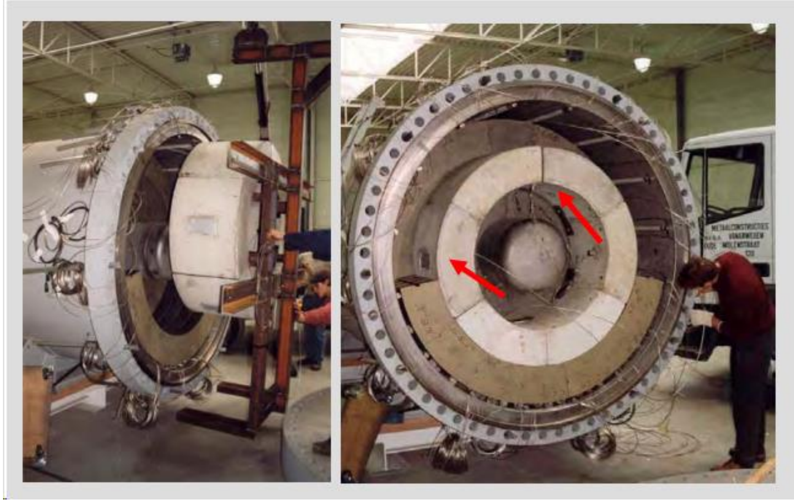
on a large scale and using a direct experiment. As several technical aspects of the in-situ test had not yet been worked out in detail, in 1995 ONDRAF/NIRAS and EURIDICE decided to first construct and operate a large-scale surface mock-up called OPHELIE. The mock-up simulated the engineered barriers of the disposal system as far as the disposal tube and the buffer material are concerned. Its design and the temperature, hydration and pressure conditions were as similar as possible to the in-situ ones.

More specifically, the OPHELIE mock-up was intended to verify some practical aspects like the robustness and performance of the sensors in harsh conditions over a period of several years, the manufacture and placement procedure for the buffer material and the hydration process for this material. Taking advantage of such large-scale infrastructure, the mock-up also served as a preliminary investigation into the buffer material's THM behavior and an observation of its evolution after several years of hydration and heating.

General description

The OPHELIE mock-up simulated (full-scale with respect to the diameter, and with a length of 5m) a section of a disposal gallery of the SAFIR-2 reference design as far as the buffer material and the disposal tube were concerned.

The mock-up's metallic structure was composed of a main jacket, two covers and the central tube simulating the disposal tube. The hydration system was fixed at 1 MPa to saturate the buffer. The buffer material consisted of pre-fabricated blocks of a mixture of 60% FoCa clay, 35% sand and 5% graphite uniaxially compacted at 61 MPa. A complete buffer section consisted for three concentric rings. A concrete ring was installed at the end of the mock-up to test the behavior of measuring instruments.



The thermal conditions for the OPHELIE mock-up were implemented using an internal heater simulating the heat generated by the HLW canisters (464 W/canister or 350 W/m), and an external heating and insulation system simulating the boundary conditions imposed in an actual repository by the host formation. A thermal insulation of 60 mm of Rockwool was specified on the outside of the jacket. To obtain a radial heat flow, the axial heat flow was limited as much as possible.

The experiment's operational stage started in December 1997 and lasted about 4.5 years. Several parameters were monitored, mainly dealing with the buffer material's THM behavior and verification of the robustness and performance of different types of sensors in harsh pressure and temperature conditions and in contact with the saturated medium. Unexpected phenomena and processes were observed. Corrosion problems were also identified.

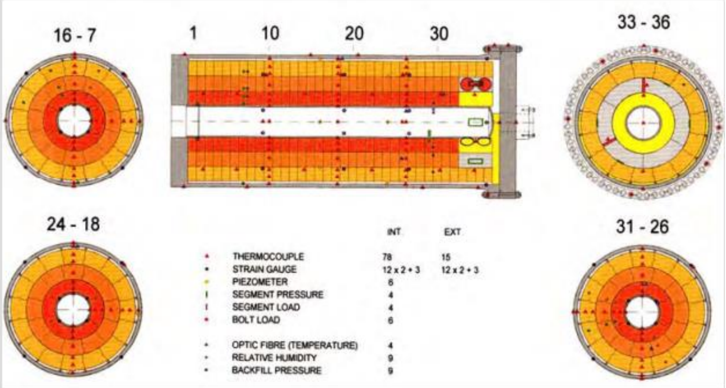


Figure 5-1: The instrumentation inside and outside the mock-up; the sensors were installed according to radial and longitudinal profiles.

The operational stage of the mock-up consisted of the following phases: hydration at ambient temperature, heating with continuing hydration and cooling phase. The heating phase started six months after the start of hydration (when the buffer was mostly saturated and a high thermal conductivity was measured). The mock-up was then cooled down rapidly by switching off all heating elements six weeks before dismantling began.

Main learning points concerning bentonite homogenization / mechanical evolution and relevance for the project

Unexpected observations: the maximum temperature reached at different points within the buffer material and the radial temperature gradient were dependent on the direction. This resulted in a high thermal conductivity.

General conclusions: the swelling buffer had closed all initial voids. Expansion had mainly taken place in the outer ring. The swelling process of the M14 material, unlike the M2 material, seems to have been homogeneous because of the higher clay content and the larger accessible void in its immediate neighbourhood.

With regards to chemical and mineralogical properties, no major change or spatial variation was observed in the buffer material.

The evolution of the swelling pressure followed the hydration process and was lower than expected.

How could this work inform a new experimental or modelling study in BEACON?

References (ideally with web links)

Van Humbeeck H., Verstricht J., Li X.L., De Cannière P., Bernier F., Kursten B., 2009. The OPHELIE mock-up. Final report. EURIDICE report 09-134. http://www.euridice.be/sites/default/files/scientific/OPHELIE%20mock-up%20final%20report%20low%20resolution.pdf

Recommendations for BEACON project

In future, multidisciplinary studies should be better integrated from the start of the project. Indeed, geochemical measurements and microbiological analyses are particularly important for determining the chemical boundary conditions needed by the corrosion studies. They should be taken into account in the initial design of the experiment.

Project Acronym REM (Resaturation à l'Echelle Métrique)	**Location** Bure URL, France (Callovo-Oxfordian claystone-COX)	**Type** Surface experiment
Lead organiser Andra (France)	**Start date** September 2014	**End date** In progress
Main partners involved in the project	**Characteristics of swelling clay** MX80 powder/pellets: same mixture as FSS experiment	**Water Saturation** Artificial
Instrumentation • pore pressure, • relative humidity, • total pressure, • temperature	**Main elements related to homogenization** Relatively homogeneous pellets and powder mixture	**Interfaces with other material** none
Modelling Yes: Hydraulic simulation Groups/Codes: internal with Code_Bright-	**Main processes studied** ☐T ☒H ☒M ☒Swelling pressure ☐Gas transfer ☐Other	**Reference concept if pertinent** tunnel seal in Andra reference concept for radioactive waste disposal

Main objectives of the experiment

The REM (Metric Scale Resaturation) experiment has been designed to study the water saturation of the bentonite mixture of 32 mm pellets and crushed pellets used in FSS experiment (Full-Scale Seal see Dopas project D3.30). FSS demonstrator and REM mock-up are complementary: FSS objective is to demonstrate the construction feasibility of a seal and REM is dedicated to study the behavior of the bentonite during water saturation phase.

General description

The vessel is cylindrical with a 1 m internal diameter and an inside height of 1 m. The vessel comprises a 40 mm thick confinement cylinder, with 2 lids fitted with sintered stainless steel porous discs in the bottom part and air vents in the top part (Figure 1).

The vessel is filled with pellets and crushed pellets in the mass proportions of 70%/30% of MX80 bentonite (Figure 2). A total amount of 100 layers of pellets has been poured in the vessel to achieve final dry density of 1.50 ± 0.01 g/cm^3. The initial average relative humidity is closed to 27 %.

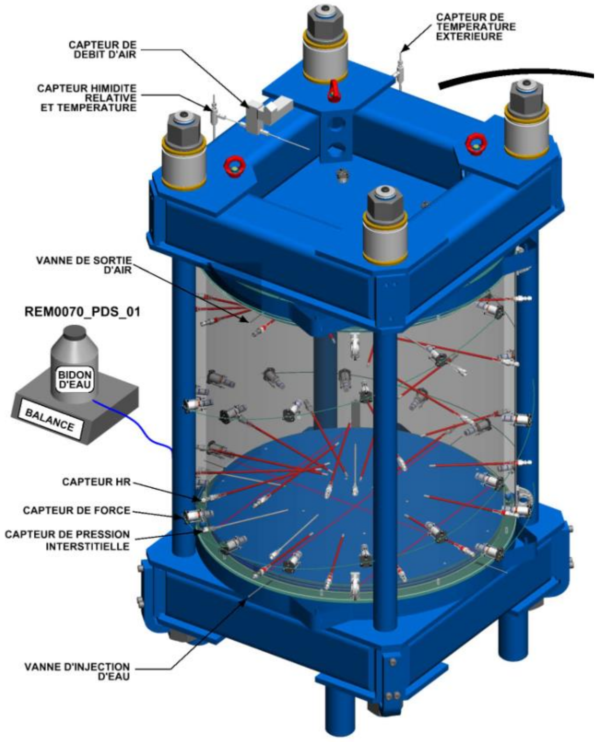


Figure 1 Schematic representation of the REM vessel

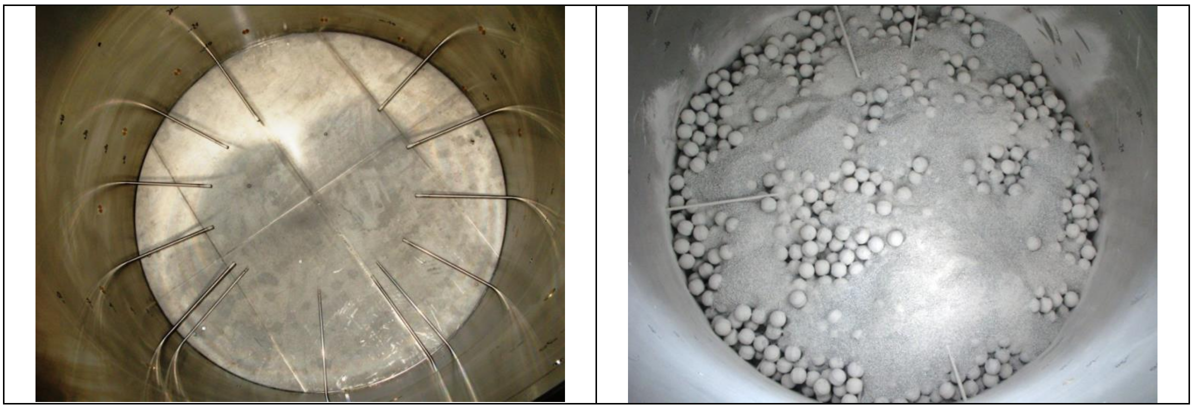
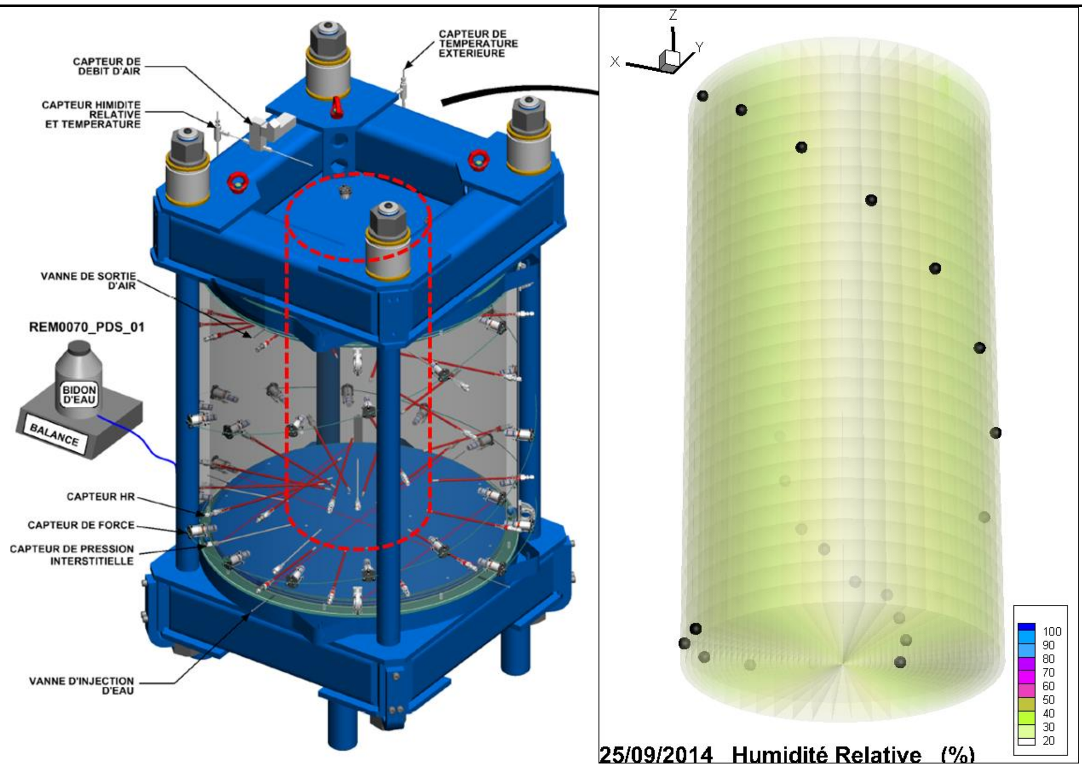


Figure 2 Left: first level of RH sensors. Right: first layer of pellet / crushed pellet mixture

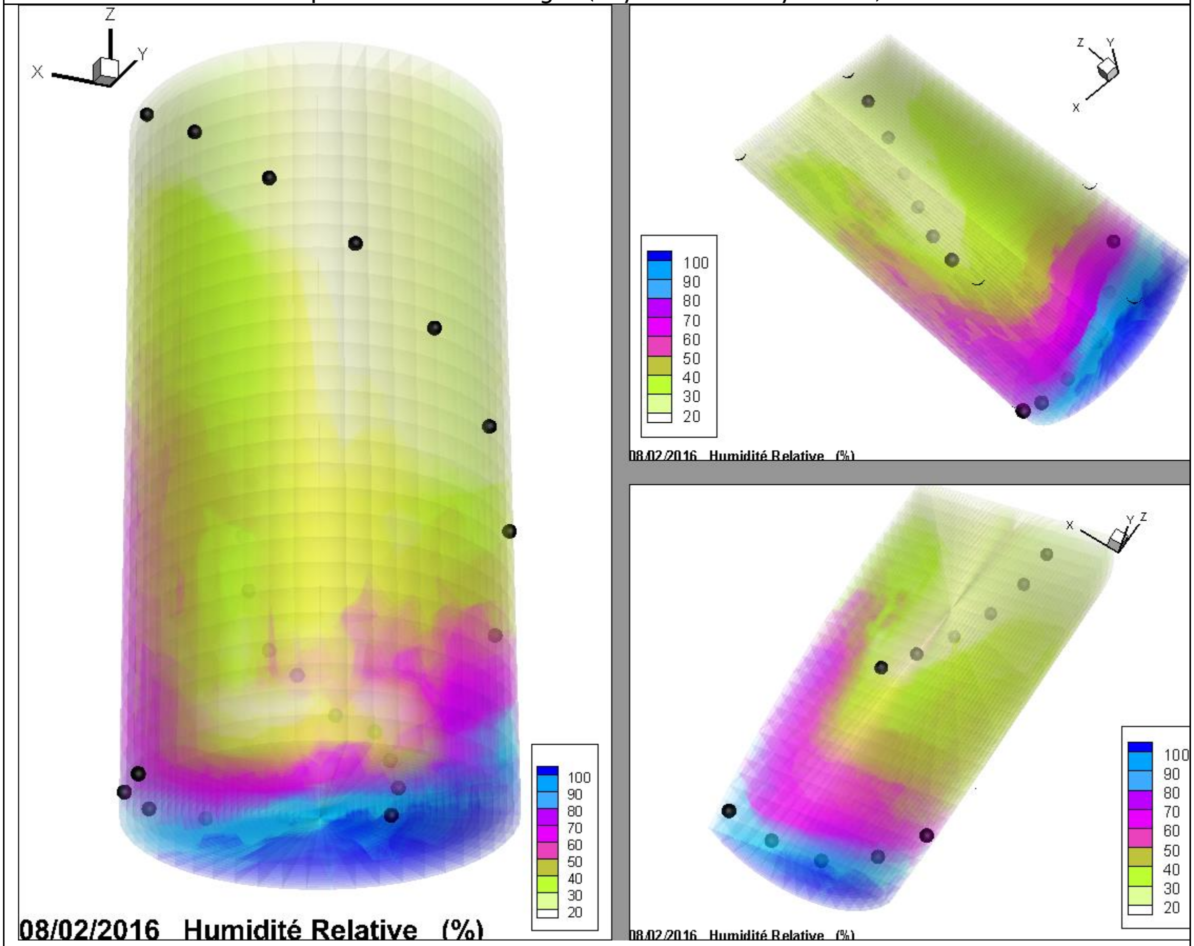
Monitoring: A total of 30 relative humidity/temperature (Figure 2), 38 total pressure (30 radials and 8 axials) and 5 pore pressure sensors have been installed. The injected water volume is also monitored and entrapped air could escape from the top (open valve).

Example of results: Artificial hydration has started in September 2014 at constant flowrate (50 mL/day) in the bottom part of the vessel. In June 2017, ~ 41 L of water has been injected.

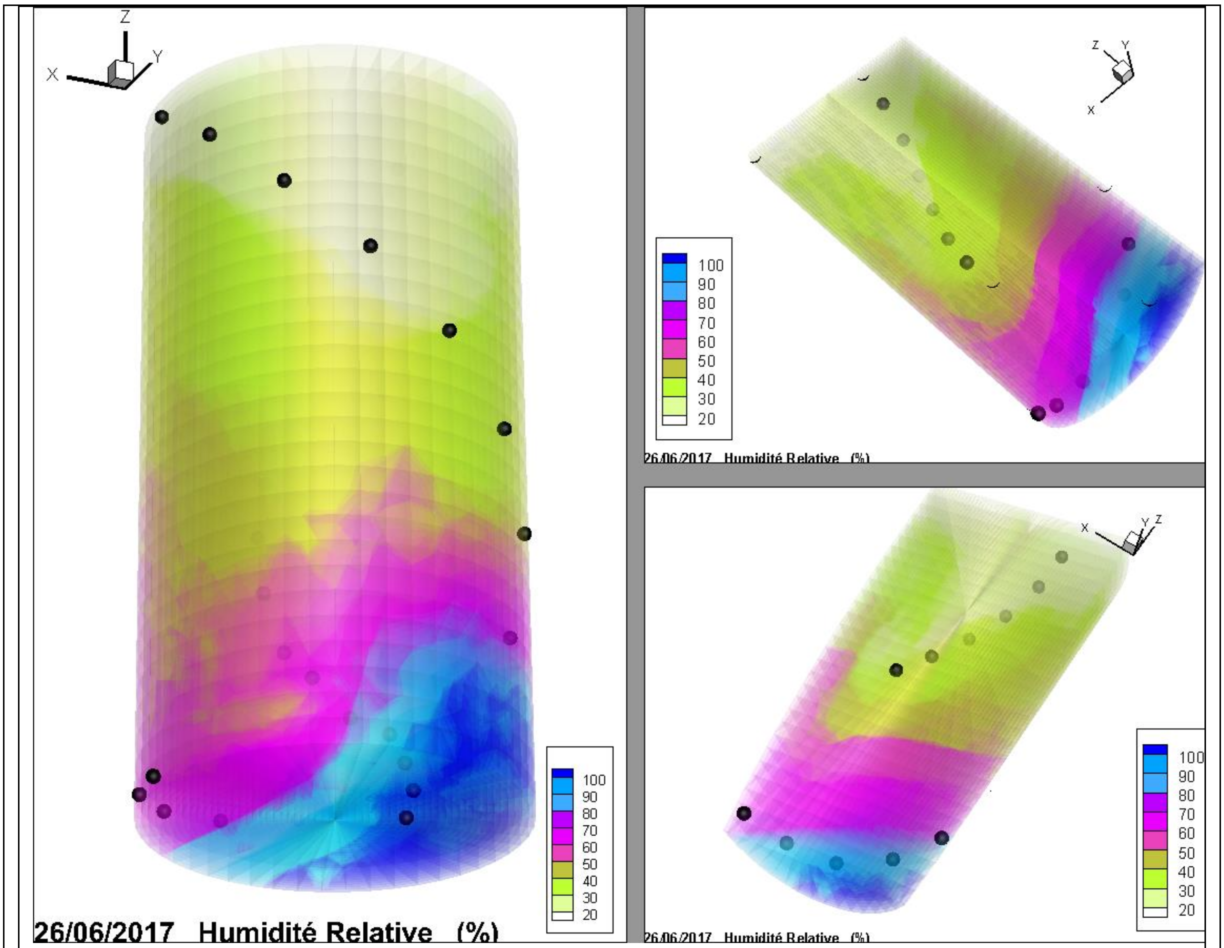
On **Error! Reference source not found.**, relative humidity measured inside bentonite core indicates heterogeneity on the hydration process due to gravity effect. In fact, the vessel is not perfectly horizontal and injected water could accumulate in one local area. Currently, there is no measured swelling pressure.



The red dotted cylinder on the left defines the cylinder volume in which the interpolation is performed on the right (day 1: start of hydration)



Interpolation of RH measurements at 500 days



Interpolation of RH measurements at 1000 days

Main learning points concerning bentonite homogenization / mechanical evolution and relevance for the project

The heterogeneous response during the transient phase needs to be investigated and especially the role of a local accumulation of water.

How could this work inform a new experimental or modelling study in BEACON?

This experiment has a well-defined geometry. The initial characterization HM of the material involved has been done. A large number of sensors allows to follow the hydromechanical evolution of the bentonite core.

This lead to consider this experiment as a good candidate for blind prediction to modelling test within WP 5.

Based on this project what suggestions could be helpful to BEACON in terms of bentonite characterisations, specific problems to treat, pitfalls to be avoided, model to develop…

- Local accumulation of water due to gravity must be taken into account

References (ideally with web links)

REM (Resaturation Test at Metric Scale) setup and first results (DOPAS Project), Nathalie Conil, J. Talandier and G. Armand. Proceeding of Dopas 2016 seminar, pp. 226-232

REM (Resaturation test at metric scale): Preliminary hydraulic simulation (DOPAS Project), Antoine Pasteau, , Jacques Wendling, Nathalie Conil and Claude Gatabin. Proceeding of Dopas 2016 seminar, pp. 159-163

http://www.posiva.fi/files/4528/Dopas_Deliverable_D7_3_DOPAS_2016_proceedings_final_public_ver

3.pdf

Project Acronym SB (preceding mock-up test)	**Location** Mont Terri rock lab, CH	**Type** Mock-up
Lead organiser GRS	**Start date** January 1995	**End date** December 2007
Main partners involved in the project Nagra	**Characteristics of swelling clay** Sand/bentonite mixtures (calcigel)	**Water Saturation** artificial
Instrumentation Fluid and total pressure sensors	**Main elements related to homogenization**	**Interfaces with other material**
Modelling Yes Groups/Codes : GRS, Code_Bright	**Main processes studied** ☐T ☒H ☒M ☐Swelling pressure ☐Gas transfer ☐Other:	**Reference concept if pertinent**

Main objectives of the experiment or modelling study

Qualify sand/bentonite mixtures as material for engineered barriers with reduced cohesion and gas entry pressure to allow for discharge of corrosion gases while maintaining sufficiently low permeability to water and sufficiently high swelling pressure

General description

This text follows closely the respective section of a publication for the Mont Terri 20th anniversary (Wieczorek et al. 2017).

1 Preceding mock-up test

The mixture with 65/35 sand/bentonite ratio was chosen for two mock-up experiments in steel tubes of 300 mm diameter (Fig. 1), which represents a 1:1 scale with respect to the later in-situ experiment. The test procedure was to

- Instrument the test tubes
- Determine initial installation density of the granular sand/bentonite mixture
- Determine the initial gas permeability
- Inject water from the bottom to re-saturate the seal
- Determine seal permeability to water at full saturation
- Inject gas and determine gas entry pressure and permeability after break-through
- Determine the final water content in the seal by post-mortem sampling and analysis

The results of the mock-up tests, in terms of dry density, permeability, swelling pressure, and gas entry pressure were in line with the laboratory values. It was, however, found that the time to reach full saturation was much longer than expected (29 months instead of 6 months) from scoping calculations. Water content was determined after dismantling. An average value of 18.4% was obtained.

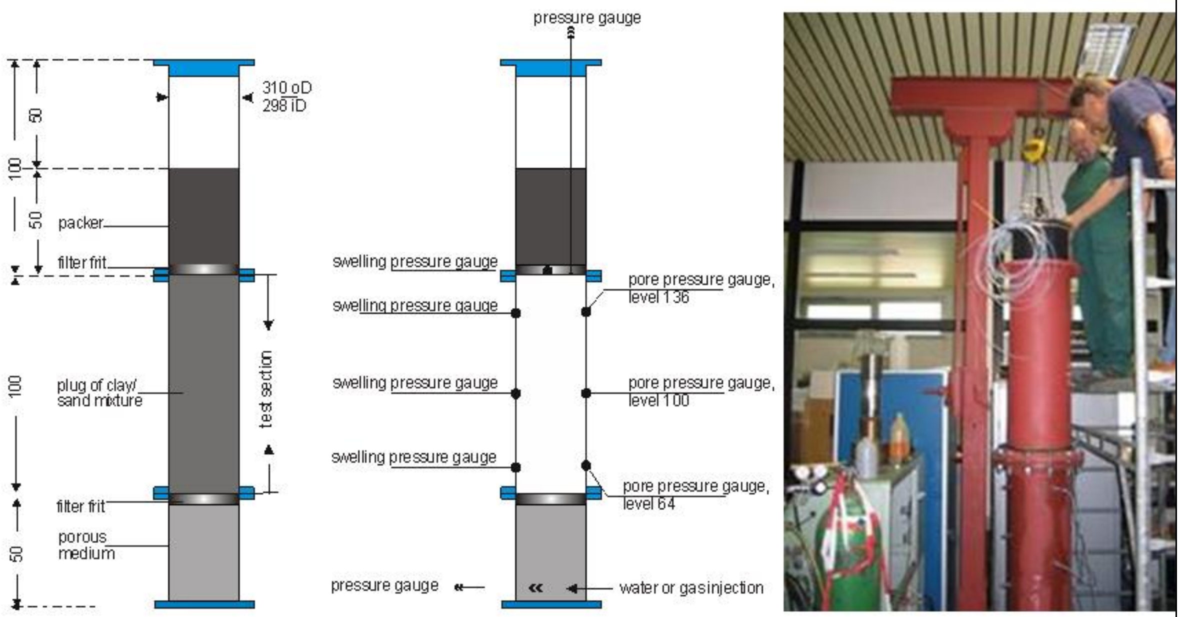


Fig. 1 Overview of SB mock-up design and instrumentation (Rothfuchs et al. 2012).

Main learning points concerning bentonite homogenization / mechanical evolution and relevance for the project

The focus of the experiment was on sand-bentonite mixtures.

How could this work inform a new experimental or modelling study in BEACON?

The mock-up deals only with sand-bentonite mixtures.

References (ideally with web links)

Rothfuchs, T., Czaikowski, O., Hartwig, L., Hellwald, K., Komischke, M., Miehe, R., & Zhang, C.-L. (2012). Self-sealing Barriers of sand/bentonite mixtures in a clay repository - SB Experiment in the Mont Terri Rock **Laboratory**. *Final Report, Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) MbH, GRS-302*, 146 pp. Gesellschaft für Anlagen-und Reaktorsicherheit (GRS) mbH, Köln, Germany. **http://www.grs.de/german-publications**

Wieczorek, K., I. Gaus, J.C. Mayor, K. Schuster, J.-L. García- Sineriz, T. Sakaki (2017). In-situ experiments on bentonite-based buffer and sealing materials at the Mont Terri rock laboratory (Switzerland). Swiss Journal of Geosciences, 110.

Recommendations for BEACON project/ What would I do differently, were I to repeat my earlier study?

Appendix B 3: Field-scale experiments

Project Acronym 40% scale Buffer tests	**Location** ONKALO	**Type** In situ
Lead organiser VTT	**Start date** 2011	**End date** ongoing
Main partners involved in the project	**Characteristics of swelling clay**	**Water Saturation** Artificial/natural
Instrumentation	**Main elements related to homogenization**	**Interfaces with other material**
Modelling Yes/no: Groups/Codes :	**Main processes studied** ☐T ☐H ☐M ☐Swelling pressure ☐Gas transfer ☐Other	**Reference concept if pertinent** KBS-3V

Main objectives of the experiment

The 40 % scale buffer tests aimed at understanding the planning, building, instrumentation and sampling of KBS-3V demonstration tests under repository conditions. Another goal was to gain information for initial and early stage performance assessments of the bentonite buffer including distribution of heat, rate of saturation from the pellet-filled gap to the middle of the buffer block, artificial watering effects, piping and erosion, swelling and buffer uplift.

General description

From November 2011 up to the present, 40 % scale buffer tests have been performed in ONKALO[3] at 140 m underground. The geotechnical design of the tests was in accordance with Posiva's current reference buffer design[4]. Two approximately 3 m deep experimental deposition holes with diameters of 800 mm were dilled 4 m apart. The thickness of the Excavation Disturbance Zone (EDZ) around the test holes was between 500-700 mm, including a few large cracks. While hole 1 was subjected to natural groundwater inflow through fractures, artificial wetting was used in hole 2 with a flow rate of mostly 8-10 l/min (pressure of 360 kPa) and a water salinity of 10-12 g/l TDS.

In holes 1 and 2 the number of installed buffer blocks with outer diameter of 730 mm was 11 and 10, respectively. Except for one block in hole 1, which was made in two parts of 200 mm and 80 mm height, the height of each block was 280 mm. There was a 7 mm gap between the buffer blocks and the dummy canister, which had the surface temperature increased stepwise up to 90 °C. The outer gap width between the buffer blocks and the deposition hole wall varied between 15-65 mm, with an average of 38 mm. The isostatic compression method (compression pressure of 120 MPa) was used to manufacture MX-80 bentonite buffer blocks having an average bulk density of 2094 kg/m^3. The average water content of the buffer blocks was 17.6 %. The dimensions and properties of the installed buffer blocks are shown in Figure 4. For filling the outer gap, roller-compacted pillow-shaped pellets of MX-80 bentonite were used resulting in an estimated pellet fill bulk density of 1075 kg/m^3. In total, 114 sensors were installed in both tests to monitor temperature, relative humidity, swelling pressure pore water pressure, axial forces and displacements.

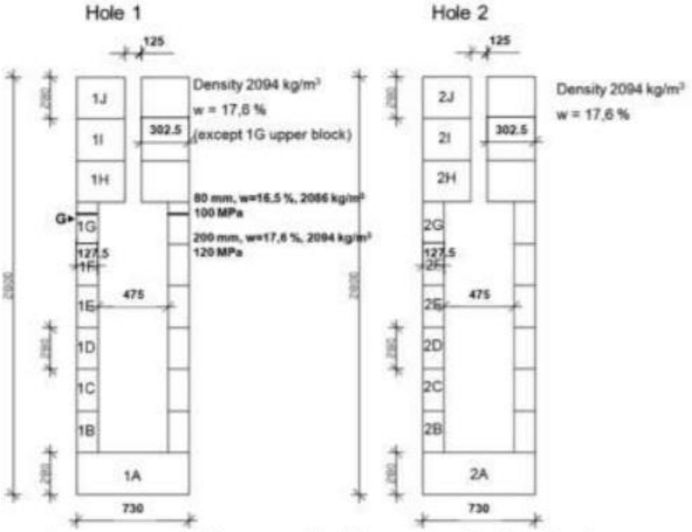


Figure 4. Dimensions and properties of the installed bentonite buffer blocks.

The test in hole 2 is still ongoing but the buffer in hole 1 was dismantled in September 2013 after a test duration of 2 years. During dismantling (Figure 5), more than 1000 samples were taken from the blocks and the pellet fill after 13-24 days from switching off the heater..

Figure 5. Buffer block 1A during core drilling with a template (left) and block 1J after all samples were taken and first piece of excess bentonite removed showing the dry top face of block 1I (right).

Post-mortem analyses were performed for determining the bulk density, dry density water content distributions in horizontal direction for different height levels in the deposition hole and in vertical direction for different radial positions of the buffer blocks and in the pellet fill. As an example, the vertical dry density distribution at three different radial positions of the buffer blocks (inner, center and outer part) and in the pellet fill measured in four different directions (1, 3, 5 and 7) is depicted in Figure 6.

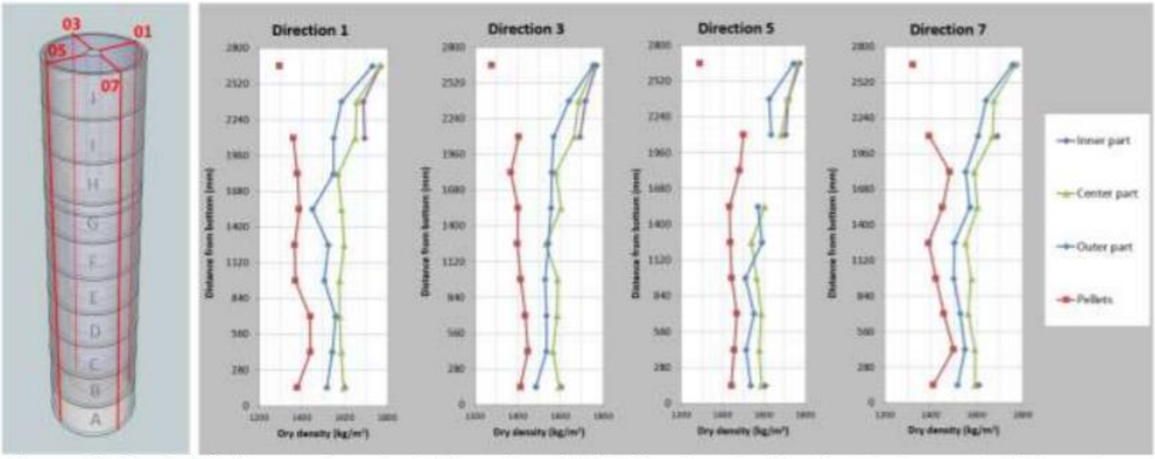


Figure 6. Block labeling and analysis directions (left). Dry density distribution in vertical direction (right).

Main learning points concerning bentonite homogenization / mechanical evolution and relevance for the project

Results from these two experiments of BBI and 40% scale buffer test are used to update Posiva's buffer and backfill designs, material specifications, material manufacturing and safety case analysis. The results are used in modelling of homogenization of density differences and can be utilised by other parties interested in understanding bentonite clay material performance and homogenisation processes.

How could this work inform a new experimental or modelling study in BEACON?

References (ideally with web links)

[2] Hakola, I., Kivikoski, H., Löija, M., Marjavaara, P., 2015. Designing, Commissioning and Monitoring of 40% Scale Bentonite Buffer Test. Working Report 2015-08. Posiva Oy, Eurajoki, Finland.
[3] ONKALO is Posiva's Underground Rock Characterization Facility for rock characterization for the final disposal of spent nuclear fuel, located in Olkiluoto, Finland
[4] Juvankoski, M., 2013. Buffer Design 2012, Posiva Report 2012-14. Posiva Oy, Eurajoki, Finland.

Recommendations for BEACON project

Project Acronym BACCHUS I	**Location** Hades underground research facility, Mol, Belgium	**Type** URL
Lead organiser CEA/DRDD	**Start date** 23/11/1988 (heating phase began 16/03/1989)	**End date** 12/08/1990 (power shut down)
Main partners involved in the project ANDRA, ONDRAF/NIRAS	**Characteristics of swelling clay** 50% FoCa clay, 45% sand, 5% graphite Buffer has density 20.7 kN/m^3, compacting pressure 15 MPa, thermal conductivity 1.7 W/m K, max swelling pressure 5 MPa, hydraulic conductivity 0.8-2 x 10^{-12} m/s	**Water Saturation** natural
Instrumentation Temperature, pressure and humidity sensors in the barrier and host clay. Thermal shock probe and TDR probe used to measure water content. 18 temp sensors in clay (boreholes), 8 humidity sensors, 10 piezometers…	**Main elements related to homogenization**	**Interfaces with other material**
Modelling Yes/no: Yes Groups/Codes: TEMPPRES, MPGSTN	**Main processes studied** ☒T ☒H ☒M ☒Swelling pressure ☐Gas transfer ☐Other	**Reference concept if pertinent**

Main objectives of the experiment

This large-scale experiment considered a compacted clay-based material around a heater implanted in the host clay in order to investigate the thermal behavior of the Boom clay as well as the thermal and hydraulic transfers through a highly compacted material. The focus was on the in-situ behavior of potential compacted clay-based materials (prefabricated blocks) placed around a heater; material characterization; concept design, and instrumentation survey.

Beside the experiment itself and its original design, material characterization and instrumentation survey were important aspects in which considerable experience has been gained. In this respect, the development of specific sensors (thermal shock and Time Domain reflectometry probes) adapted to the particular experimental conditions is worth mentioning.

General description

BACCHUS is the acronym for BACkfilling Control experiment for High level wastes in Underground Storage. The backfill approach was integrated in the design of a heating experiment by considering the in-situ behavior of potential compacted clay-based materials (prefabricated blocks) placed around a heater.

The composition of a compacted buffer material (Ca-smectite + sand + graphite) was defined by both parties in order to meet the experimental conditions prevailing at Mol and the ability of Boom Clay to compaction was also investigated (seal plug). A heater was providing temperature conditions likely to take place around a waste canister after a cooling period of 50 to 60 years (surface interim storage). The experiment was implanted in the Boom clay formation of the HADES underground research facility (URF) at 240 m depth; it was aimed at investigating the thermal behavior of the host clay as well as the thermal and hydraulic transfers through a highly compacted material. The heating period, scheduled to last for about one year, was limited to 5 months due to an unexpected power shut down.

Both materials (engineered barrier, host clay) were fully instrumented with temperature, pressure and humidity sensors.

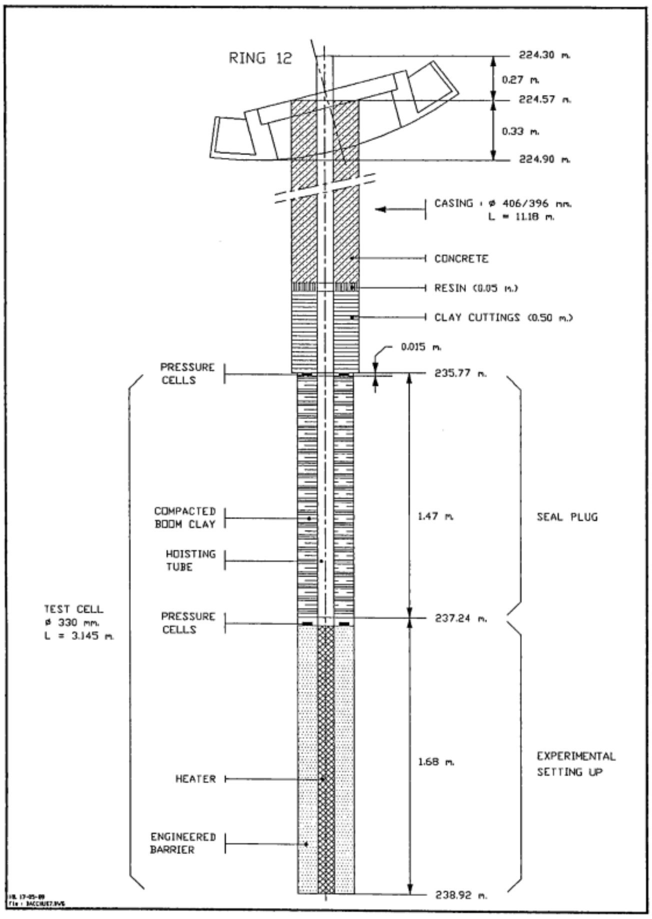


Fig. 2 : Location of the Bacchus experiment from ring 12

Main learning points concerning bentonite homogenization / mechanical evolution and relevance for the project

Homogeneous water content – global variation of 1% or less during the period considered.

The BACCHUS experiment, despite having been stopped earlier than foreseen, brought an important set of observations and in-situ measurements, e.g. 2 months required to reach the maximum excess pressure, instantaneous pore water pressure decrease etc.

How could this work inform a new experimental or modelling study in BEACON?

The data and results obtained cover the preparation, heating and cooling phases; they allow the comparison and validation of thermomechanical and heat transfer computer codes.

Most of the data could be reproduced using the computer code available at CEN/SCK but some important limitations have to be overcome in the future, as for example the behaviour of partially saturated materials.

This experiment pointed out the necessity to install the instrumentation of the host rock (and/or the test cell) as soon as possible so that a relative equilibrium can be reached before starting the experiment itself – for the Boom clay, the period of time necessary to restore the initial ground conditions can easily range from 6 to 9 months, sometimes more.

References (ideally with web links)

Neerdael B., Meynendonckx P., Voet M., 1992. The Bacchus backfill experiment at the Hades underground research facility at Mol, Belgium. Final report EUR 14155.

Recommendations for BEACON project

Project Acronym BACCHUS II	**Location** Hades underground research facility, Mol, Belgium	**Type** URL
Lead organiser SKN/CEN	**Start date** June 1993	**End date**
Main partners involved in the project ENRESA, ANDRA, CEA	**Characteristics of swelling clay** A mixture of Boom clay pellets and powder. Dry density 1.6-1.8 g/cm^3	**Water Saturation** Artificial and natural
Instrumentation Total pressure transducers, neutron/gamma source, heat pulse generator, hydrostatic pressure sensors, thermocouples	**Main elements related to homogenization**	**Interfaces with other material**
Modelling Yes/no: Groups/Codes:	**Main processes studied** ☒T ☒H ☒M ☒Swelling pressure ☐Gas transfer ☐Other	**Reference concept if pertinent**

Main objectives of the experiment

The BACCHUS 2 experiment aims to optimize and demonstrate an installation procedure for a clay based backfill material.

General description

The installation procedure, materials and techniques were kept as close as possible to realistic industrial processes and capabilities.

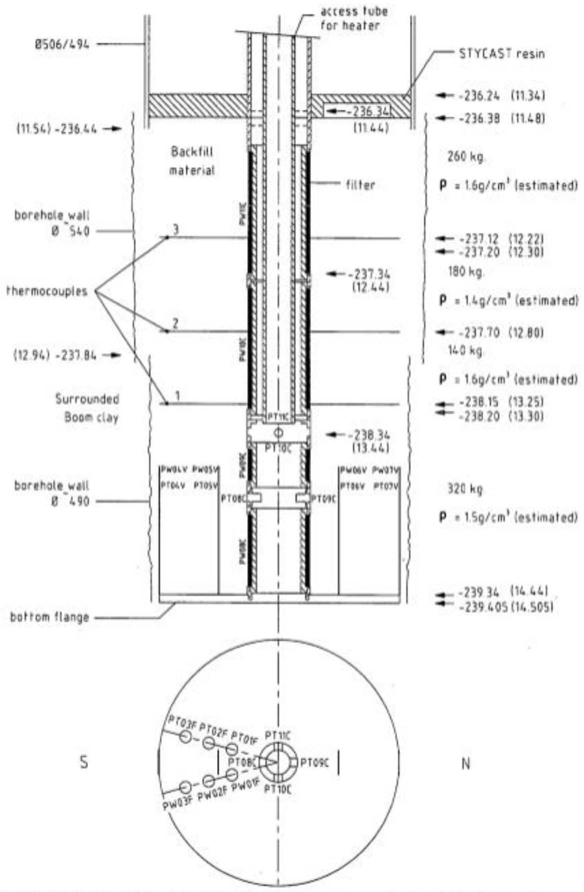


Fig. 4.7: Location, orientation and codes of the sensors on the BACCHUS 2 mock up.

Main learning points concerning bentonite homogenization / mechanical evolution and relevance for the project

The thermal conductivity was higher on the south side than on the north side, resulting from a consolidation anisotropy. Likewise, the values of total stress were higher on the south side. During the artificial hydration, the increase of thermal conductivity is very fast. After 550 days it has reached equilibrium corresponding to the saturation state. During the natural hydration, no pore water pressure increase in the backfill was observed.

During the heating phase, the dilation of the water induces a fast increase of the pore water pressure and the total stress. The artificial hydration phase causes a decrease of the total stress, explained by the increase of the backfill material plasticity. This is faster where consolidation is less important.

The material becomes homogenous during hydration.

How could this work inform a new experimental or modelling study in BEACON?

References (ideally with web links)

Volckaert G., Bernier F., Dardaine M., 1996. Demonstration of the *in situ* application of an industrial clay-based backfill material. Final report EUR 16860.

Recommendations for BEACON project

Project Acronym Bentonite Rock Interaction Experiment (BRIE)	**Location** Äspö HRL	**Type** URL
Lead organiser Clay Technology AB/Chalmers University of Technology/SKB	**Start date** September 2012 (Installation)	**End date** March 2014 (Dismantling)
Main partners involved in the project	**Characteristics of swelling clay** MX-80 bentonite	**Water Saturation** Natural
Instrumentation RH sensors Total pressure sensors Pore pressure sensors	**Main elements related to homogenization** No	**Interfaces with other material** Fractured (granitic) host rock
Modelling Joint modelling task for SKB Taskforces on Engineered Barrier System (EBS) and on Groundwater Flow and Transport of Solutes (GFTS).	**Main processes studied** ☐T ☒H ☐M ☐Swelling pressure ☐Gas transfer ☒Other Localised water entry from fractured host rock	**Reference concept if pertinent** No

Main objectives of the experiment

The Bentonite Rock Interaction Experiment (BRIE) was a field experiment which addressed the hydraulic interaction between the system components of compacted bentonite and near-field host rock composed of hard and fractured crystalline bedrock. This experiment was also addressed in a joint modelling task (Task 8) of the SKB Task forces on Engineered Barrier Systems (EBS) and on Groundwater Flow and Transport of Solutes (GWFTS). The objective of BRIE, and Task 8 as a whole, was to enable: i) an enhanced understanding of the exchange of water across the bentonite-rock interface; ii) better predictions of the hydration of the bentonite buffer; and iii) better characterization methods of the deposition holes.

General description

The experiment was performed in the TASO tunnel located at a depth of 420 m at Äspö Hard Rock Laboratory in Sweden (Figure 1), and was subdivided into two main parts: i) the selection and characterization of a test site and two central boreholes; and ii) the installation, hydration and dismantling of two bentonite parcels.

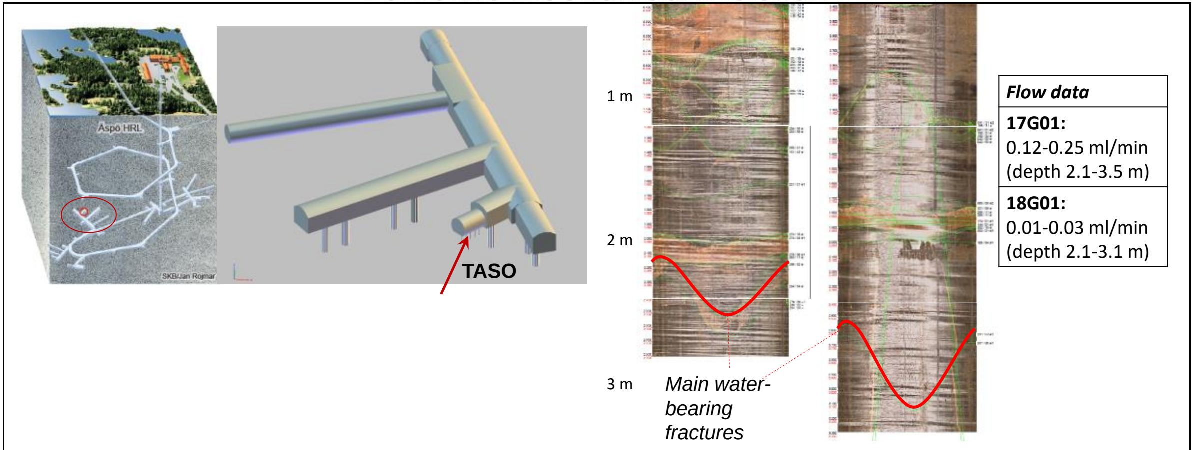


Figure 1*. Location of TASO tunnel (left) and BIPS images of two test holes (right).*

Rock characterization

Investigation boreholes have been central for the characterization of the rock, which was divided in three phases: the site selection, the site characterization; and the characterization of two central boreholes. Five primary boreholes (Ø76 mm and approximately 3 m deep) were drilled in the tunnel floor during the site selection, whereas 14 additional vertical boreholes and four horizontal holes were drilled during the site characterization. Two of the primary boreholes (17G01 and 18G01) were finally enlarged to Ø300 mm, and the depth of one of the holes (17G01) was increased to approximately 3.5 m. The core drillings have shown that the main rock type is diorite, and that two types of granite (Ävrö granite and fine-grained granite) also can be found. The five primary boreholes and the two Ø300 mm *test holes* were characterized through BIPS (borehole image processing system) imaging (Figure 1) and core mapping. These measurements have resulted in information concerning depth and orientation of individual fractures intersecting the boreholes. The *hydraulic characterization* has consisted of different types of measurements. Inflow measurements were performed as: i) pump tests in different packed-off sections in the boreholes; ii) Posiva flow log measurements; iii) nappy tests; and iv) with sorbing mats. Pressure measurements were performed in packed-off sections in all primary boreholes. Transient hydraulic tests were performed for quantification of properties for individual fractures. In addition to this, characterization of the rock matrix was performed in the laboratory.

Bentonite parcels

Two bentonite parcels (denoted Hole 17 and 18) were installed in the two Ø300 mm test holes in September 2012. The lengths of the parcels were 3.5 and 3.0 m, respectively, and were put together with compacted blocks of MX-80 bentonite (Ø298 mm and height 100 mm) which were threaded on a central tube (Ø40 mm), and confined with steel plates in the bottom and the top (Figure 2).

Each bentonite parcel was instrumented at two sections: one wet section dominated by flow from a main fracture of interest in each hole, and one dry section potentially dominated by matrix flow. These sections consisted, in turn, by two blocks which were instrumented with sensors for measurement of relative humidity, total pressure and pore pressure (Figure 2). The installed sensors subsequently displayed data on the evolution of the analysed variables at the different sensor positions and therefore reflected the hydration of the bentonite. This monitoring was performed during a period of 419 days for Hole 17 and 515 days for Hole 18. Data from Hole 17 showed a clear response from sensors in the wet section, whereas the corresponding response in the dry section was very slow. Data from Hole 18 indicated less difference between the wet and dry sections (Figure 3).

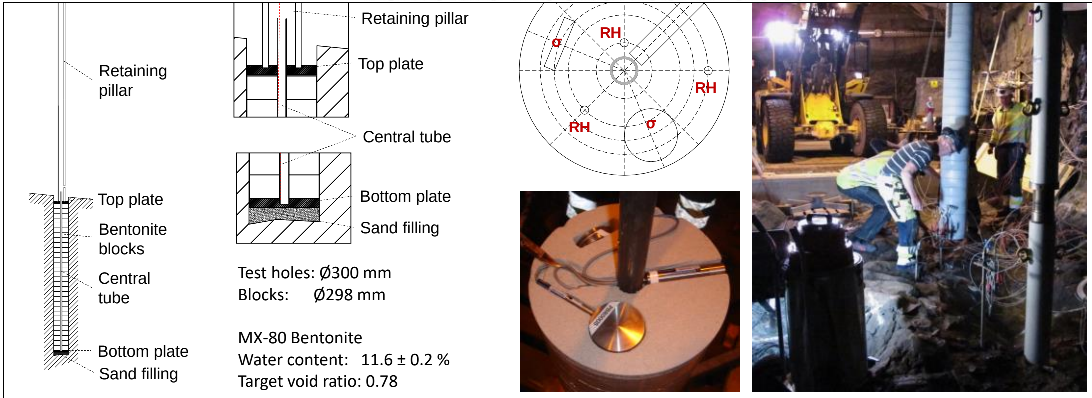


***Figure 2.** Principal design of bentonite parcels (left), instrumentation and installation (right).*

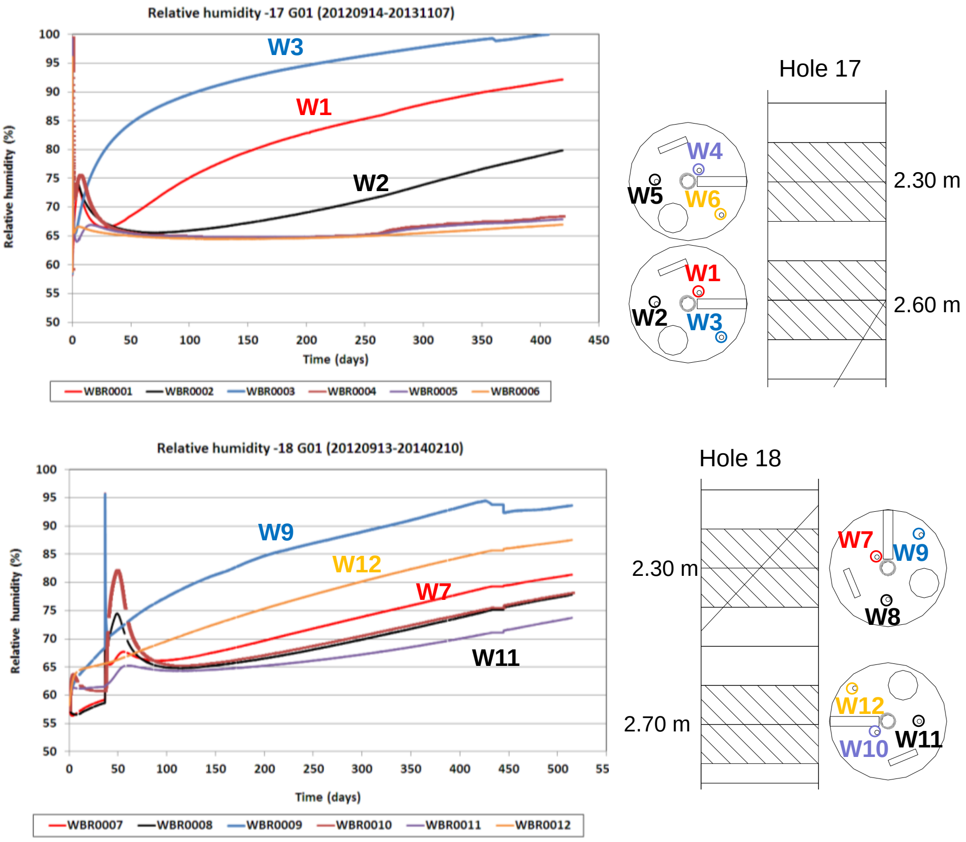
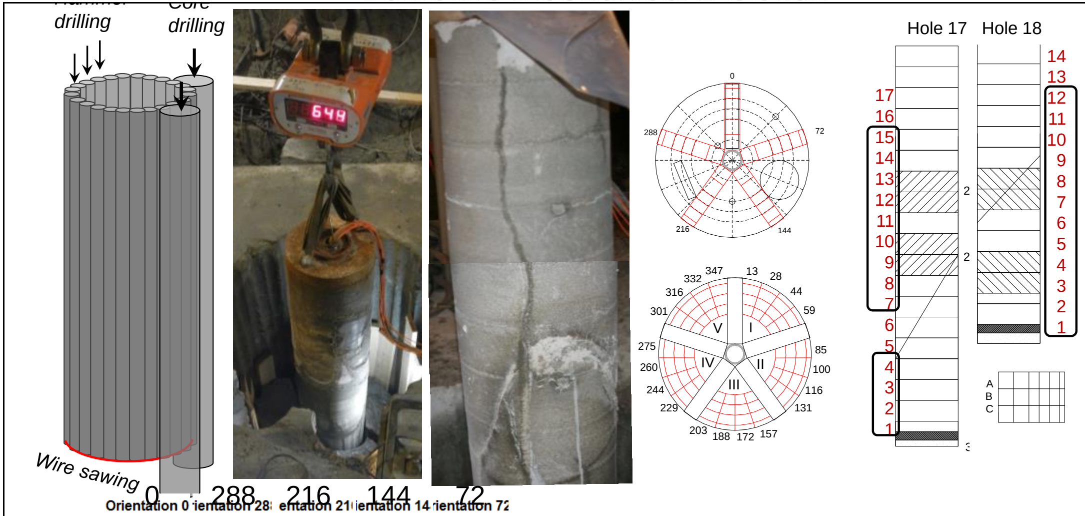


***Figure 3.** Evolution of RH at sensor positions.*

The bentonite parcels were dismantled during the winter of 2013/2014. The dismantling operation followed a procedure of stitch-drilling of cylindrical rock pillars with a diameter of 0.7 m which was cut in the lower end through wire sawing (Figure 4). Since the rock cover around the bentonite parcels was cracked, however, both bentonite parcels were finally pulled out directly from the test holes without any rock cover. The parcels were subsequently documented, partitioned, sampled (Figure 4) and analyzed with respect to water content and density. In addition, the sensors were salvaged and the function of the RH sensors was checked. Photographs of the parcel surfaces displayed traces of the main fractures of interest as well as previously uncharted fractures. These traces were in many cases correlated with measured water content distribution (Figure 5). The results from the water content measurements were consistent with the recorded RH data: the contrasts between the wet and dry section were more pronounced in Hole 17 than in Hole 18.



Figu… ft); pulling of parcels (center); sampling scheme (right).

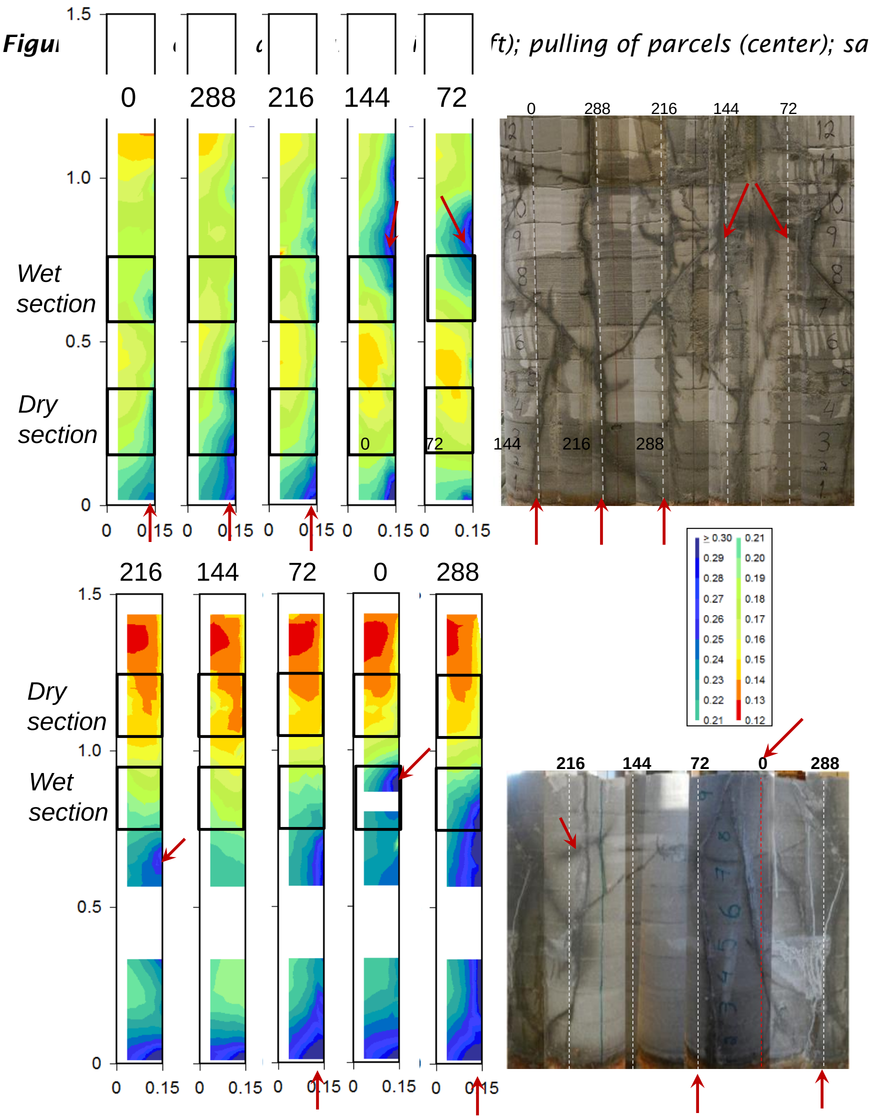


***Figure 5.** Water content contour plots. Vertical plots for Hole 18 (upper) and 17 (lower).*

Concluding remarks regarding the bentonite and the bentonite-rock interaction:

The bentonite parcels have resulted in consistent data sets with major increases of RH and water content close to the main fractures of interest, especially in the lower parts of 17G01 and 18G01.

Similarly, they have resulted in consistent data sets with minor increases of RH and water content in a borehole section with low water inflow, especially in section at 2.3 m depth in 17G01.

The average water content increase in the lower part of Hole 18 was consistent with the measured water inflow during the last phase of the characterization program.

A pronounced gradient in water content in 17G01 between the main fracture of interest and the dry section indicates that the slow increase of RH observed in this section was caused by water from the fracture in question.

Inward directed gradients in water content in the lower part of 18G01 (Block 5) suggest that the inflow is *distributed* along the entire circumference, rather than a *localized* to discrete fractures only. A definite clarification of this question will probably require some form of modeling.

Wetting seems to be governed by fractures providing water from the geosphere, water that is further transported (axially) within the bentonite. This is expected to be particularly pronounced for fractured rock with low conductivity rock “matrix”.

Water-uptake tests, performed within the framework of the project, have resulted in a complete set of independently determined hydraulic parameter values, and have also contributed to a validation of the material model for MX-80.

Main learning points concerning bentonite homogenization / mechanical evolution and relevance for the project

The experiment was designed in order to minimize the influence of the mechanical processes: i) by making the outer slot between the bentonite blocks and the rock wall very small in relation to the diameter of the borehole; and ii) by confining the bentonite in axial direction with the top and bottom plates (Figure 2). This means that the BRIE experiment is not suited as a modelling task in the BEACON project.

How could this work inform a new experimental or modelling study in BEACON?

See above.

References

Fransson Å, Åkesson M, Andersson L, 2014. Bentonite Rock Interaction Experiment. Characterization of rock and installation, hydration and dismantling of bentonite parcels. SKB R-14-11. Svensk Kärnbränslehantering AB. (in press).

Recommendations for BEACON project

Project Acronym CRT (Canister Retrieval Test)	**Location** Äspö Hard Rock Laboratory	**Type** Full scale experiment
Lead organiser SKB	**Start date** October 2000	**End date** October 2005
Main partners involved in the project SKB	**Characteristics of swelling clay** Compacted blocks of MX-80 Roller compacted pellets of MX-80	**Water Saturation** Artificial and natural
Instrumentation In total 128 sensors: • pore pressure • total pressure • relative humidity • temperature	**Main elements related to homogenization** Initial heterogeneity in density and water content	**Interfaces with other material** Bentonite/rock Bentonite/canister of copper
Modelling Yes: Groups/Codes : SKB/Abacus SKB/Code_Bright CIMNE/Code_Bright CRIEPI/LOSTUF POSIVA/freefem++ GRS/Code Viper AECL/Code_Bright	**Main processes studied** ☒T ☒H ☒M ☐Swelling pressure ☐Gas transfer ☐Other	**Reference concept if pertinent** The Swedish KBS3-concept for the buffer
Main objectives of the experiment This test, 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.		

General description

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 et al. 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 1. 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.

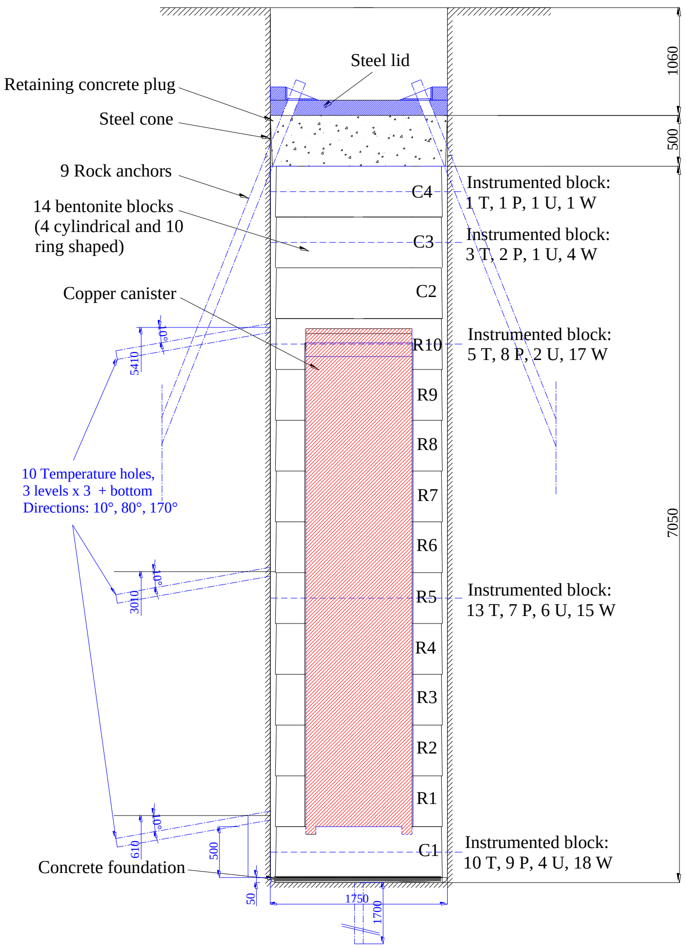


__Figure 1__. Schematic drawing of the Canister Retrieval Test. Sampling of the bentonite occurred down to the level of the upper surface of block R5. The bentonite below this level was removed using a non-mechanical retrieval technique. The drawing also shows the number and positions of the installed sensors (T=temperature, P=total pressure, U=pore pressure and W=relative humidity) (Thorsager et al. 2002).

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. The data from the sensors was collected continuously during the saturation phase (Goudarzi et al. 2006). An example of data from measurements of the total pressure in the buffer is shown in Figure 2.

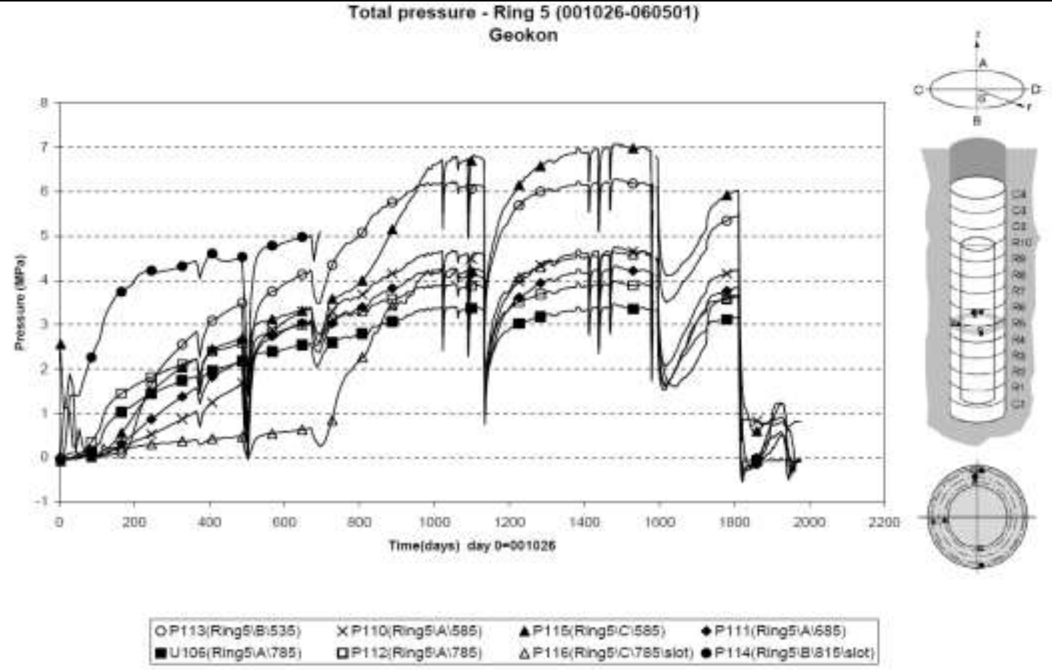


***Figure 2**. Measurements of total pressure as function of time in block R5 in CRT (Goudarzi et al. 2006)*

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 1500 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. The sampling and the determination of the density and water content of the buffer is described in detail in (Johannesson 2007).

a) b)

***Figure 3**. a) The drilling rig placed over the deposition hole. b) Cores taken form the buffer (Johannesson 2007).*

An example of data from the determination of the water content and the density is shown in Figure 4. 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. Most of the modelling was made within the EBS Task Force. Several different groups have modelled the test with different codes (Kristensson et al. 2015).

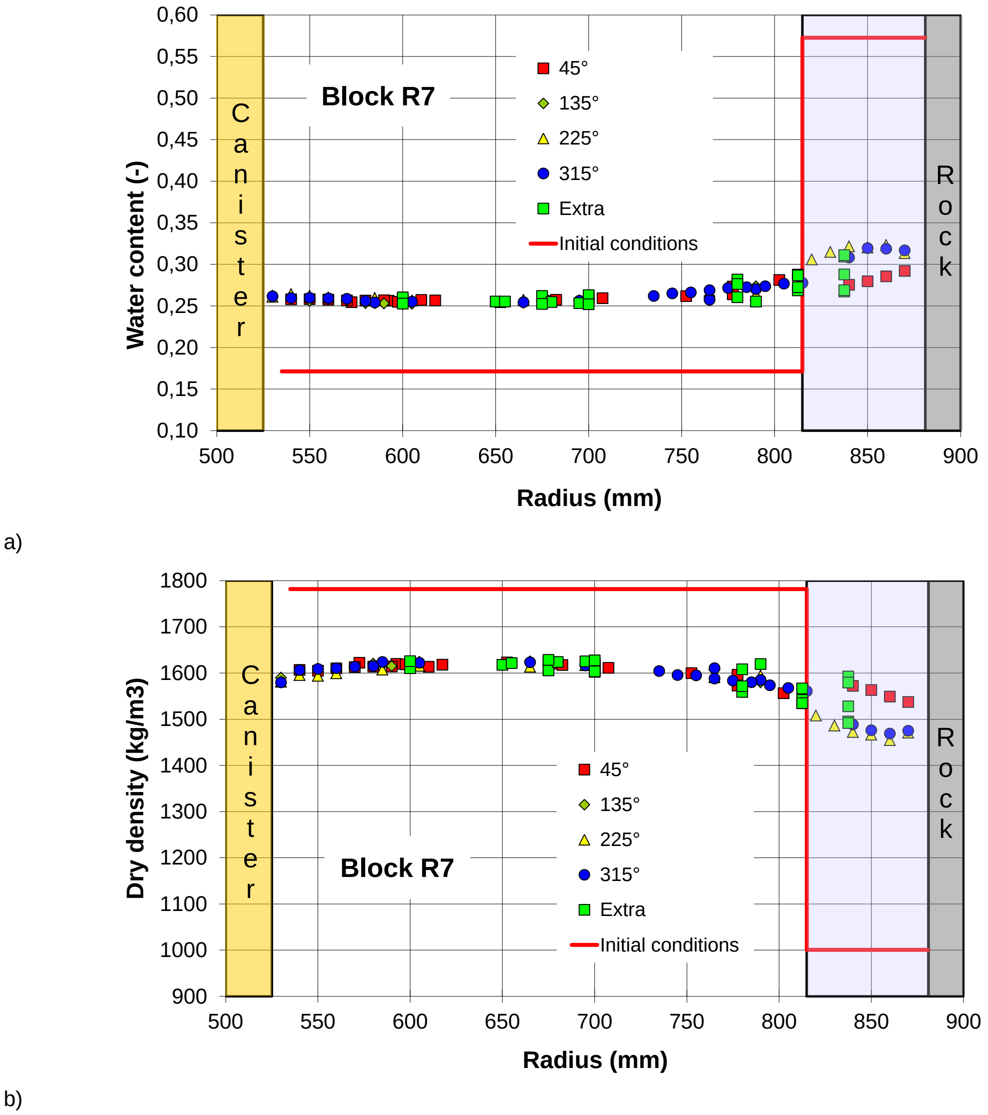


Figure 4. *The water content (a) and the dry density (b) of the buffer block R7 as function of the radial distance from the centre of the deposition hole (Johannesson 2007).*

Main learning points concerning bentonite homogenization / mechanical evolution and relevance for the project

The water uptake of the buffer was measured during a period of 5 years. The bentonite above the canister was not fully saturated and not homogenized. The buffer around the canister was close to fully saturated but not homogenized.

How could this work inform a new experimental or modelling study in BEACON?

The experiment had a well-defined geometry with defined boundary conditions. The used bentonite (MX-80) is well characterised and the initial conditions of the pellets and the buffer blocks were known. The water uptake of the buffer was followed by the installed sensors and the final condition (water content and density) was measured accurately at the dismantling of the test.

References (ideally with web links)

Goudarzi R, Börgesson L, Röshoff K, Edelmann M, 2006. Äspö Hard Rock Laboratory. Canister Retrieval Test. Sensors data report (Period 001026–060501). Report No:12. SKB IPR-06-35, Svensk Kärnbränslehantering AB.

Kristensson O, Börgesson L, 2015. Canister Retrieval Test. Final Report SKB TR-14-19, Svensk Kärnbränslehantering AB.

Johannesson L-E, 2007. Äspö Hard Rock Laboratory. Canister Retrieval Test. Dismantling and sampling of the buffer and determination of density and water ratio. SKB IPR-07-16, Svensk Kärnbränslehantering AB.

Sandén T, Börgesson L, 2000. Äspö Hard Rock Laboratory. Canister Retrieval Test. Report on instrument positions and preparation of bentonite blocks for instruments and cables. SKB IPR-00-14, Svensk Kärnbränslehantering AB.

Thorsager P, Börgesson L, Johannesson L-E, Sandén T, 2002. Äspö Hard Rock Laboratory. Canister Retrieval Test. Report on installation. SKB IPR-02-30, Svensk Kärnbränslehantering AB.

Recommendations for BEACON project/ What would I do differently, were I to repeat my earlier study?

Project Acronym DOPAS EPSP	**Location** Prague, CZ	**Type** mock up (in-situ)
Lead organiser CTU in Prague	**Start date** 2015	**End date** 2016/On-going
Main partners involved in the project CTU, SURAO	**Characteristics of swelling clay** - Ca-Mg bentonite - Pellets (vibration compacted or sprayed) - dry density after emaplcement ρ_d=>1400kg/m^3	**Water Saturation** Artificial
Instrumentation - thermometers, - hydraulic pressure cells, - humidity sensors of varying construction - piezometers	**Main elements related to homogenization** Evolution bentonite sealing core	**Interfaces with other material** Steel heater and vessel Corrosion samples of various metals
Modelling Yes/no: Limited modelling only (no fully coupled analysis done). Groups/Codes :	**Main processes studied** ☒T ☒H ☒M ☒Swelling pressure ☐Gas transfer ☐Other – Mineralogicall changes, corrosion	**Reference concept if pertinent**

Main objectives of the experiment or modelling study

The EPSP is not a specific DGR plug or seal; rather it was built at a similar scale to a deposition tunnel plug and contributed specifically towards the development of a reference design for such structures. The objective of the EPSP experiment was to test both the materials and technology to be used for implementation, not to test the design and performance of the reference disposal tunnel plug. At this early stage in the Czech geological disposal programme (SÚRAO 2011), more than 50 years prior to the scheduled commencement of operation, it is considered by those involved more important to build knowledge and experience rather than to refine implementation designs for an, as yet, unidentified site with unknown mechanical, hydrogeological and chemical characteristics. The experiences for testing the plug components in the Josef Underground Laboratory also give indications on crystalline host rock requirements and may support the site selection programme. The EPSP experiment is the first time that SÚRAO has carried out detailed work on plugs and seals.

General description

The complete information on the experiment's design is included in D3.15 (*Svoboda et al., 2015*). The conceptual design for EPSP (Figure 1) includes the following components:

- Pressure Chamber: The pressure chamber (or the injection chamber) is an open space that can be used to pressurise the inner concrete plug. The chamber contains an inlet valve and a drain valve that can be used to fill the chamber with gas (air), water or bentonite slurry. The chamber was built to be as small as possible to allow the pressure to be readily controlled. The pressure chamber was sealed with a membrane.
- Concrete Walls: The walls, constructed from concrete blocks, were used to facilitate the construction of the EPSP. Three concrete walls were built: one between the pressure chamber and the inner concrete plug, one between the bentonite layer and the filter, and one between the filter and the outer concrete plug.
- Inner Concrete Plug: The inner concrete plug forms one of the sealing components of EPSP and was constructed using sprayed glass-fibre concrete. The fibre concrete is of relatively low pH; the mix and pH values were determined during the laboratory testing stage.
- Bentonite Pellets: The bentonite pellet zone is composed of B75 bentonite (a locally extracted material), i.e. a natural and high-smectite content Ca-Mg bentonite with notably high iron content in the octahedral layer of the smectite. The purpose of the 2m-long bentonite zone is to seal and absorb/adsorb water that flows through the inner concrete plug.
- Filter: The filter collects water that is not absorbed by the bentonite layer. The filter may also be used to reverse the direction of pressurisation of the EPSP.
- Outer Concrete Plug: The outer concrete plug is similar to the inner plug (i.e. constructed using glass-fibre-reinforced low-pH shotcrete) and was designed to hold the other components of EPSP in place.

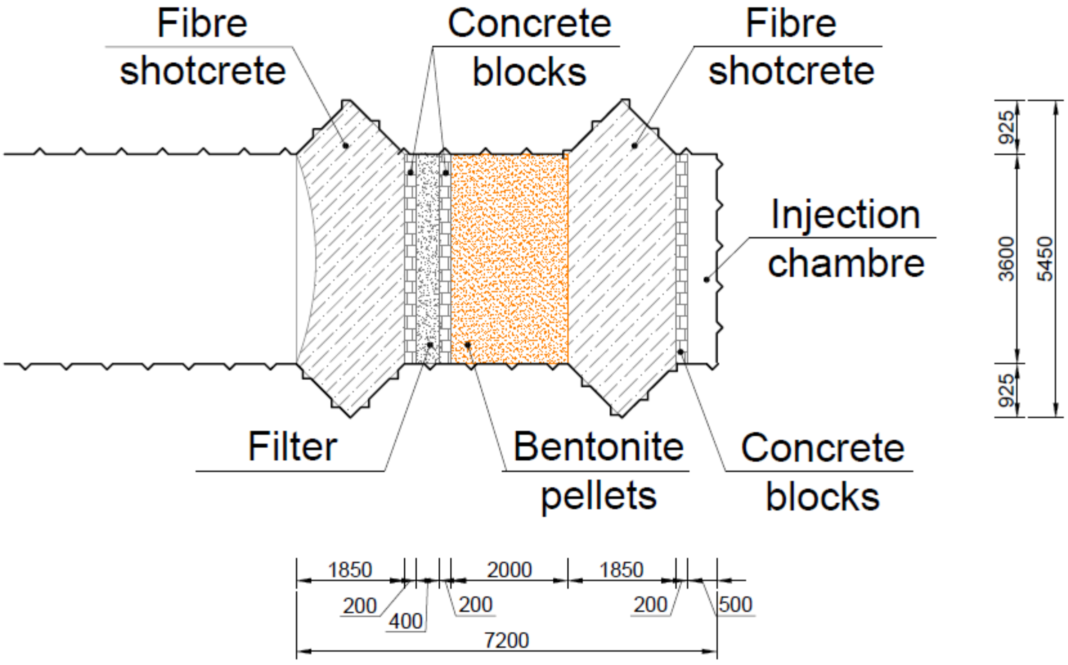


Figure 1 - Scheme of the EPSP

The EPSP experiment was built at the Josef Underground Laboratory. The EPSP experimental plug itself is located in the M-SCH-Z/SP-59 niche. The measurement system technology and the data loggers are located in the nearby M-SCH-Z/SP-55 niche (Figure 2).

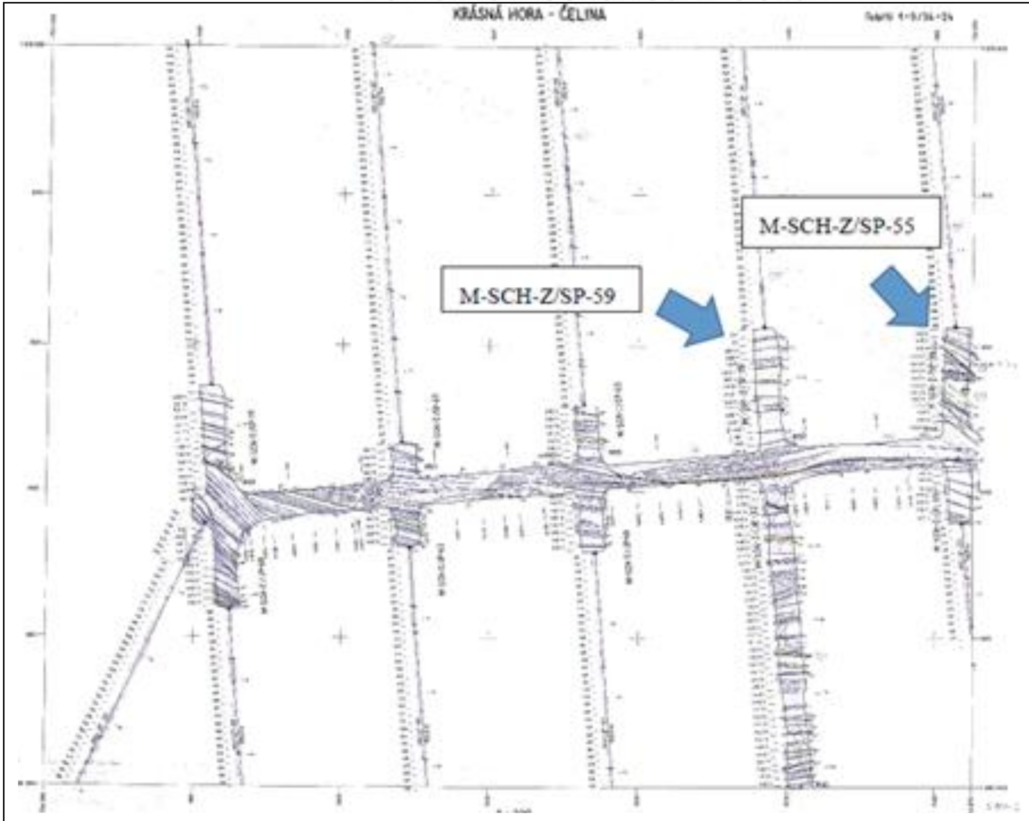


Figure 2 - EPSP location

Experimental run

The experimental run commenced on 21 July 2015. The original plan for the loading of the experiment consisted of the injection of water into the pressure chamber with a gradual increase in pressure (with the potential to inject water into the filter and reverse the flow if necessary). The injection of a bentonite slurry was also planned.
However, it was found necessary to alter the plan based on the results obtained during the initial part of the experimental phase. The experimental run (based on the updated plan) was divided into 5 phases based on the character of the loading of the experiment (Table 1**Error! Reference source not found.**).
Complete information on the experimental phase of the EPSP can be found in D4.6 (*Svoboda et. al, 2016*).

Table 1 Experimental programme schedule

Phase	**Sub phase**	**Start**	**End**	**Duration of phase [days]**	**Pressure [MPa]**
Phase 1 – Water injection into the chamber		21-07-2015	13-08-2015	23	0.5 - 1
Phase 2 - Saturation phase (water injection into the chamber and filter)		25-08-2015	29-02-2016	188	
	2.1 Constant injection	25-08-2015	08-10-2015		0.2
	2.2 Pulse tests, Constant Pressure tests	13-10-2015	02-11-2015		0.2
	2.3 Constant injection long-term test	03-11-2015	14-01-2016		0.2
	2.4 Constant injection (several pressure levels)	14-01-2016	29-02-2016		0.2 – 1.2
Phase 3 - Water injection into the chamber		07-03-2016	12-03-2016	5	0.1 - 0.4
Phase 4 - Injection of bentonite slurry into the chamber		15-03-2016	17-03-2016	3	1.5 - 3
Phase 5 - Water injection into the chamber		22-03-2016	2016/Ongoing		0.15 - **1.25**

Main learning points concerning bentonite homogenization / mechanical evolution and relevance for the project

The experiment uses pellets as a basic material for the sealing section. Current data provide information about the saturation process and overall development of the sealing barrier. Some interesting events have been recorded and the data available provide insight in transient effect including results of the bentonite suspension injection.

How could this work inform a new experimental or modelling study in BEACON?

The experiment can serve as benchmarking tool for mathematical models. Although it is relatively complex it is an experiment which provides data on behaviour of gradually saturated pellet sealing in larger scale.

References (ideally with web links)

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Recommendations for BEACON project

Acronym EB (Engineered Barrier Emplacement Experiment)	**Location** Mont Terri URL, Switzerland (Opalinus Clay Formation)	**Type** Field scale experiment Full scale (horseshoe section 2,65 m high, 3 m wide; length 6 m)
Project Coordinator Enresa (Spain)	**Start date** May 2002 (hydration starts)	**End date** February 2013 (dismantling ends)
Main partners involved in the project Enresa, Nagra, Aitemin, UPC, BGR, Ciemat, Andra The EB project was co-financed by the EC (contract FIKW-CT-2000-00017) The PEBS project was co-financed by the EC (contract FP7-249681)	**Characteristics of swelling clay** 1. Pre-compacted FEBEX blocks: dry density 1,69 g/cm^3 , water content 14,4% 2. Granular bentonite material (GBM): dry density pellets (emplaced) 1,36 g/cm^3, water content 4,2%	**Water Saturation** Artificial and natural
Instrumentation 55 sensors: • pore pressure • relative humidity • total pressure • temperature • rock displacement • canister displacement	**Main elements related to homogenization** Initial heterogeneity of density: • Pellets (upper part of the section), bentonite blocks (bottom) • Initial gaps and voids • Pellets segregation • Presence of hydration tubes	**Interfaces with other material** Bentonite/Opalinus Clay Bentonite/Concrete Bentonite/Canister
Modelling Yes (HM coupled modelling) Code: Code-Bright	**Main processes studied** ☐T ☒H ☒M ☒Swelling pressure ☐Gas transfer ☒Other Water transmissivity of the damaged zone	**Reference concept if pertinent** Nagra concept Enresa concept in clay rock

Main objectives of the experiment

1. "In situ" demonstration of an emplacement technique in horizontal drifts in consolidated clay formations, using pellets as backfill material in the upper part of the clay barrier, and bentonite blocks at the bottom.
2. HM process understanding, including development of new constitutive laws of the GBM for the modelling of the experiment, adjusted with the experimental data both from the monitoring sensors and the dismantling operation after full saturation of the bentonite

General description

The experiment was carried out in a short gallery, the "EB niche", which is 15 m long and has a horseshoe section, 2,65 m high and 3 m wide (Figure 1). The aim was to install a dummy canister, of the same dimensions and weight than the reference canister, on the top of a bentonite blocks bed. The remaining gap between the canister and the rock was backfilled with bentonite pellets. The experimental area was isolated by a concrete plug (Figure 1).

To accelerate the hydration process an artificial system was installed. This system is comprised of a combination of pipes and mats arranged around the canister. To monitor the evolution of the experiment, different sensors and a data acquisition system were installed, including remote access.

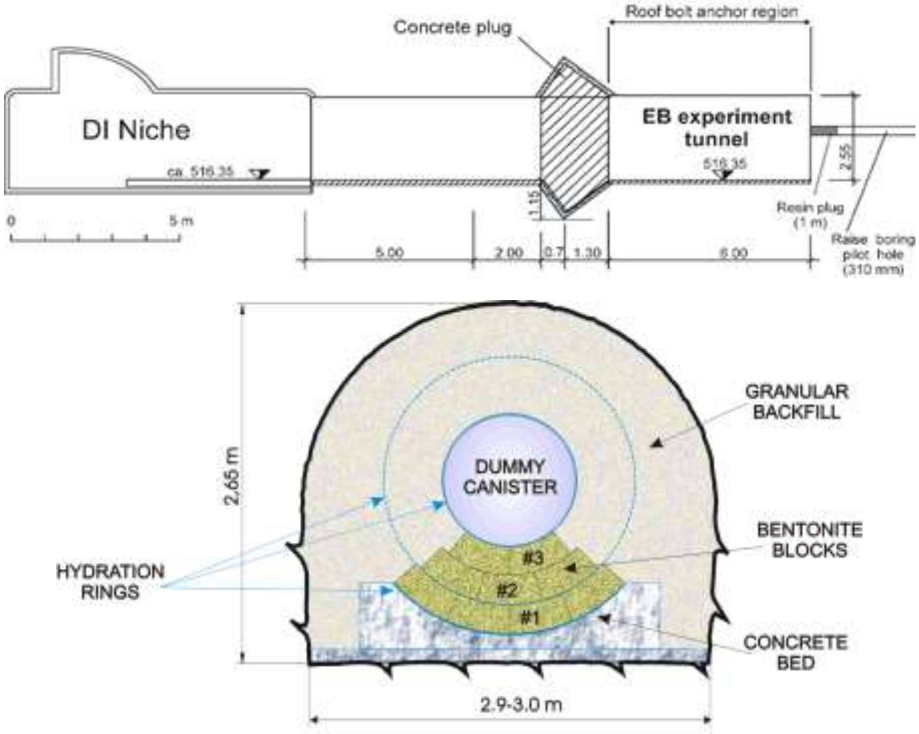

Figure 1: EB niche at Mont Terri URL, longitudinal and cross sections

Concrete bed: It is a mass concrete bed of the same length than the dummy canister and with a circular shape to use bentonite blocks of the FEBEX project.

Bentonite blocks bed: The blocks have a dry density of 1,69 g/cm^3 and the water content was 14,36 %. The bentonite blocks bed is composed by three layers (#1, #2 and #3)

Granular bentonite material (GBM): it is made of a bi-modal mixture of pellets also of FEBEX bentonite, which grain size distribution could be represented by the following average values: D_{95} = 10 mm; D_{50} = 6,3 mm; and D_{10} = 0,25 mm. The total emplaced GBM mass was approximately 40,2 tonnes, in an estimated volume of 28,4 m^3. As the initial average water content of the GBM pellets was 4,2%, the obtained average dry density of the emplaced GBM was 1,36 t/m^3. According to the laboratory characterization of the GBM, for a dry density of 1.36 t/m^3 its hydraulic conductivity (saturated condition) is lower than 5×10^{-12} m/s; and its swelling pressure at least 1,3 MPa.

Dummy canister: it is similar in weight and dimensions to the one in the Enresa and Nagra reference concepts, and has a length of 4,54 m and a diameter of 0,97 m. It was made of carbon steel and filled of a barite emulsion, density 2,65 g/m^3, to obtain the needed weight, being the empty weight of 4000 kg and the final weight approximately 11000 kg.

Hydration system: it has two separated parts: test and service area. The test area components of the hydration system include the hydration tubes and geotextile hydration mats (Figure 2). A water distribution system feeds the hydration tubes and geotextile mats at different levels: floor level, canister level and top level. The water used is synthetic and its composition is chemically similar to the Opalinus Clay formation water.

Figure 2: Test elements prior to GBM emplacement and sealing

Instrumentation: To monitor the relative humidity, temperature, pore and total pressure and displacements, sensors were installed in different sections along the niche (Figure 3). In the rock mass: 20 Piezometers, 8 Capacitive humidity sensors, 3 Extensometers, Seismic sensors and Electrode chains. In the bentonite buffer: 8 Total pressure cells, 4 Extensometers (for canister displacements), 8 Capacitive humidity sensors

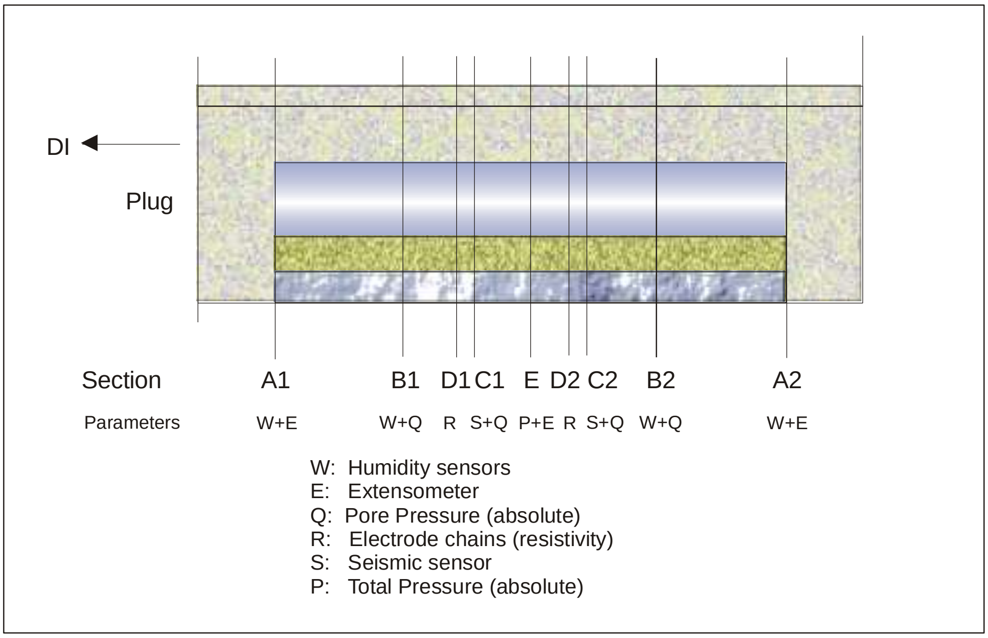

Figure 3: Position of instrumented sections in EB Niche

Dismantling operation and sampling: The main objective was to evaluate the actual state and properties (specially the hydraulic conductivity) of the emplaced bentonite barrier after its complete isothermal saturation. It was carefully coordinated with and extensive sampling programme: more than 500 samples were taken for on-site and laboratory analyses; most of them of the bentonite materials (GBM and blocks) of the barrier, but also of the concrete plug, concrete-bentonite and rock-bentonite interfaces, rock massif, water, monitoring sensors and elements of the hydration system.

Specifically, the scope of the sampling was to determine in the barrier the dry density, moisture content (and then the degree of saturation); hydraulic conductivity; thermal conductivity; pore size distribution; basal spacing; suction; swelling strain and swelling pressure; mostly with samples of the GBM, but also with samples from the original bentonite blocks ; Microbiology analyses and study of the concrete-bentonite and rock-bentonite interfaces ; and Assessment of the EDZ evolution during the dismantling.

The bentonite samples (GBM and blocks) were taken in eight sampling sections (named A1-25; CMT1; B1; CMT2; E; B2; A2; and CMT3), shown in Figure 4.

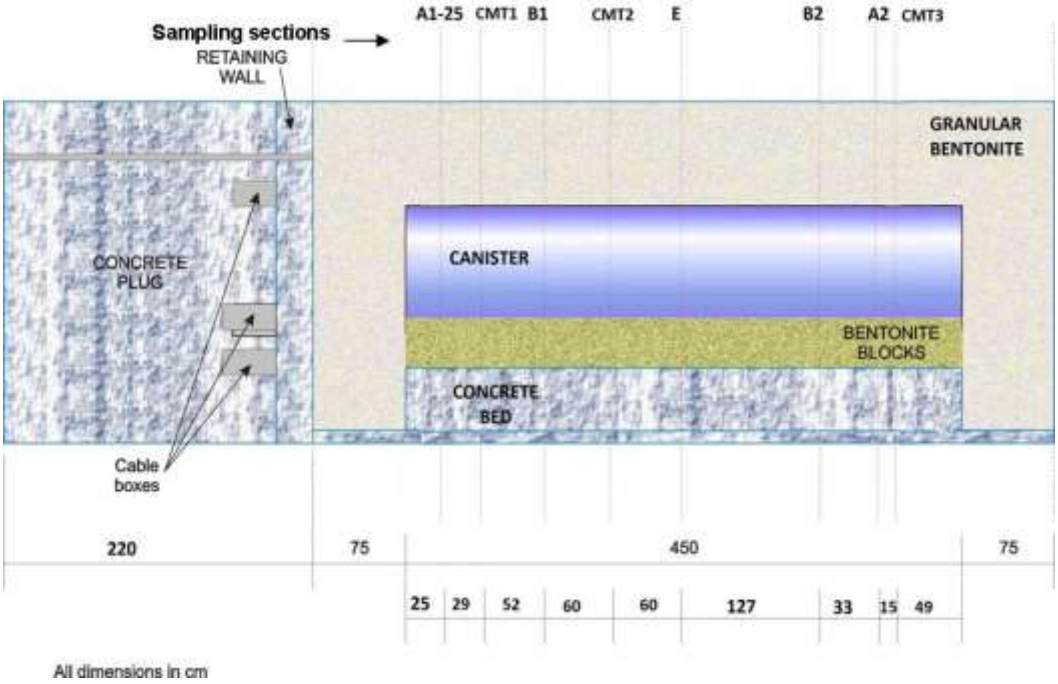

Figure 4: Position of the bentonite sampling sections

More than two hundred (203) samples of the bentonite (GBM and blocks) were analysed on-site. Each sample was cut into three subsamples, of between 6 and 12 cm^3. The water content was obtained in the three subsamples and the dry density in two of them. The degree of saturation was then calculated assuming a value of the specific weight (G) of the bentonite equal to 2,70.

To check the on-site analyses results, some of the samples (36; in sampling sections A1-25, E and B2) were taken bigger and divided in two parts. One for the on-site analysis and the other sent to CIEMAT'S laboratory, in order to compare the results. It was found when comparing both laboratory results that the obtained water content and dry density values had not significant differences.

Main results: The controlled dismantling of the EB experiment 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 was fully confirmed that the use of a GBM is a good option to construct bentonite barriers. The hydraulic conductivity of the saturated GBM is low enough (less than 5×10^{-12} m/s), even if emplaced with a relatively low average dry density (1,36 g/cm^3 in this experiment). Then, it was shown that this key safety indicator falls between the acceptable limits considered in the Performance Assessment of the repository concepts.

As an example of results, the water content and the dry density values are shown in *Figure 5* for section E.

The modelling results concerning the final state of the bentonite barrier are in reasonable agreement with the actual observations, such as the achieved degree of homogenization of the barrier, especially between the blocks and the GBM. In some sections of the barrier, it was observed that the final GBM dry density is even a little higher than the one of the blocks; and also it has been registered that the lowest densities were measured in the lower lateral zones (between the concrete bed and the excavated rock sidewalls). These observations are qualitatively well reproduced by the model.

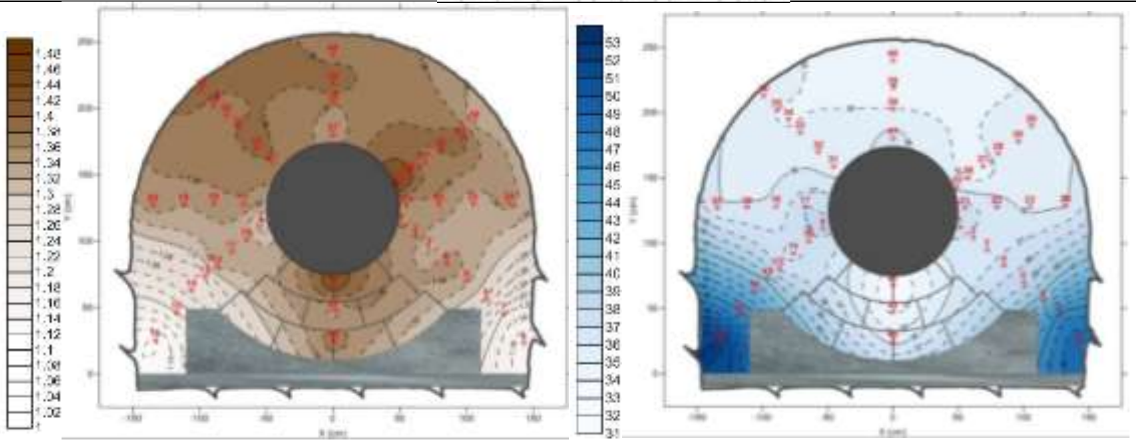

*Figure 5: Isolines of the dry density (g/*cm³*), left, and water content (%), right, in Section E*

Main point concerning bentonite homogenization and relevant for the project

Homogenization between the two types of bentonite emplaced (blocks and GBM) took place. Nevertheless, through the bentonite mass, still (and after the experiment life of more than ten years) some heterogeneities persist: 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 the GBM emplacement was difficult in this case due to the existing hydration tubes.

References

"Engineered barrier emplacement experiment in Opalinus clay for the disposal of radioactive waste in underground repositories". Publicación Técnica ENRESA 02/05 (February 2005).

PEBS Project Deliverable D2.1-8. "EB dismantling. Synthesis report". Juan Carlos Mayor (Enresa) and Manuel Velasco (Golder). [http://www.pebs-eu.de/PEBS/EN/Downloads/downloads_node_en.html]

Project Acronym FE	**Location** URL Mont Terri	**Type** URL~~/mock up/lab-test~~
Lead organiser Nagra	**Start date**	**End date**
Main partners involved in the project	**Characteristics of swelling clay**	**Water Saturation** ~~Artificial/~~natural
Instrumentation	**Main elements related to homogenization**	**Interfaces with other material**
Modelling Yes/no: Groups/Codes :	**Main processes studied** ☒T ☒H ☒M ☒Swelling pressure ☐Gas transfer ☒Other	**Reference concept if pertinent**

Main objectives of the experiment

The FE experiment is the latest step in a series of investigations starting with small-scale laboratory tests, followed by mid-scale in-situ heater experiments at the Mont Terri URL, such as the HE-D experiment and the HE-E experiment. With regard to its size and relevance, the FE experiment is comparable to large-scale heater experiments in other URLs, such as the FEBEX experiment at the Grimsel Test Site in Switzerland, the ‘prototype repository’ experiment at the ÄSPÖ URL in Sweden, the PRACLAY experiment in Boom Clay at the HADES URL in Belgium and the ALC experiment in Callovo-Oxfordian Clay at ANDRA’s URL in France.

The main aim of the FE experiment is the investigation of SF / HLW repository-induced thermo-hydro-mechanical (THM) coupled effects on the host rock at this scale and the validation of existing coupled THM models. Further experimental aims are (i) the verification of the technical feasibility of constructing a disposal tunnel using standard industrial equipment, (ii) the optimisation of the bentonite buffer material production and (iii) the investigation of (horizontal) canister and bentonite buffer emplacement procedures for underground conditions.

General description

The Swiss repository concept for spent fuel (SF) / vitrified high-level waste (HLW) disposal tunnels foresees the sequential emplacement of waste canisters in several hundred metre long horizontal tunnels in Opalinus Clay. The cylindrical waste canisters are to be emplaced in the middle of the tunnel section and separated from the tunnel wall by a bentonite buffer. The term bentonite buffer refers to all bentonite materials in a disposal tunnel. The bentonite buffer is part of the ‘engineered barrier system’ (EBS) and thus of the multi-barrier concept contributing to the retardation of radionuclides. At every 10th canister position, the concept foresees the installation of an ‘interjacent sealing section‘ (ISS) where the normal (cement-containing) tunnel support is replaced by e.g. steel arches in order to have direct contact between the rock and the ‘bentonite backfill’ and to intercept potential axial flow paths for radionuclides along the tunnel lining.

The layout of the ‘Full-Scale Emplacement’ (FE) experiment was designed to simulate these conditions in one single tunnel at the Mont Terri ‘underground research laboratory’ (URL). First, a 50 m long experimental tunnel was constructed. At the deep end of the FE tunnel an ISS was built using only steel arches for rock support, while the rest of the tunnel is supported by shotcrete. A ‘bentonite block wall’ (BBW) was erected manually in a section of the ISS. In the FE tunnel, 3 heaters with dimensions similar to those of waste canisters were emplaced on top of ‘bentonite block pedestals’ (BBP). The first heater emplaced at the deep end of the FE tunnel was named H1, the middle one H2 and the most ‘shallow’ heater (close to the plug) H3. The remaining space was backfilled with a highly compacted ‘granulated bentonite mixture’ (GBM). For the purpose of backfilling the GBM as densely and homogeneously into a horizontal tunnel as possible, a prototype ‘backfilling machine’ (BFM) with 5 screw conveyors was developed. Finally, the experiment was sealed off (towards the FE cavern) with a concrete plug holding the bentonite buffer in place and reducing air and water fluxes. Figure 2 shows the overall timeline of the FE experiment with the main implementation steps.

Bentonite is considered as a potential sealing and backfill material in most concepts for geological disposal of radioactive waste. Bentonite is essentially a natural clay mixture consisting mostly of montmorillonite of volcanic, hydrothermally altered origin. There are 2 main types of bentonite on the market: calcium-rich and sodium-rich depending on the dominant interlayer cation (Ca^{2+} / Na^{+}). Sodium-rich bentonite was chosen for the FE experiment, based on the requirements specified by Karnland (2010) and Leupin et al. (2014). Table 3 summarises the raw material specifications that had to be fulfilled during the bentonite buffer production for the FE experiment and that were checked by independent laboratories.

Bentonite blocks

After concluding all test productions and pre-tests, the block production parameters for the FE experiment were set to obtain stable blocks that are able to support the 5,000 kg heaters under the expected climatic conditions at the Mont Terri URL. The chosen production parameters were (i) a raw material WC (= mass of water lost during oven drying at 105oC divided by the dry mass of the material) of 18 % and (ii) a compaction pressure of 130 MPa. With these production parameters, around 2,500 rectangular blocks (each with a weight of 24.4 kg and dimensions of 40 cm by 20 cm by 14.5 cm) and 500 curved ‘top layer’ blocks (each with a weight of 11.65 kg and dimensions of 40 cm by 10 cm by 10.7 – 20.5 cm) were produced in March 2014.

The bentonite blocks were produced at a rate of 1 block per minute using a natural sodium bentonite. The selected compaction pressure and WC resulted in an average ‘dry density’ (DD) of 1.78 g/cm3. Besides compaction pressure and WC, the following parameters were submitted to an intensive quality control, acting as rejection criteria during the block production: (i) block dimensions, (ii) density, (iii) no visible cracks / damage and (iv) a minimum UCS of 6 MPa.

Block storage

After production, the bentonite blocks were stacked on pallets and then wrapped tightly with plastic foil to prevent water absorption from the environment, which could have caused damage. 5 % of the pallets were equipped with a wireless RH sensor to detect potential leakage of the packaging. All RH sensors showed that the tightness of the pallet packaging was assured throughout the storage period and that the bentonite blocks were unaffected by the RH evolution outside the packaging.

Granulated bentonite mixture

The raw bentonite material needed for the production of the highly compacted and ‘granulated bentonite mixture’ (GBM) used for backfilling the FE tunnel was obtained through open tender. Approximately 350,000 kg of raw bentonite were transformed into a GBM. The aim of the GBM production process was to increase the bulk DD of the raw bentonite material (approximately 0.9 g/cm3) to an emplaced DD of at least 1.45 g/cm3.

The production of a GBM includes several processing steps. For the FE experiment, the raw material was provided at a WC of about 10 % – 15 %. It was then dried by heating to obtain a lower WC in the range of 4 % – 6 %, close to the Proctor’s optimum, which is associated with a higher pellet DD. The maximum temperature to which the raw bentonite was exposed during the drying process was 80

°C. Considering the upper temperature limit, the drying capacity depended exclusively on the GSD of the raw material and the residence time in the heating chamber. Approximately 1,500 kg of raw bentonite were dried per hour in the production for the FE experiment.

The aim during the pelletizing process is to increase the pellet DD. For the FE experiment, the pellets were produced by compaction between flat rollers (resulting in pellets of irregular shape). Although alternative methods exist, this method was found to be better from an economic point of view, with a reasonable production rate (1,000 – 2,000 kg per hour). The negative side of this production method was that the desired maximum grain size could not be reached. The bentonite pellets produced were then mixed in a Kniele mixer, providing enough energy to break some of the pellets, resulting in a mixture with a broad GSD (Figure 15), the aim being to fill larger pores between large particles with smaller particles at all scales. A specific mixing cycle was designed to obtain a GSD close to a 'Fuller distribution' (cf. Fuller & Thompson 1907). The mixture production rate for the FE experiment was approximately 2,000 kg per hour.

Backfilling concept and machine

A 'backfilling machine' (BFM) is needed to backfill a horizontal disposal tunnel with GBM as tightly and homogeneously as possible. Density is considered the key property for ensuring adequate long-term performance of the bentonite-based backfill material in a repository since it directly influences the safety-relevant attributes such as swelling pressure, gas- and water permeability, porosity and suppression of microbial activity. Suppression of microbial activity sets perhaps the most stringent density requirement: microbial activity is clearly suppressed in highly compacted bentonite. In different studies it was concluded that a saturated density of 1.90 g/cm3 (corresponding to a DD of 1.45 g/cm3) for MX-80 bentonite is a desirable target as it may decrease the likelihood of microbially induced corrosion.

Based on the experience from the EB experiment and the ESDRED project, the decision was made to design and fabricate a BFM with 5 screw conveyors for the FE experiment. The aim of using 5 screw conveyors was to improve the backfilling quality in terms of homogeneity, since segregation effects had been observed during previous projects. A staggered alignment of the screw conveyors was chosen with respect to the expected slope angle of the backfilled material. Moreover, an increased compaction was expected as each screw conveyor was designed to remain within the material bulk, building up a conveyance pressure.

Backfilling pre-tests

Before the BFM was built, 2 pre-tests were carried out at a test facility close to Flums in Switzerland. The first pre-test (performed in September 2012) focused on the coupled effects of (i) the material conveyance, (ii) the resulting backfilling pressure, (iii) the potential to push the material upwards and (iv) the corresponding actuation parameters of the screw conveyors. It was found that the ESDRED screw conveyors had the power to push GBM up to 70 cm upwards, if the resulting push back forces were kept under control by strong brakes.

The second pre-test (performed in March 2013) aimed at (i) a better understanding of the bulk material behaviour as influenced by additional measures (such as slope coverage, insertion of vibration needles, etc.) and (ii) collecting data on the achievable bulk DD with regard to the GSD of the GBM. It was found that, without additional measures (such as a slope coverage), small material avalanches occur at the front of the slope, resulting in 'fir-tree like' segregation effects in the backfilled material (Figure 16).

Mock-up backfilling tests

Before acceptance of the prototype BFM, it had to be extensively tested. For this purpose, a test site was set up at a workshop in Grono, Switzerland, where all relevant processes related to heater emplacement and backfilling could be tested. Temporary rails and a full-scale 'test tunnel' (made of industrial steel sheets) with a diameter of 2.5 m and a length of 8 m were installed. The test set-up had the advantage that the backfilled material could be accessed not only through the slope, but also radially through the wall of the 'test tunnel'. Local density measurements were performed with dielectric sensors and radioactive logging tools as well as horizontal 'cone penetration testing' (CPT) equipment.

This 'test tunnel' was filled twice within the framework of the FE experiment. During the first 'mock-up backfilling test' (MBT) performed in May 2014, the focus was on technical functionality and procedural optimisation. During the second MBT performed in August 2014, the backfilling process was optimised in order to achieve higher bulk densities.

Regarding 'quality control' (QC) measures, the bulk density was calculated by mass-volume balance (= backfilled weight divided by backfilled volume). In the first MBT, the volume was estimated by combining the known geometry of the 'test tunnel' and the application of a 3D camera based on time-of-flight technology to capture the slope geometry. For the second MBT, the slope was laser scanned with a geodetic total station.

The average bulk DDs achieved with the MBTs are listed in Table 4. The target DD of 1.45 g/cm3 was clearly exceeded, especially around the canister where a bulk DD of approximately 1.53 g/cm3 was reached. At the same time, the required functionality demonstration of the BFM, before using it at the Mont Terri URL, was performed successfully.

Emplacement and backfilling

The backfilling of the FE tunnel was performed in several steps. The filling of the deep end of the FE tunnel was done in July 2014 with porous concrete for a potential future artificial saturation of the 'bentonite block wall' (BBW).

Bentonite block wall

In the FE tunnel, a 2 m long BBW was constructed in the 'interjacent sealing section' (ISS) between TM44.6 and TM46.6 to (i) investigate what DD can reasonably be expected with bentonite blocks assembled in such a tunnel section, (ii) verify the construction feasibility of a BBW considering the irregular tunnel surface and (iii) be able to potentially measure the sealing effectiveness of the wall at a later experimental stage.

The construction of the BBW (Figure 19) took place in early September 2014, when the RH of the seasonally changing tunnel air in the Mont Terri URL was at around 80 – 85 %. The bentonite blocks survived the 2 weeks of emplacement without any degradation.

In total, about 14 m^3 of bentonite blocks were emplaced manually within 9 working days. The average DD of each block was 1.78 g/cm^3; the average WC was 18 %. Finally, a global bulk DD of 1.69+/-0.05 g/cm^3 was achieved for the entire BBW.

Bentonite block pedestal

As preparation for each heater emplacement and backfilling, a 'bentonite block pedestal' (BBP) was assembled on a prepared concrete surface. Because of the numerous sensors and cables within this BBP, the work was done manually, not exhibiting any demonstration character with respect to the Swiss disposal concept. Each BBP was 4.4 m long, 0.8 m wide and 0.54 m high (Figure 20). In total, each BBP consisted of 132 rectangular blocks (à 24.4 kg) and 88 curved top layer blocks (à 11.65 kg).

After the completion of each BBP, the appropriate heater was driven into the FE tunnel with an emplacement wagon specially designed for this purpose. After precisely manoeuvring the 5,000 kg heater over the heavily instrumented pedestal, the heater was carefully lowered onto the BBP with the help of hydraulic cylinders, avoiding any point loads on the bentonite blocks.

In this manner heater H1 was emplaced in October 2014, heater H2 in November 2014 and heater H3 in January 2015. Due to the intensive instrumentation, cable routing and QC work, the construction of one BBP including the associated heater emplacement took between 8 and 13 working days.

Backfilling

First, the remaining 6.6 m of the ISS were backfilled with the help of the BFM. A total of around 70,000 kg of GBM were emplaced in the ISS within 4 working days. The large cavities, particularly also in the top part of the tunnel, were filled without any problems.

After the construction of each BBP and the subsequent emplacement of the associated heater, each section was then backfilled individually. The BFM with its 8.5 m long top screw conveyor (Figure 21) was designed to be able to drive over the BBP with the emplaced heater so that the screw conveyor tips could still be inserted into the (last) GBM slope (covering the preceding BBP and heater).

Each feeding wagon carried 4 bigbags of GBM, which corresponded to approximately 0.5 – 0.75 m of backfilled length in the FE tunnel. To complete the whole sequence for each heater, around 60 bigbags (à 1,000 kg) had to be backfilled, resulting in the feeding wagon being reloaded 15 times. The reloading of bigbags was done at a distance of 75 m from the FE tunnel at the intersection of the MB tunnel with GA08, while the backfilling unit remained in the FE tunnel with the screw conveyor tips inserted in the GBM slope. This sequence was repeated for each of the 3 heaters. Backfilling one 4.5 m long heater including the 3 m long gap between two heaters took 2 to 3 working days. Together with the relevant section of the ISS and the volume towards the plug, 29.6 m of the FE tunnel were filled with approximately 255,000 kg of GBM.

Each of the 11 times the BFM was driven out of the FE tunnel, for instrumentation and QC purposes the available GBM slopes were scanned with a 3D laser scanner in order to determine the backfilled volumes. Together with the weighing of each bigbag used for backfilling, the backfilled bulk DD was calculated for each of these 12 sections (Figure 22). Considering the disturbance by e.g. sensors and cables, the global DD of approximately 1.49 g/cm^3 achieved in the FE tunnel without any break-downs or accidents can be considered as a very satisfactory result.

Main learning points concerning bentonite homogenization / mechanical evolution and relevance for the project

Experience from previous experiments led to a design of a prototype BFM with 5 screw conveyors, allowing the horizontal backfilling of disposal tunnels with GBM as densely and homogeneously as possible. After construction, this machine underwent intensive testing In order to test the newly built prototype backfilling machine and to verify the achievable density of the emplaced GBM, an 1:1 scale mock-up tunnel with a dummy waste canister and pedestal was constructed and filled with GBM (see Figure 1). The minimum bulk DD of 1.45 g/cm^3, as targeted for the bentonite backfill according to the Swiss repository concept, was exceeded in the MBTs and in the FE tunnel.

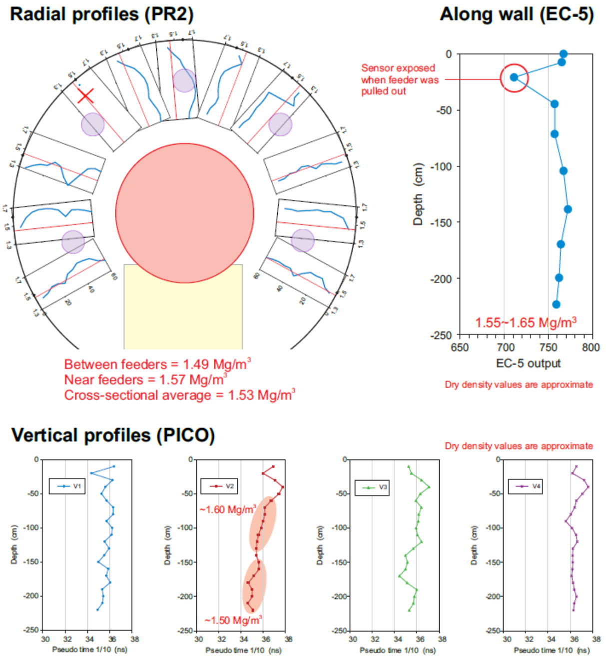

Figure 1: DD density profile of the backfilling pre- tests.

Monitoring Water Saturation

For monitoring water saturation of the backfill material of the FE tunnel, repeated ground-penetrating-radar (GPR) and seismic measurements have been identified to be a useful option. For that purpose, suitable fiberglass tubes have been installed along the tunnel, in which such measurements could be carried out. After initial test measurements and completion of the backfilling of the FE tunnel, the first suites of measurements were carried out in the framework of the Mont Terri Phases 20 and 2.

As in previous campaigns, four different types of measurements were performed, namely (i) calibration measurements, (ii) single hole measurements, (iii) zero-offset profiling and (iv) tomographic measurements. Here, only the results are provided. A more detailed description of the measurement procedures and the data analyses can be provided up-on request.

Results of the tomographic inversions are shown in Figure 2. Clearly, the biggest changes can be observed between experiments 1 and 2. Within the GB section the velocities have reduced considerably. Between experiments 2 to 6 (not shown), minor but significant changes are observed in the GB section. It is noteworthy that also temporal changes within the concrete plug can be recognized.

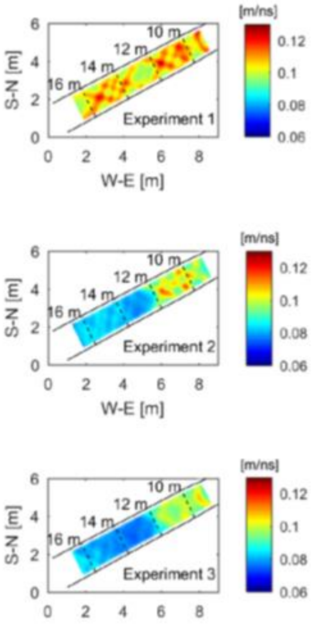

Figure 2: Travel time tomography results from the four experiments performed so far.
Tubes are indicated with solid black lines, and antenna positions are marked with white dots. The dashed black lines indicate distances along the tubes.

The seismic data were acquired with 0.1 m source and receiver spacing at tube distances between 9.5 m to 17.5 m. The data quality was initially quite poor, and it was difficult to recognize the first breaks. Although the data quality improved over time (compaction effects), the first break picking remained challenging. Therefore, it was not yet possible to apply the sophisticated picking and pick refinement procedures applied to the GPR data. Instead the arrival times were picked manually.

We observe a general velocity increase from experiment 1 to 2 in figure 3. During experiments 3 and 4 (not shown), several high-velocities start appearing, but there is no clear temporal trend visible. This changes quite dramatically for experiments 5 and 6 (not shown). The velocities have increased considerably, and the increase seems to continue. This is also associated with an increase of the signal-to-noise ratio in the seismograms. These observations are a clear sign that the compaction of the sand-bentonite mixture has increased. Possibly, even some swelling of the GB may have started.

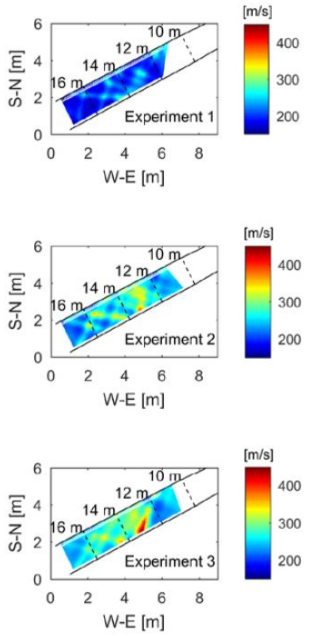

Figure 3: Seismic tomography results from the four experiments performed so far. Tubes are indicated with solid black lines, and antenna positions are marked with white dots. The dashed black lines indicate distances along the tubes.

How could this work inform a new experimental or modelling study in BEACON?

The initial conditions of the FE-Backfill have been well documented. Ongoing geophysical measurements report on the material property evolution. The material property evolution is dependent on the initial material properties and its behaviour during the backfill process and process related to the resaturation of this non-isothermal experiment.

References (ideally with web links)

https://link.springer.com/article/10.1007/s00015-016-0251-2

Recommendations for BEACON project

Acronym FEBEX-DP and FEBEX	**Location** Grimsel Test Site (Switzerland)	**Type** URL
Promoter ENRESA – FEBEX-DP consortium	**Start date** February 1997	**End date** September 2015
Main partners involved in the project Nagra, SKB, Ciemat, Posiva, Kaeri, ENRESA (FEBEX)	**Characteristics of swelling clay** FEBEX bentonite: >90% montmorillonite, exchangeable cations: Ca, Mg and Na Initial ρ_d and *w* of blocks: 1.7 g/cm^3 and 14%	**Water Saturation** Natural
Instrumentation 632 instruments (temperature, humidity, total and pore pressure, displacements, etc)	**Main elements related to homogenization** Spatial distribution of density and water content after 5 and 18 years operation	**Interfaces with other material** Concrete plug, steel liner, metallic sensors, granite
Modelling Yes Groups/Codes	**Main processes studied** x T x H x M x Swelling pressure ☐ Gas transfer	**Reference concept if pertinent** Spanish (horizontal, granite, barrier of highly compacted bentonite blocks)

Main objectives of the experiment

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. The main objectives of the project may be grouped in two areas:

- Demonstration of the feasibility of constructing the engineered barrier system in a horizontal configuration according to the Spanish concept for deep geological storage (AGP), and analysis of the technical problems to be solved for this type of disposal method.
- Better understanding of the thermo-hydro-mechanical (THM) and thermo-hydro-geochemical (THG) processes in the near field, and development and validation of the modelling tools required for interpretation and prediction of the evolution of such processes.

General description

As part of the FEBEX 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, 2006). The thermal effect of the wastes was simulated by means of heaters, whereas hydration was natural. The test was monitored, this allowing the evolution of the temperature, total pressure, water content, water pressure, displacements and other parameters to be obtained continuously in different parts of the barrier and the host rock, this information being used as a contrast to the predictions of the thermo-hydro-mechanical (THM) and themo-hydro-geochemical (THG) models.

The basic components of the test (Fig. 1) were: the gallery, measuring 70 m in length and 2.3 m in diameter, excavated through the Aare granite; the heating system, made up of two heaters placed inside a liner installed concentrically with the gallery and separated one from the other by a distance of 1.0 m, with dimensions and weights analogous to those of the real canisters; the clay barrier, formed by blocks of compacted bentonite; the instrumentation and the monitoring and control system for data acquisition and supervision and control of the test both autonomously and remotely from Madrid. Up to 632 sensors of very diverse types were initially installed to monitor the different thermo-hydro-mechanical processes that occurred in both the clay barrier and the surrounding rock throughout the entire life of the test. The gallery was closed by a concrete plug.

The clay barrier was made of FEBEX bentonite, which was extracted from the Cortijo de Archidona deposit (Almería, Spain). The physico-chemical properties of the FEBEX bentonite, as well as its most relevant thermo-hydro-mechanical and geochemical characteristics obtained during the projects FEBEX I and II were summarised in the final reports of the project (ENRESA 2000, 2006) and later documents (Villar & Gómez-Espina 2009). To build the clay barrier, various types of blocks were manufactured from the bentonite in the shape of 12-cm thick circular crown sectors. The blocks were arranged in vertical slices with three concentric rings. In the heater areas the interior ring was in contact with the steel liner, whereas in the non-heater areas a core of bentonite blocks replaced the heaters (Fig. 2). The thickness of the bentonite barrier in the heater areas was 65 cm (distance from liner to granite). The blocks were obtained by uniaxial compaction of the FEBEX clay with its hygroscopic water content at pressures of between 40 and 45 MPa, what gave place to dry densities of 1.69-1.70 g/cm^3. The initial dry density of the blocks was selected by taking into account the probable volume of the construction gaps and the need to have a barrier with an average dry density of 1.60 g/cm^3 (ENRESA, 2000).

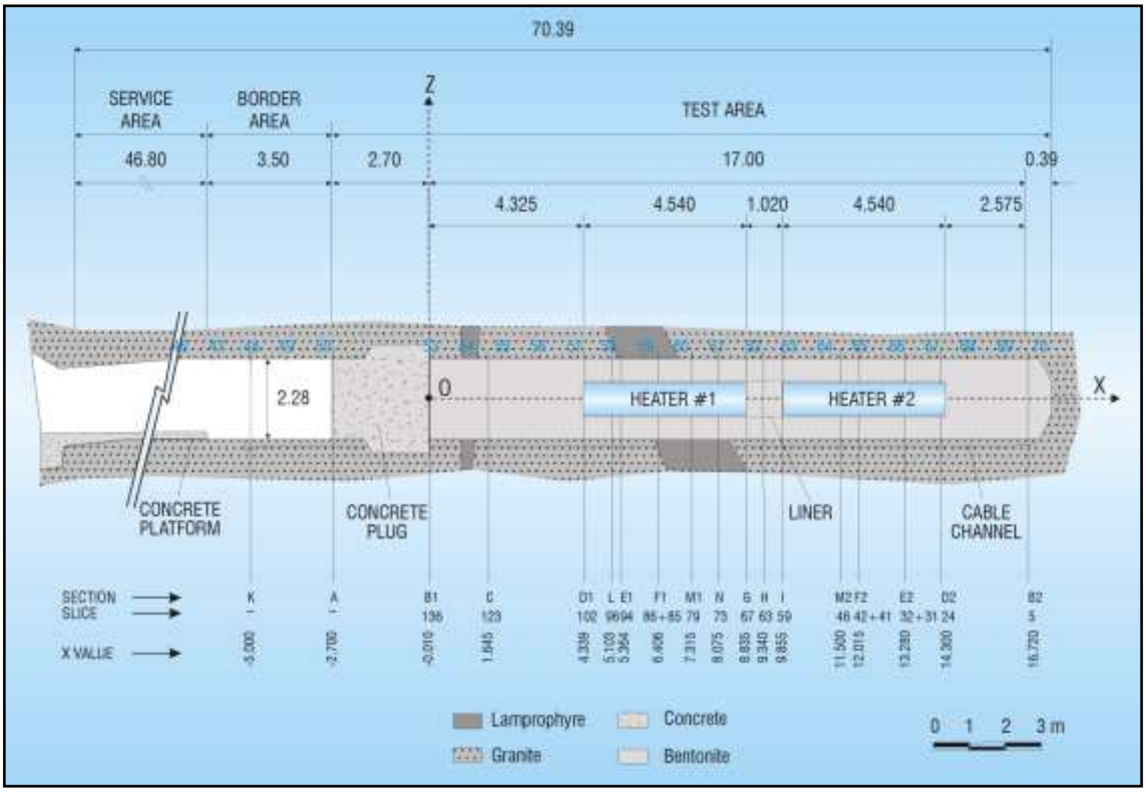

Fig. 1: General layout of the in situ test during phase I, including instrumented sections (ENRESA, 2000)

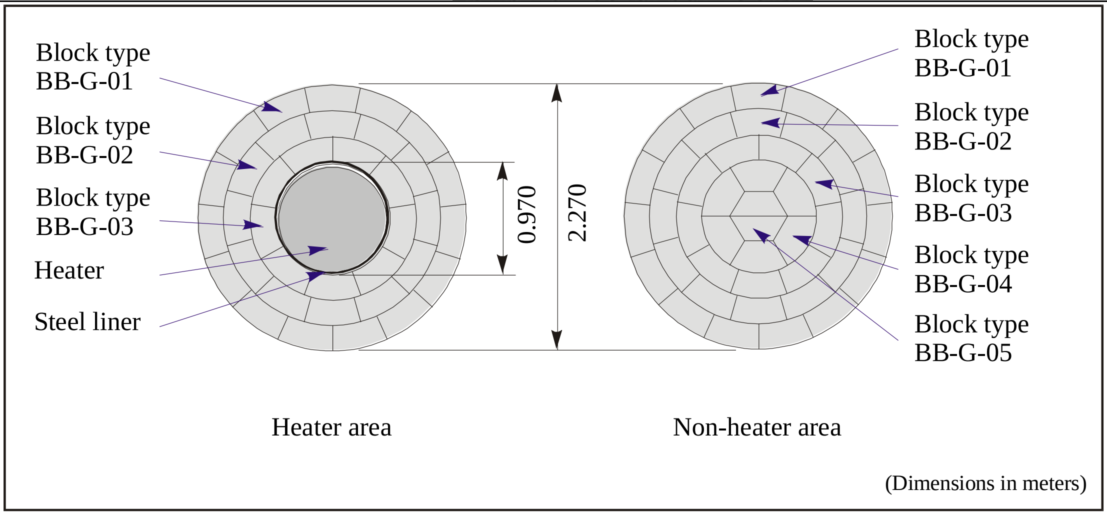

Fig. 2: Geometry of the clay barrier in the FEBEX *in situ* test at GTS (ENRESA 2000)

The heating stage of the in situ test began on February 27th 1997. The power of the heaters was adjusted so that to keep the temperatures at their surfaces at 100ºC. After five years of uninterrupted heating at constant temperature, the heater closer to the gallery entrance (heater #1) was switched off (February 2002). In the following months this heater and all the bentonite and instruments preceding and surrounding it were extracted (Bárcena et al., 2003). A large number of bentonite samples were also taken for analysis in different laboratories (Villar et al. 2006). The remaining part of the experiment was sealed with a new sprayed concrete plug. New sensors were installed in the buffer through the concrete plug, and a second operational phase started with the test configuration shown in Fig. 3.

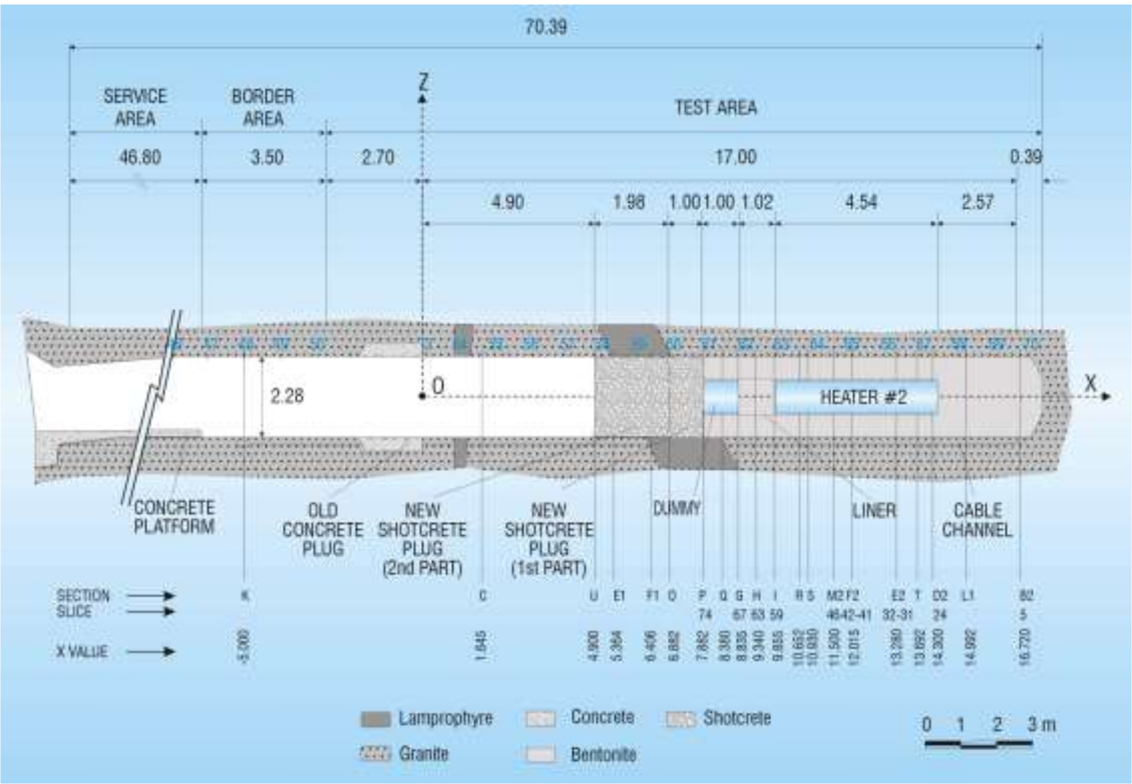

Fig. 3: General layout of the in situ test during phase II, including instrumented sections (ENRESA 2006)

The test continued running until April 2015, when heater #2 was switched off. The concrete plug started to be demolished some days earlier, and the buffer removal and sampling took place between May 8th and August 5th (AITEMIN 2016). An exhaustive postmortem bentonite sampling program was designed (AITEMIN 2015). Clay samples were taken to characterise the solid and liquid phases, in order to confirm predictions and validate existing models of THM and THG processes. In particular, samples were taken to determine on site their water content and dry density, with the aim of assessing the final state of the barrier and supply data to validate and check the capacity of the THM numerical codes to predict the bentonite evolution in an engineered barrier.

Main point concerning bentonite homogenization and relevant for the project

The physical state of the barrier after 18 years of operation was very much affected by the processes to which it had been subjected, namely hydration from the granite and/or thermal gradient-induced moisture redistribution. A brief summary of these observations and common/distinct patterns found is as follows (Villar et al. 2016a):

- All the construction gaps between blocks had sealed, both those among blocks of the same section and the gaps between bentonite slices. The granite/bentonite contact was also tight at all locations and the gaps hewn in the blocks to allow for the passing of cables had been completely filled by the swelling of the bentonite.
- The water content and dry density in every section followed a radial distribution around the axis of the gallery, with the water content decreasing from the granite towards the axis of the gallery and the dry density following the inverse pattern. The water content at all points in the barrier, even those close to the heater, was higher than the initial one, i.e. greater than 14%. The water content and density gradients were more noticeable in those sections affected by the heater (Fig. 4).

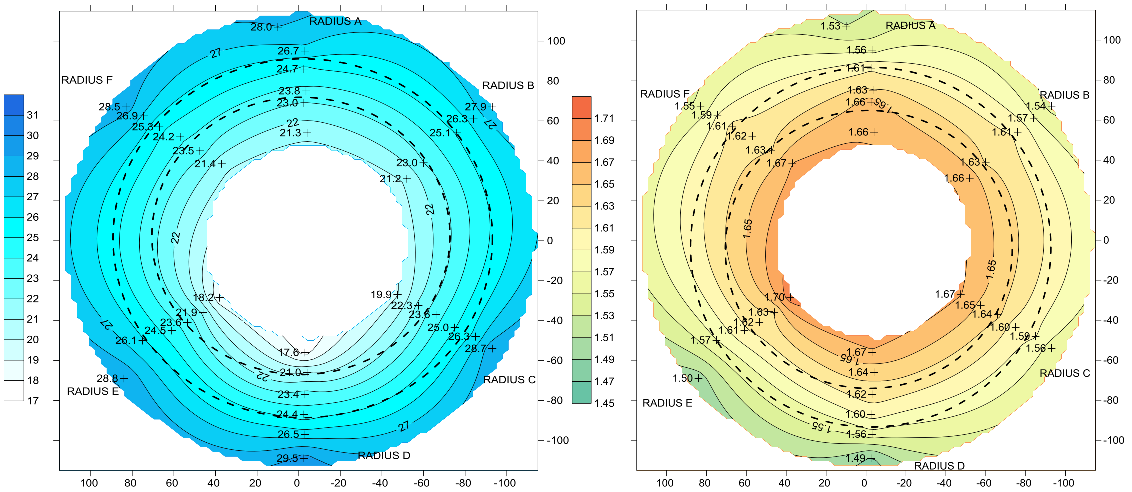

Fig. 4: Final water content and dry density distribution in a vertical section around the heater

- However, the degree of saturation tended to be homogeneous and very high in all the sections, with no clear spatial trend in most of them. Only the sections around the heater or very close to it had degrees of saturation that decreased towards the gallery axis, but were at all points higher than 80%.
- There were also significant changes in dry density and water content along the axis of the tunnel, which caused that the average of these properties in different sections were different along the gallery (Fig. 5).

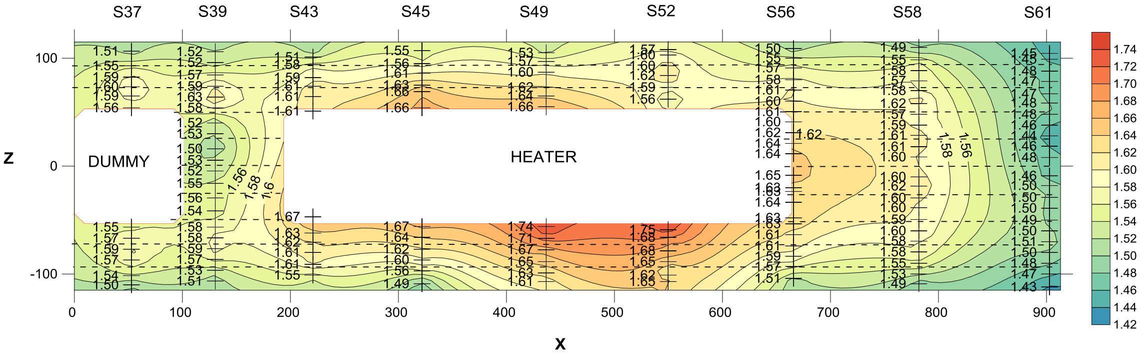

Fig. 5: Dry density distribution in a vertical longitudinal section

The comparison of these results and those obtained during the partial dismantling performed after 5 years operation will allow describing the first stages of the evolution of a bentonite barrier under thermal gradient and under isothermal conditions (some sections of the experiment were not affected by the heaters). A comparison of the state of the bentonite barrier after 5 and 18 years operation shows that the main changes during the 2nd Phase took place in the internal part of the barrier (Villar et al. 2016b). In particular, the water content in the 10 cm closest to the granite of the cold slices was the same after 18 years operation as after 5 years, whereas the additional operation time allowed for the saturated region to extend further towards the interior of the barrier. Naturally, these changes in water content were reflected in dry density changes (Fig. 6, left). In the slices around the heater the water content near the granite decreased between that observed at 5 years and what was present after 13 additional years of operation. In contrast, the water content increased in the internal part of the barrier. However, the dry density gradient around the heater was similar after 5 years than after 18 yeards (Fig. 6, right).

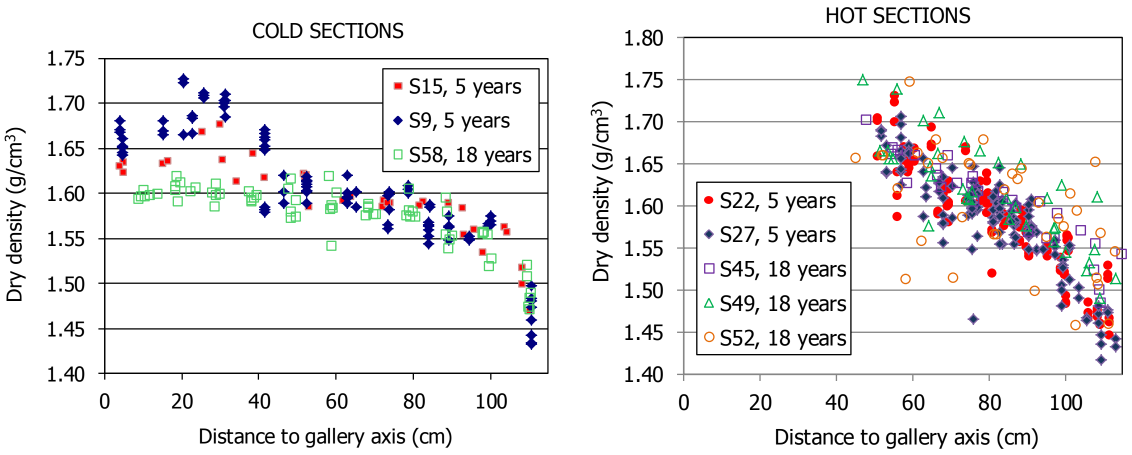

Fig. 6: Water content measured in samples from different vertical slices during the partial (5 years) and final dismantling (18 years)

The analysis of the microstructural changes (pore size distribution) of the FEBEX barrier after 18 years of operation will be also carried out. The main expected outcome is a conceptual understanding of the evolution of bentonite fabric and microstructure upon hydration (and heating) and of the factors affecting it.

References

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Project Acronym GAST	**Location** Grimsel Test Site	**Type** URL/mock up/~~lab-test~~
Lead organiser Nagra	**Start date** 2011	**End date** On - going
Main partners involved in the project ANDRA, KORAD, Nagra, NWMO	**Characteristics of swelling clay** Sand-Bentonite Mix 80/20	**Water Saturation** Artificial/~~natural~~
Instrumentation	**Main elements related to homogenization**	**Interfaces with other material**
Modelling Yes/~~no~~: Groups/Codes : Finsterele at Berkeley TOUGH	**Main processes studied** ☐T ☒H ☒M ☐Swelling pressure ☒Gas transfer ☐Other	**Reference concept if pertinent** Nagra EGTS

Main objectives of the experiment

With the concept of the "engineered gas transport system" (EGTS), a backfill and sealing system was developed that allows the controlled transport of gases along the access structures without compromising the radionuclide retention capacity of the engineered barrier system. High-porosity cementitious mortar is used to fill the void spaces within the emplacement caverns. After backfilling of a cavern, it is closed with a gas-permeable seal. Other underground structures in the host rock are backfilled with sand/bentonite or with processed excavated Opalinus Clay. A gas-permeable seal separates the underground structures in the host rock from the backfilled ramp and contact with the overlying confining rock units. Access or ventilation shafts involve vertical repository seals.

Two larger scale experiments have been implemented to demonstrate the effective functioning of the sand/bentonite mixture for gas permeable tunnel seals. The medium scale FORGE Mock-up experiment features a cylindrical sand/bentonite body of 0.6 m length and 0.54 m diameter. High-permeable filter elements at both ends facilitate water and gas tests with pressures up to the vessel's design pressure of 2 MPa. The design-analogue large scale Gas Permeable Seal Test (GAST; 8 m length, 3.0 m diameter) was implemented at the end of a gallery in the granitic rocks of the Grimsel Test Site and instrumented for detailed monitoring (e.g., total pressures, pore pressures, relative humidity, etc.).

GAST focuses on the behaviour of a gas permeable seal under realistic boundary conditions and features a large scale in situ experiment. The main aims of the in situ experiment are to (1) demonstrate the effective functioning of gas permeable seals at a realistic scale and pore pressure; and (2) determine up-scaled gas and water permeabilities of S/B seals (i.e. two-phase flow parameters for large-scale models). For GAST water and gas injection pressures up to 5 MPa were considered as design values to approximate the expected hydrostatic pressures in a repository seal at ~500 m depth. Secondary objectives include the evaluation of emplacement techniques and necessary methods for quality assurance (QA).

The requirement for the S/B seal of the GAST project was to obtain an intrinsic hydraulic permeability of 10 $^{-18}$ m^2. The test design encompassed the use of natural sodium Wyoming bentonite (MX80) and a high degree of homogeneity in the emplaced S/B mixture. Laboratory tests indicated that mixtures of 80% sand, 20% bentonite combine the required low water permeability with enhanced gas permeability. Recent laboratory tests at the École polytechnique fédérale de Lausanne for samples compacted at 1.5 and 1.8 Mg/m3 were fitted with a van Genuchten model and confirmed gas entry pressures varying between 10 and 360 kPa dependent on dry density wetting/drying curve and the suction range over which the model was fitted. A second series of permeability tests showed that emplacement dry densities of 1.6-1.65 Mg/m^3 are necessary to achieve an intrinsic S/B permeability of 10 $^{-18}$ m^2. Finally an average dry density of 1.7 Mg/m^3 was chosen as target value, and a minimum of 1.6 Mg/m^3 was considered acceptable at locations where compaction was difficult. Proctor tests indicated an optimum water content for the S/B mixtures between 10-13%.

General description

The GAST experiment is located at the end of a 3.5 m diameter tunnel in the GTS ~400 m below surface. The hydraulic conductivity of the excavation damage zone in the vicinity of the tunnel – it had been excavated by a tunnel boring machine – is believed to be in the same range or lower than that of the seal and is therefore disregarded. The very few geological structures found in this part of the tunnel were sealed with two-component resin and impermeable mats to ensure a tight and stiff boundary against the expected injection pressures.

The hart of the test consists of 28 horizontal layers of in situ compacted S/B (Figure 1) with a length of 8 m and a target dry density of 1.7 Mg/m^3. The radial rock/seal interfaces were filled with a 25 cm thick section of granular bentonite material to obtain a tight confinement against the surrounding host rock and minimize preferential water or gas flow paths along the interfaces. Granular bentonite was also used to backfill the headspace above the seal, where insufficient space made the vibrators unsuitable. Vertical gravel filters were emplaced at both ends for controlled water and gas injections. Material volumes and bulk parameters are summarised in Table 1. Two walls, made of compacted bentonite blocks and granular bentonite, constitute the watertight seals at the tunnel end and at the confining concrete bulkhead. On-site construction started in 24th October 2011 and was completed on 16th May 2012.

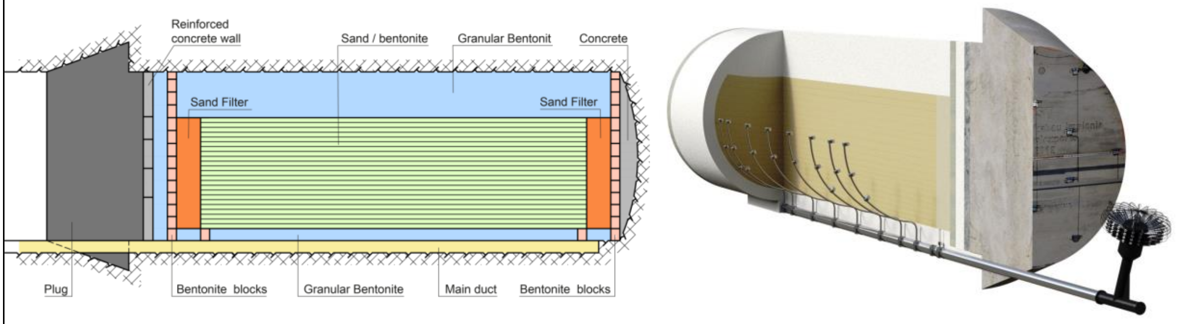


Figure 1. Conceptual experimental layout (left) and cut-away visualization (right) showing sand/bentonite and granular bentonite bodies with instrument risers and main duct below the tunnel

Table 1. Bulk parameter of emplaced materials.

Element		***S/B***	***GBM***	***Sand***
Material		80/20 sand / bentonite	Granular bentonite	Quartz san
Total volumes	[m^3]	46	~36	2×3
Average dry density	[Mg/m^3]	1.65	1.45	not measure
Target permeabilities	[m^2]	1.00E-18	<1E-18	1.00E-15

The GAST experiment is equipped with multiple sensors to monitor the sealing behaviour during saturation phase and gas transport in the subsequent gas injection phase as well as the hydraulic effects on the host rock and concrete bulkhead. The expected injection pressures of 5 MPa set the constraints for instrumentation design. A variety of sensors are placed at the rock and bulkhead walls (total pressure), at the top of selected S/B layers (piezometers) and in the granular bentonite head space (relative humidity). Upper and lower filter sections are equipped with hydraulic steel tubes (port lines) used for water and later gas injections. The interface between filter and S/B at the bulkhead side (see Figure 1) is equipped with elongated ribbon TDR sensors (TDL) with capability to localise saturation changes along the sensor.

Two cable ducts feed all cables from the sensors in granular bentonite through the upper part of the concrete bulkhead. Cables and lines from the sensors within the S/B seal are routed in steel tubes to the risers and then to the main duct that runs below the seal as shown in Figure 1. Initially the main duct cable outlet was open. After a leakage event with water outflow through the main duct it had to be closed with a well head featuring individual cable feedthroughs. The well head is shown to the right in Figure 1.

Mass balance observations just after emplacement assured that the required emplacement dry density was met. Dry densities were computed for each completed S/B layer using layer thicknesses from approximately 1 m spaced layer surface coordinates and water content corrected weights of emplaced mixture. An alternative mass balance approach was assessed additionally by performing 3D laser scans typically after four or five layers had been emplaced (Figure 1). The dry densities obtained by these methods ranged between 1.6 and 1.73 Mg/m^3 with an average of 1.65 Mg/m^3 for the complete S/B volume. The third QA method employed direct sampling with a ring cutter (sampling volume ~50 cm^3) at ~1 m spacing, oven drying and on site weighing of the recovered material. Variogram models were derived from this data for density visualisation. The cut-out views in Figure 3 3 exhibit contiguous areas where dry densities range around or above the target value. Local high and low dry densities are highlighted by plotting only values below or above the target value (Figure 2 left and right, respectively).

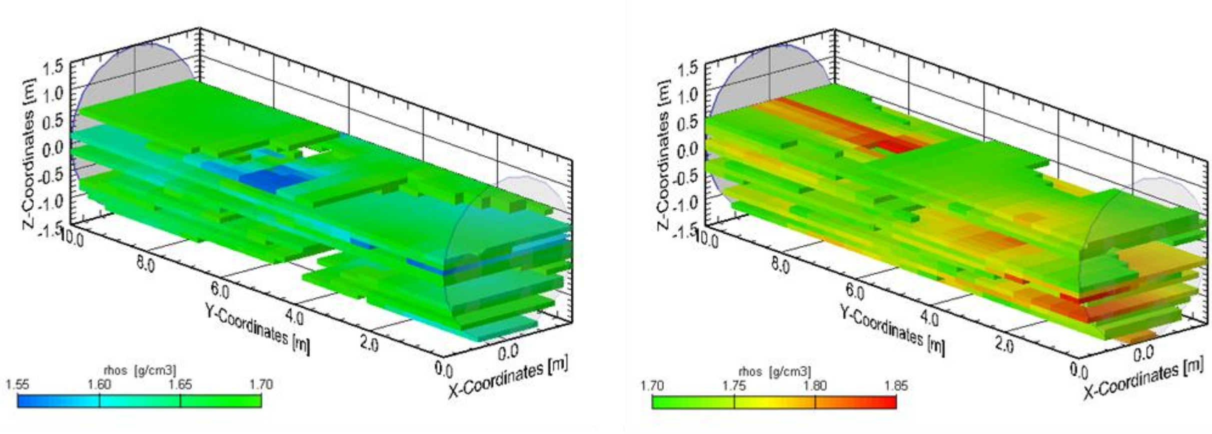
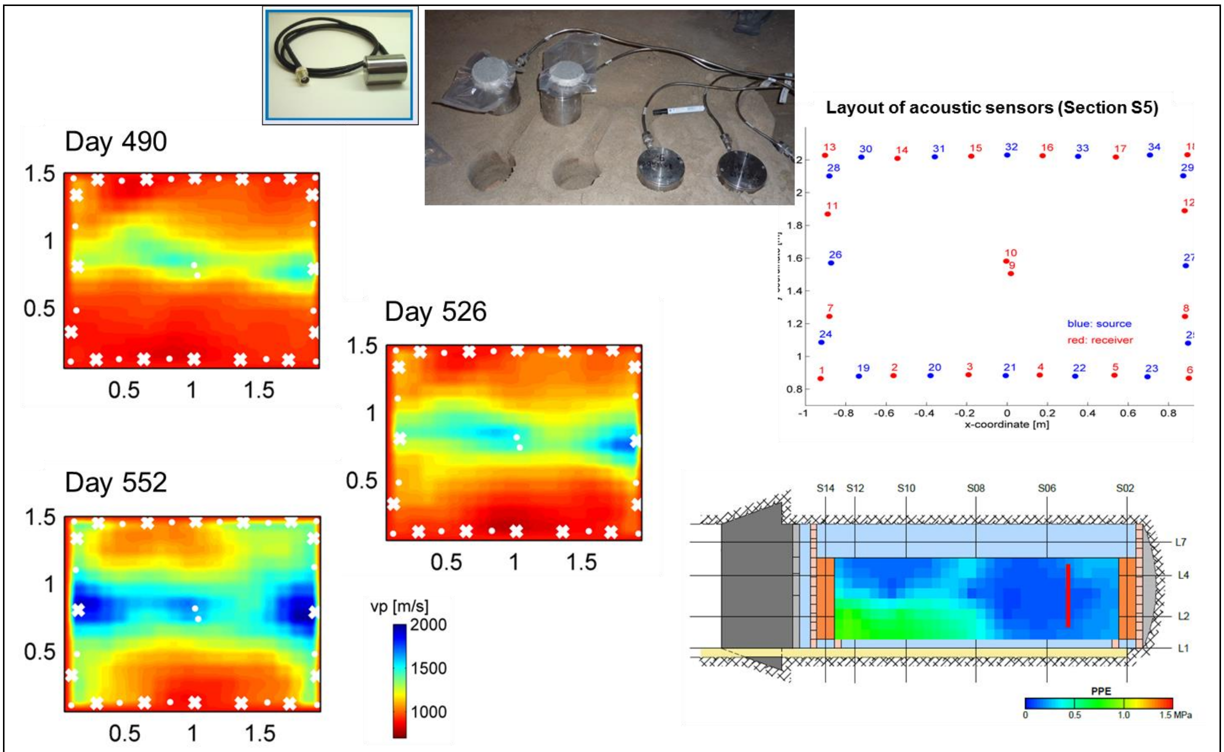


Figure 2. Distribution of S/B dry densities smaller (left) and larger (right) than 1.7 Mg/m^3.

Since July 2012 the system is being artificially saturated by water injections into the front gravel filter element. The filter volume was quickly filled but the main bodies of S/B and granular bentonite are slow to saturate. A water leakage that occurred in January 2014 at an injection pressure of about 1.7 MPa interrupted the artificial saturation process. Saturation has been resumed after the necessary remediation works were successfully completed in August 2015. Recent index tests indicated that large volumes of the S/B body are nearly saturated. The upper layers of the S/B and the granular bentonite above it are still partially saturated.

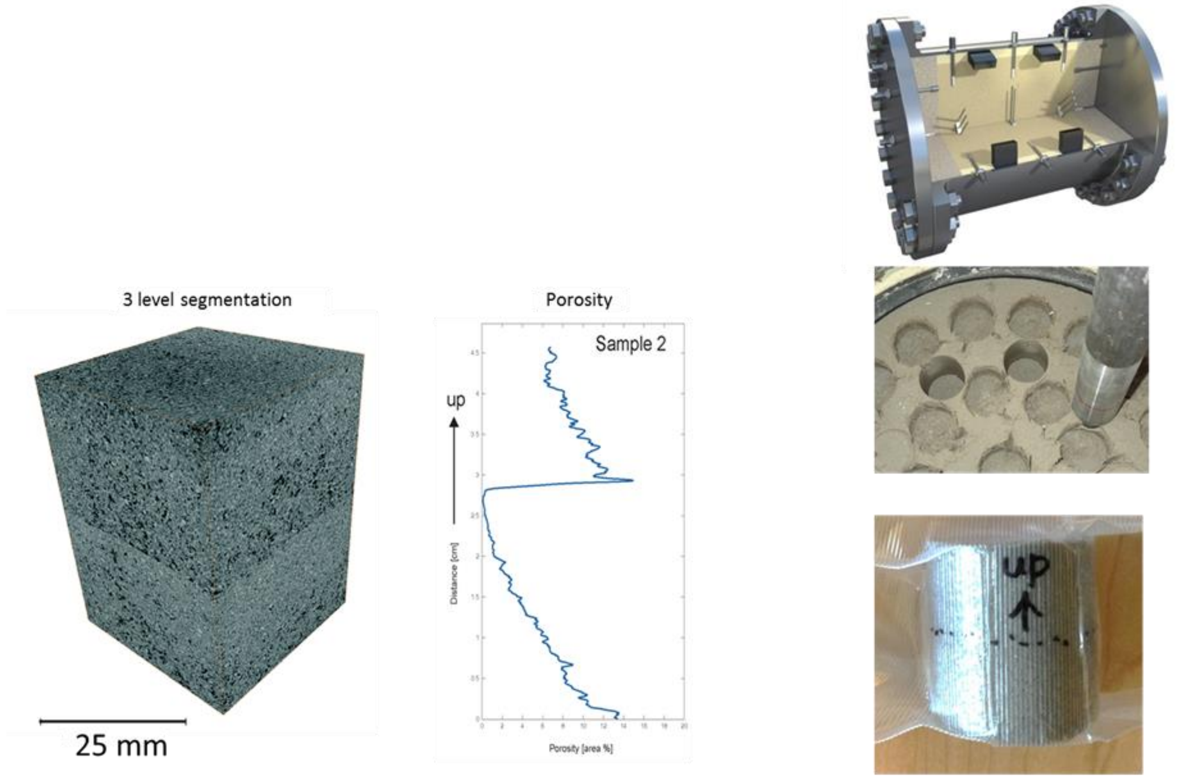
The FORGE Mock-up is a fully instrumented medium scale experiment to investigate sand/bentonite water and gas permeabilities and investigate potential chemical interaction between cementitious mortar and sand/bentonite. The FORGE Mock-up has been described elsewhere (see references).



Main learning points concerning bentonite homogenization / mechanical evolution and relevance for the project

Figure 3: Acoustic tomography indicates heterogeneous saturation

- Saturation of the large sand/bentonite seal volume (see figure 3)
    - Piezometers and seismic tomography suggest heterogeneous saturation
    - Tough models reproduce saturation trend
    - Partial saturation achieved after 550 days but interrupted by leakage (probably associated with instrumentation ducting)



- Figure 4: FORGE Mock-up density inspection

- FORGE Mock-up density inspection (see figure 4)
    - Analysis of S/B layers from Mock-up column (DM 60 cm)
    - Dismantling: S/B tends to separate at emplacement layer joints □ anisotropy in strength, hydraulic permeability?
    - X-ray CT imaging of joint samples resolves discontinuous parameter

How could this work inform a new experimental or modelling study in BEACON?

The initial conditions of the GAST have been well documented and a Mock-up experiment allows for detailed studies. Ongoing geophysical measurements report on the material property evolution. The material property evolution is dependent on the initial material properties and its behaviour during the backfill process and process related to the resaturation of this isothermal experiment**.**

References (ideally with web links)

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Recommendations for BEACON project

Project Acronym HE-B	**Location** Mont Terri URL, Switzerland Opalinus clay formation	**Type** URL/mock up/lab-test URL
Lead organiser BGR	**Start date** 5 May 1999: Installation of heater/buffer 22 February 2002: Start of heating	**End date** 23 January 2004
Main partners involved in the project BGR, ENRESA, GRS, NAGRA Aitemin, CIMNE, Colenco, ETHZ, Solexperts	**Characteristics of swelling clay** Pre-compacted FEBEX blocks dry density: 1.8 g/cm^3	**Water Saturation** Artificial/natural
Instrumentation 112 sensors in buffer and rock: • Temperature • Total pressure • Pore Pressure • Water content • Electrolevel • Fluid pressure • Weight • Voltage meter • Current meter • Electrode chains • Packer	**Main elements related to homogenization** The bentonite buffer is basically homogenous except for gaps between blocks and at the outer and inner blocks' boundaries Heterogeneity mar arise due to the effects of hydration and heating	**Interfaces with other material** Bentonite/Opalinus clay Bentonite/steel
Modelling Yes/no: Yes Groups/Codes : UPC/Code_Bright (near field) Colenco/MEHRLIN (far field)	**Main processes studied** ☒T ☒H ☒M ☐Swelling pressure ☐Gas transfer ☐Other	**Reference concept if pertinent**

Main objectives of the experiment

To improve the understanding of the coupled thermos-hydro-mechanical (THM) processes in a host rock-buffer system achieved by experimental observations as well as by numerical modelling. In detail:

- Long term monitoring in the vicinity of a heater during hydration and heating; especially observation and study of coupled THM processes in the near field
- Determination of the properties of barrier and rock done mainly by laboratory and in situ experiments
- Study of the interaction between the rock and the bentonite buffer as well as validation and refinement of existing tools for modelling THM processes
- Study of the behaviour and reliability of the instrumentation and measuring techniques

General description

The HE-B experiment involved placing a heater of 0.1 m diameter and 2.02 m length in a 300mm diameter vertical borehole. The borehole was 7.5m deep and was drilled in a niche excavated for this purpose. The heater was surrounded by a compacted clay barrier made up of ring-shaped Febex bentonite blocks with a dry density of 1.8 g/cm^3. 19 boreholes were drilled in the niche floor to install sensors. Devices to determine gas and water release were also installed in the boreholes and geoelectric measurements were performed during the test. The layout of the main borehole containing the heater and the distribution of the monitoring boreholes in the niche are depicted in Figure 1.

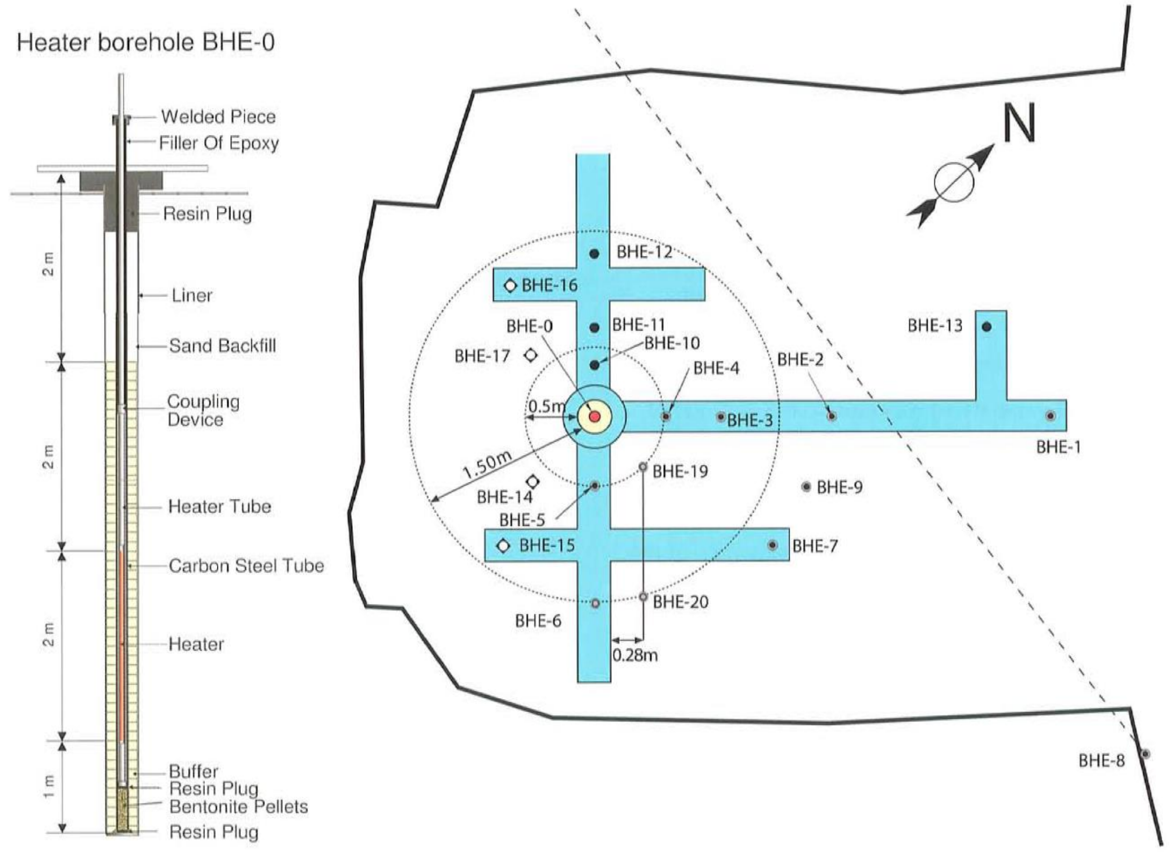

Figure 1. Central borehole layout and location of the central and instrumentation boreholes in the niche.

Due to the low permeability of Opalinus clay, an artificial hydration system was installed to accelerate the hydration process in the buffer prior to the heating phase. A cylindrical ceramic filter was fixed to the outer part of the heater tube and connected by four tubes to the water injection system. The gap between the bentonite buffer and the rock as well as the upper part of the borehole were filled with sand. Figure 2 shows a cross section pf the experiment.

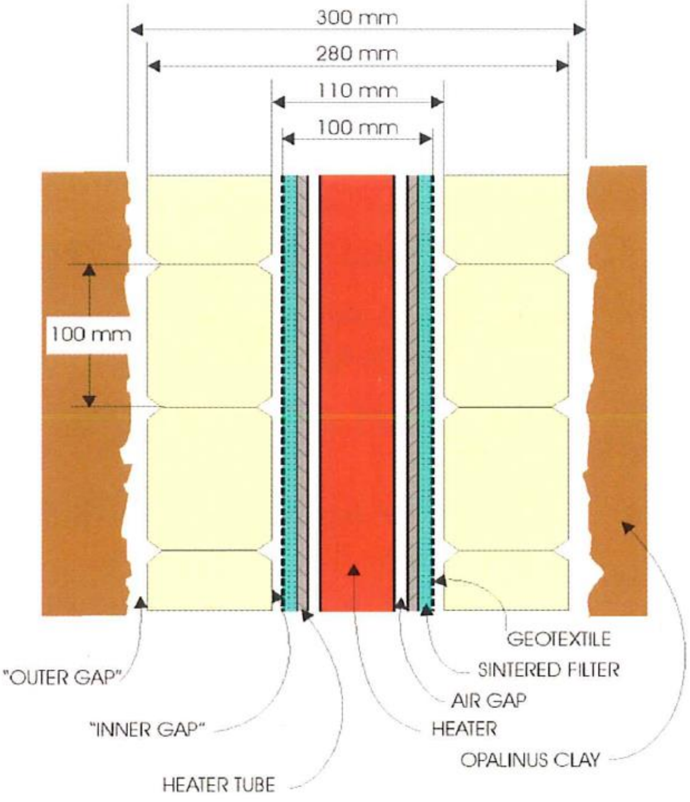

Figure 2. Cross-section of the experiment.

Before heating was started, the barrier was hydrated artificially for 35 months using synthetic Pearson water (similar in chemical composition to the water present in the Opalinus Clay). Afterwards heating was applied during an 18th month period. Once the prescribed maximum temperature of 100ºC was reached in the bentonite, heater power was adjusted in order to keep that maximum temperature constant. The heating period of the experiment spanned from February 2002 to the end of August 2003. At the end of the heating period, the heater was switched off and, after 1 month cooling period, the test was dismantled. Geotechnical, hydraulic and seismic field tests were performed at the end of the test and a number of rock samples were retrieved for testing in the laboratory. Figure 3 displays the schedule of the various activities involved in the experiment.

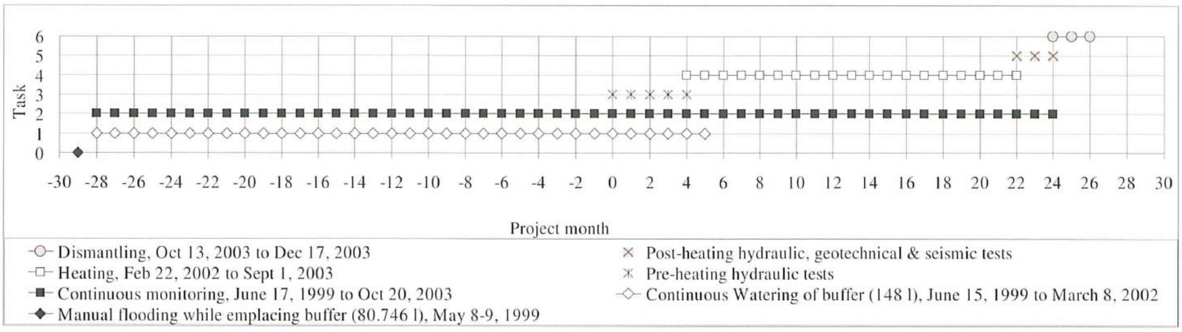

Figure 3. Schedule of the activities performed in relation to the HE-B test

The monitoring part of the experiment was less successful than expected, the sensors installed in the buffer and its vicinity were, in most cases, not resistant to conditions during hydration. As confirmed during dismantling, numerous sensors corroded in presence of Parson water. Most sensors in the peripheral boreholes, however, remained intact so the behaviour of the host rock during the test could still be examined. Dismantling took place between 1st September 2003 and 23

January 2004. The dismantling involved drilling by stages a 3m diameter shaft around the heating borehole to a final depth of 7 m. The bentonite blocks were found wetted at dismantling with a volume increase of 5% to 9%, which is below the bentonite's swelling potential suggesting that full saturation had not been achieved. The 10mm gap between bentonite blocks and Opalinus clay filled with dry loose sand at the installation of the experiment was still present. Water and dry density of the bentonite was measured, the results are collected in Figure 4. Longitudinal heterogeneity due to the localized effects of heating is observed, the radial distribution cannot be readily interpreted with the information currently available. Those observations also confirm that the bentonite was far from saturated at the end of the test.

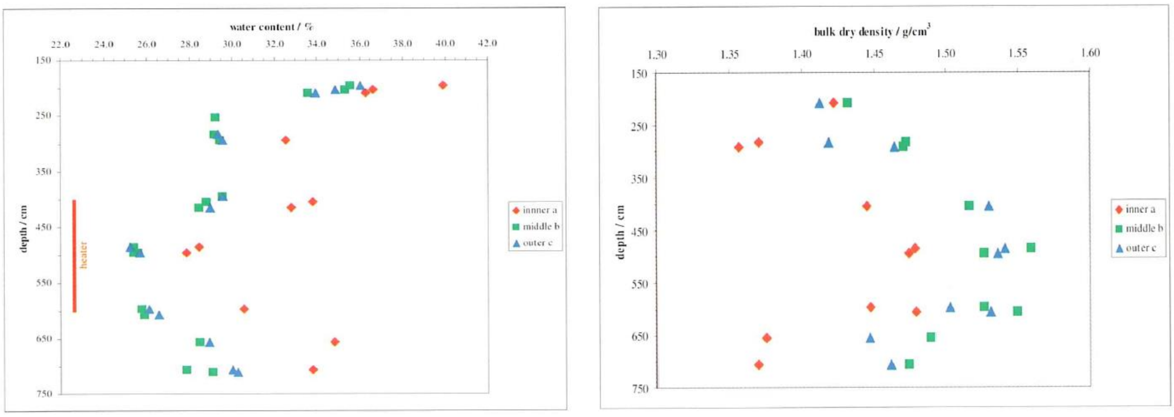

Figure 4. Distribution of water content and dry density obtained during the dismantling of the experiment

Main learning points concerning bentonite homogenization / mechanical evolution and relevance for the project

The lack of reliable data from the buffer sensors hamper the useful interpretation of this test. The distribution of dry density and water content obtained upon dismantling are of some interest showing distinctly the effects of heating. However, the fact that the buffer is far from hydraulic equilibrium and the unusual hydration procedure makes the data less valuable from the point of view of examining bentonite homogenization.

How could this work inform a new experimental or modelling study in BEACON?

This test can provide some backgrounds to the BEACON project but it is unlikely to inform a new experimental or modelling study.

References (ideally with web links)

Göbel, I., Alheid, H.-J., Alonso, E., Ammon, C., Bossart, P., Brühler, C., Emmerich, K., Fernandez, A. M., García-Siñeriz, J. L., Graf, A., Jockwer, N., Kaufhold, S., Kech, M., Klubertanz, G., Lloret, A., Mayor, J. C., Meyer, T., Miehe, R., Muñoz, J. J., Naumann, M., Nussbaum, C., Pletsch, T., Plischke, I., Ploetze, M., Rey, M., Schnier, H., Schuster, K., Sprado, K., Trick, T., Weber, H., Wieczoreck, K., & Zingg, A. (2007). Heater Experiment: Rock and bentonite thermo-hydro-mechanical (THM) processes in the near field of a thermal source for development of deep underground high level radioactive waste repositories. In P. Bossart, & C. Nussbaum (Eds.), *Mont Terri Project - Heater Experiment, Engineered Barriers Emplacement and Ventilation Tests*. Report of the Swiss Geological Survey No. 1 (pp. 7-16). Federal Office of Topography (swisstopo), Wabern, Switzerland. www.mont-terri.ch

https://www.mont-terri.ch/en/documentation/publications-from-swisstopo.detail.publication.html/mont-terri-internet/en/publications/publications-swisstopo/BLGD-01.pdf.html

Recommendations for BEACON project

Availability of dismantling data would suggest that this is an experiment that could prove valuable for the BEACON project. However, the fact that the hydration was far for complete at the end of the test, the relative paucity of dismantling data and the scarce information conceding the procedure and progress of hydration makes it questionable that this test should receive special attention from the BEACON project.

Project Acronym HE-E	**Location** Mont Terri URL, Switzerland (Opalinus clay formation)	**Type** URL/mock up/lab-test URL
Lead organiser NAGRA	**Start date** June 2011	**End date** In progress
Main partners involved in the project NAGRA, GRS, BGR, ENRESA INTERA, CIMNE-UPC, AITEMIN, ENRESA, CIEMAT, Solexperts	**Characteristics of swelling clay** Bentonite blocks: Compacted MX-80, w/c: 10.34%, dry density: 1.806 g/cm^3 Granular Bentonite. MX-80. w/c: 5.4%, dry density: 1.51 g/cm^3 (1.46 g/cm^3 dry bulk density) Sand/Bentonite mixture (65%-35%). Quartz sand + GELCÑAY sodium bentonite. .w/c: 4.1%, dry density: 1.38 g/cm^3	**Water Saturation** Natural
Instrumentation 228 sensors in buffer and rock: • Temperature • Relative humidity • Extensometer • Pore Pressure • Psychrometers • Geo-electric sensors • Seismic array	**Main elements related to homogenization** Initial heterogeneity of density: • Cross-section: Granular bentonite - bentonite blocks • Cross-section: Mixture sand/ bentonite - bentonite blocks • Potential pellets segregation • Local micropore-macropore heterogeneity	**Interfaces with other material** Bentonite/steel Bentonite/Opalinus clay
Modelling Yes/no: Yes Groups/Codes: INTERA/TOUGH2 GRS/Code_Bright CIMNE-UPC/ Code_Bright	**Main processes studied** ☒T ☒H ☒M ☐Swelling pressure ☐Gas transfer ☐Other	**Reference concept if pertinent** Swiss reference concept for high-level waste disposal

Main objectives of the experiment

The aims of the HE-E experiment are elucidating the early non-isothermal re-saturation period of the buffer and its impact on the thermo-hydro-mechanical behaviour in the near field, namely:

1. to provide the experimental data base required for the calibration and validation of existing THM models of the early re-saturation phase

2. to upscale thermal conductivity of the partially saturated EBS from laboratory to field scale (for pure bentonite and bentonite-sand mixtures)

General description

The HE-E experiment has been installed in a section of the 1.3 m diameter and 50 m long microtunnel excavated in 1999 using the raised-boring technique. The same section of the microtunnel had been used previously for a ventilation test (VE). The layout of the experiment is shown in Figure 1. Two 4 m-long heaters have been used separated by a plug. Heater 1 is surrounded by an engineer barrier composed of granular MX-80 bentonite made up of pellets with a mean diameter 1 mm approximately and sits on a bed of MX-80 compacted blocks. The dry bulk density of the granular bentonite as placed is 1.46 g/cm^3 and the dry density of the blocks is 1,806 g/cm^3. The arrangement of Heater 2 is the same except that the material used in the barrier is a mixture of sand and MX-80 bentonite. The resulting dry density of the sand/bentonite mixture is 1.51 g/cm^3. No artificial hydration is used for saturating the engineered barrier, so water uptake by the bentonite will be very limited due to the low permeability of the Opalinus Clay.

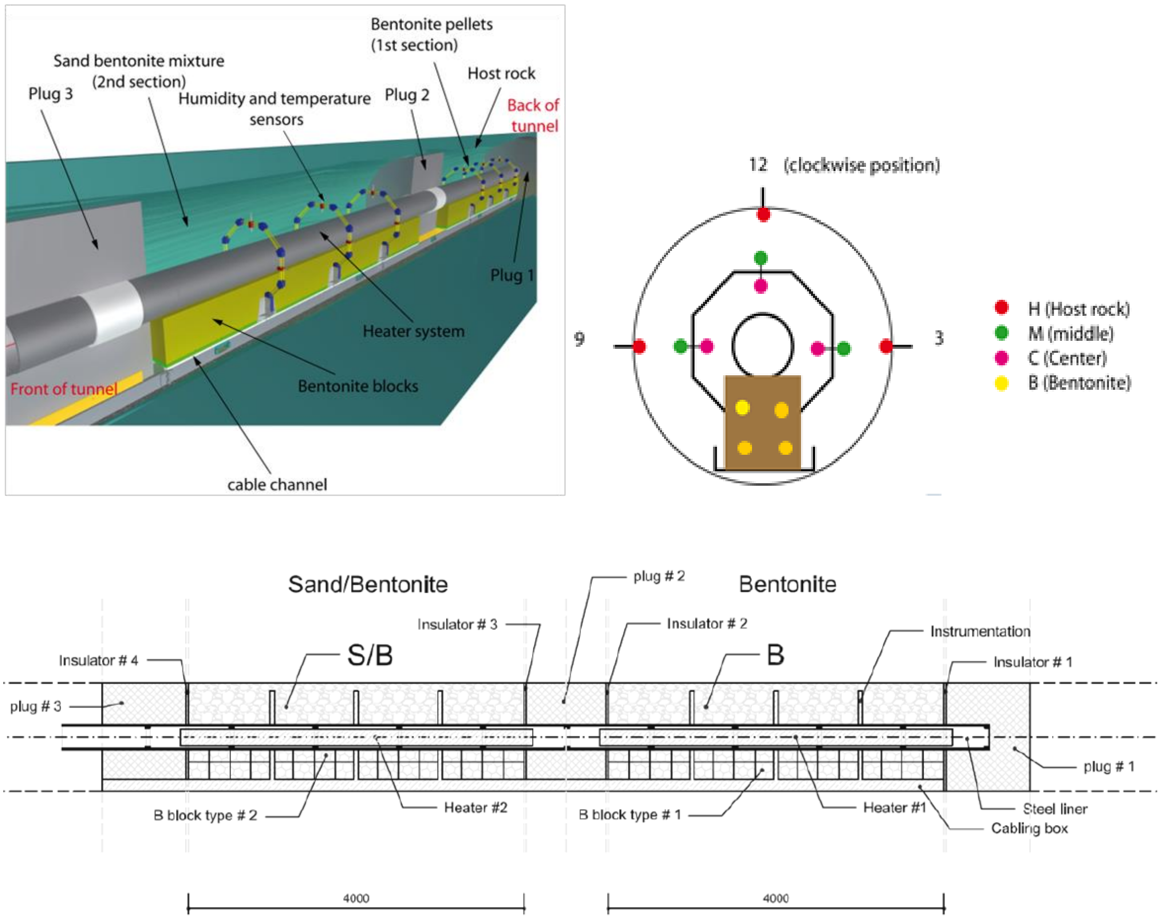

Figure 1. Schematic layout of the experiment

Extensive instrumentation has been used to monitor the progress of the test in the following locations: i) the heater surface where the temperature is controlled, ii) the engineered barrier and the interface with the Opalinus Clay (temperature and relative humidity), iii) the Opalinus Clay close to the microtunnel using the sensors from the VE test (temperature, humidity, water pressure and displacement), and iv) the Opalinus Clay at distances ranging from 2 to 6 meters from the microtunnel (pore pressures).

The heating stage started at the end of June 2011 and it is still ongoing at present as this experiment is intended as a long-term test. Heating power was gradually raised over a period of one year approximately until reaching a maximum temperature on the heater surfaces of 140ºC. From that moment on, heater power has been adjusted to keep this control temperature constant. Figure 2 shows the recorded evolution of maximum temperature and heater power. The observed difference between the two heaters is due to the different thermal conductivities of the two materials used for the engineered barriers. As an example of the monitoring data, Figure 3 shows the evolution of relative humidity in the granular bentonite section of the test. It can be observed the strong drying in the zones closer to the heater and the hydration close to the rock. This hydration is due to both water drawn from the Opalinus clay and the condensation of vapour migrating from the inner part of the buffer. Similar results are observed in the sand/bentonite section (Figure 4)

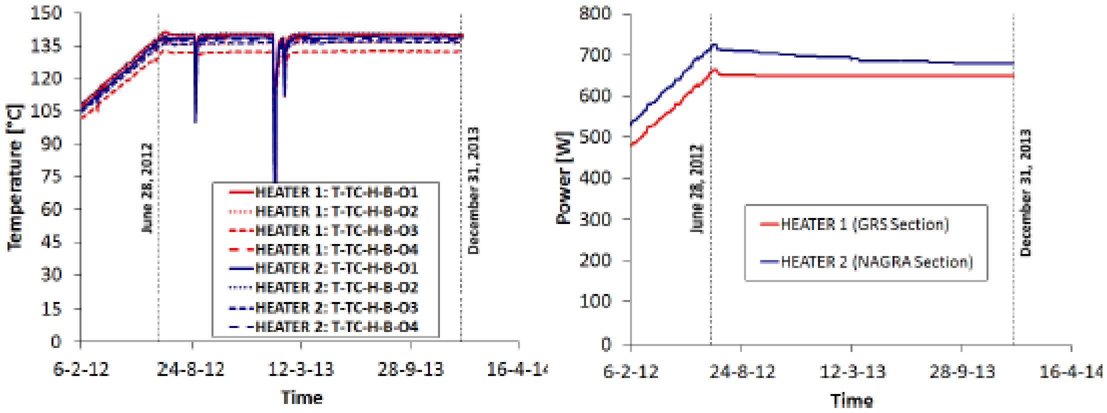

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Figure 2. Evolution of the maximum temperature and heater power in the experiment

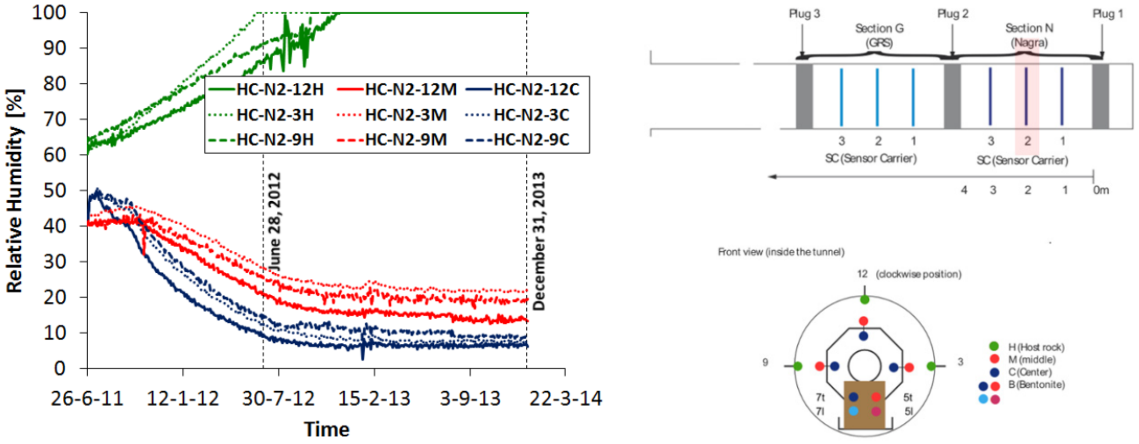


Figure 3. Evolution of relative humidity in the granular bentonite section of the test.

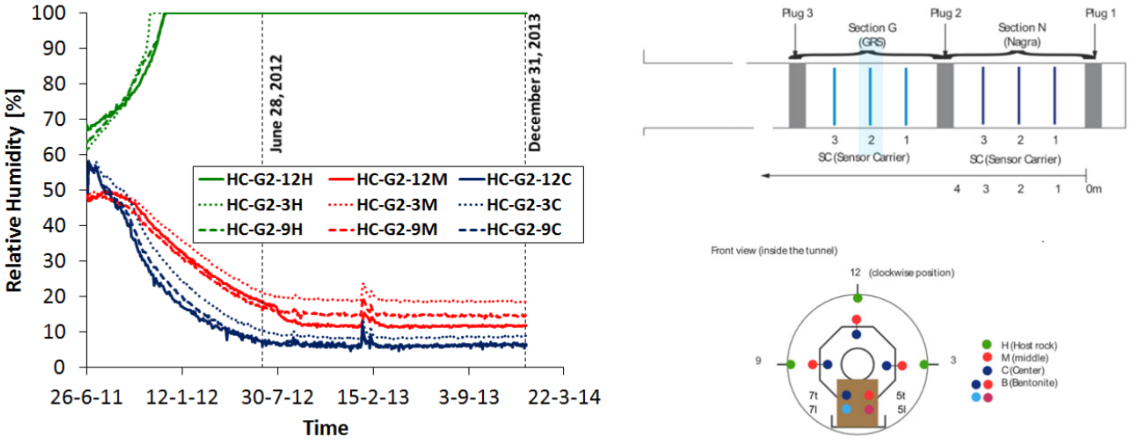


Figure 4. Evolution of relative humidity in the sand/bentonite section of the test.

Main learning points concerning bentonite homogenization / mechanical evolution and relevance for the project

This is potentially a very interesting test concerning the non-isothermal homogenization of the buffer under non-isothermal conditions. There are buffer-scale initial heterogeneities (granular bentonite-blocks, sand-bentonite mixture-blocks) whose evolution would be very interesting to examine. The fact that temperatures up to 140ºC have been reached in this experiment enlarge the scope of the temperature effects on homogenization.

In addition, there are local heterogeneities associated to the micro-macro porosity of granular bentonite that deserve to be tracked and studied. Unfortunately, since the test is not dismantled yet, no direct observations of the state of the barrier are or will be available in the near future.

How could this work inform a new experimental or modelling study in BEACON?

The two main materials used in this test (granular bentonite and sand-bentonite mixture) are being tested in Column Tests at CIEMAT. They should provide some information of the homogenization at small/meso scale. Perhaps undertaking additional laboratory tests on those materials could e contemplated in the design of WP4.

References (ideally with web links)

Gaus, I., Garitte, B., Senger, R., Gens, A., Vasconcelos, R., Garcia-Sineriz, J. L, T. Trick T., Wieczorek K., Czaikowski O., Schuster K., Mayor J.C., Velasco M., Kuhlmann U., Villar M.V. (2014). The HE-E experiment: Lay out, Interpretation and THM modelling. *Nagra Arbeitsbericht NAB 14-53,* 178 pp. Nagra, Wettingen, Switzerland. www.nagra.ch

http://www.nagra.ch/data/documents/database/dokumente/$default/Default%20Folder/Publikationen/NABs%202004%20-%202015/e_nab14-053.pdf

Recommendations for BEACON project

This is potentially an interesting test for BEACON as it involves several sources of heterogeneity (at buffer and local levels) that will evolve under a very high temperature field and strong thermal gradient. Unfortunately, no direct observation of the state of the barrier will be possible for a significant period. Some interesting information can be obtained, however, from the column cell tests carried out by CIEMAT on the same materials.

Project Acronym ITT (IsoThermal Test)	**Location** Lac du Bonnet URL	**Type** In situ
Lead organiser AECL	**Start date** 2002?	**End date** 6.5 years duration
Main partners involved in the project	**Characteristics of swelling clay** 50:50 sodium bentonite-silica sand buffer	**Water Saturation** Artificial/natural
Instrumentation Psychrometers (RH), total stress, displacements, water uptake	**Main elements related to homogenization**	**Interfaces with other material**
Modelling Yes/no: Yes Groups/Codes :	**Main processes studied** ☐T ☒H ☒M ☐Swelling pressure ☐Gas transfer ☐Other	**Reference concept if pertinent**

Main objectives of the experiment

To assess the behavior of a bentonite sand buffer when subjected to water infiltration.

General description

The ITT consisted of three types of solid materials: rock, buffer, and concrete. The buffer was installed within a borehole in the unfractured, homogeneous granite of AECL's URL and compacted in situ into the bottom 2m of the borehole. A concrete plug overlaid the buffer to provide a vertical constraint against swelling.

At the completion of the experiment, intensive sampling of the gravimetric water content and dry density of the buffer was conducted. A number of psychrometers were installed inside the buffer to monitor the changes of the relative humidity. The spatial measurements of the total stress in the buffer and the displacements at the top of the concrete were also measured during the test.

Main learning points concerning bentonite homogenization / mechanical evolution and relevance for the project

How could this work inform a new experimental or modelling study in BEACON?

References (ideally with web links)

Priyanto D. G., Blatz J. A., 2008. Modelling AECL's Isothermal Test using a porosity dependent permeability (kwn) model and an elastoplastic model. GeoEdmonton'08.

Recommendations for BEACON project

Project Acronym Lasgit	**Location** Äspö	**Type** Field scale mock up
Lead organiser SKB	**Start date** 1st February 2005	**End date** Ongoing
Main partners involved in the project SKB, Andra, Posiva, RWM, BGS, BGR, GRS, JNC, ENRESA	**Characteristics of swelling clay** Mx80 bentonite	**Water Saturation** Artificial and natural
Instrumentation 164 sensors • Pore pressure • Total stress • Relative humidity • Temperature • displacement	**Main elements related to homogenization** Full-scale mock-up with bentonite blocks and pellets	**Interfaces with other material** Bentonite/copper bentonite/granodiorite
Modelling Yes/no: limited Groups/Codes : UPC BGS	**Main processes studied** ☐T ☒H ☒M ☒Swelling pressure ☒Gas transfer ☐Other	**Reference concept if pertinent** KBS-3V

Main objectives of the experiment or modelling study

In the Swedish KBS-3 repository concept for spent nuclear fuel, copper/steel canisters containing spent fuel will be placed in large diameter (~1.8m) boreholes drilled into the floor of the repository tunnels. The space around each canister will be filled with pre-compacted bentonite blocks, which over time, will draw in the surrounding groundwater and swell, closing up any remaining construction gaps. While the copper/steel canisters are expected to have a very substantial life, from a performance assessment perspective, it is important to consider the possible impact of groundwater penetrating a canister. Under certain conditions corrosion of the steel insert of each canister will lead to the formation of hydrogen. Radioactive decay of the waste and the radiolysis of water will produce some additional gas. Depending on the gas production rate and the rate of diffusion of gas molecules in the pores of the bentonite, it is possible that gas will accumulate in the void-space of each canister. Lasgit (large scale gas injection test) is a full-scale demonstration experiment operated by SKB at the Äspö Hard Rock Laboratory at a depth of 420m. The objective of Lasgit is to provide quantitative data on the hydration of the clay (under ambient conditions), hydraulic permeability and gas migration behaviour, to improve process understanding and test/validate modelling approaches and thereby inform performance assessment activities.

General description

The Lasgit experiment has been commissioned in deposition hole number DA3147G01; the first emplacement borehole to be drilled at the Äspö Hard Rock Laboratory (HRL). The experiment is located within the Tunnel Boring Machine (TBM) assembly hall which is situated on the 420m-level of the tunnel system. The deposition hole has a length of 8.5 m and a diameter of around 1.75 m. A full scale KBS-3 canister has been modified for the Lasgit experiment with twelve circular filters of varying dimensions located on its surface to provide point sources for gas injection, mimicking potential canister defects. These filters can also be used for water injection.

Deposition hole DA3147G01 was constructed in 1999 using a specially made vertically drilling Robbins TBM. Soon after completion the hole was geologically mapped in detail from a cage hooked up to a lift. The result of the detailed fracture mapping of the deposition hole is shown in Figure .

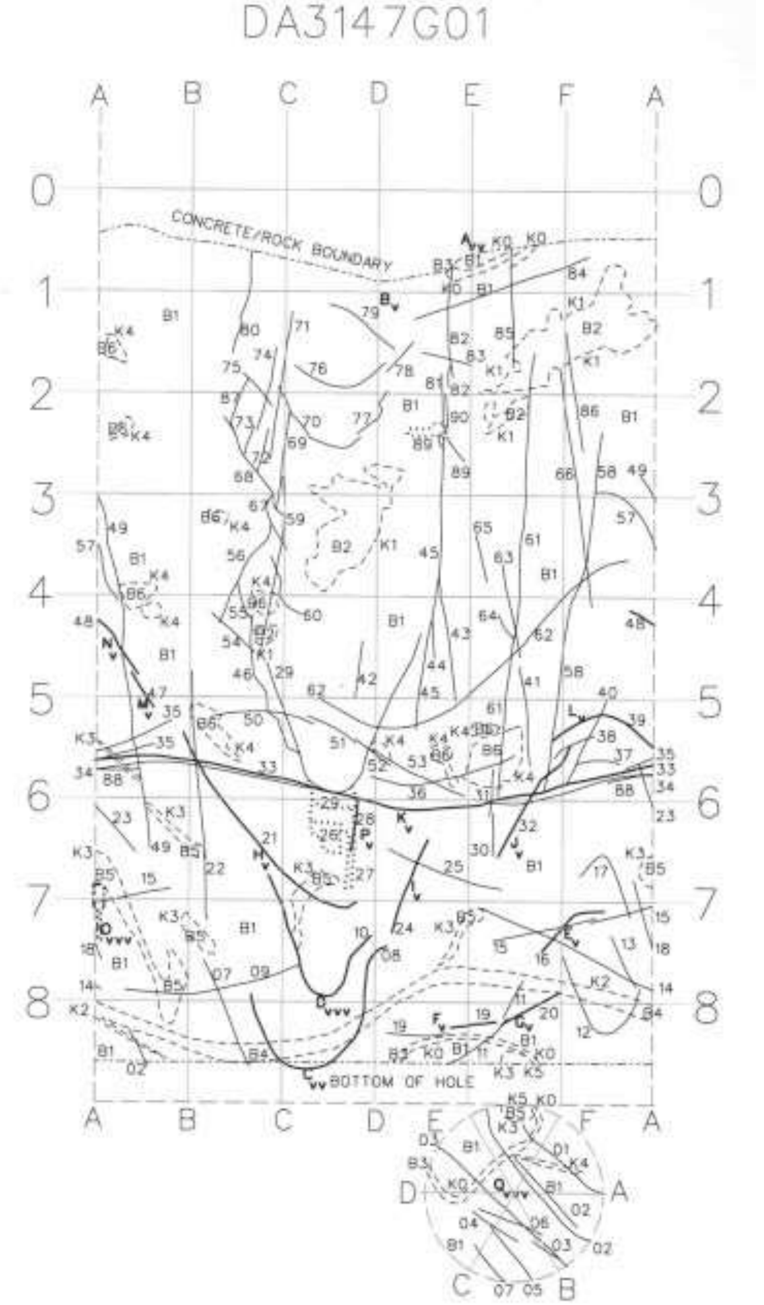


Figure 1 Geological mapping of the deposition hole DA3147G01. Legend: Rock types: B1 = Äspö diorite, greyish and medium-grained with feldspar megacrysts; B2 = greenstone xenolith, black and fine-grained, includes some B1 and B4; B3 = "fine-grained" granite, greyish red and medium-grained; B4 = pegmatite, red and coarse-grained; B5 = "fine-grained" granite – hybrid of B1 and B3, greyish red and medium grained; B6 = greenstone xenolith, black and fine-grained. Contacts: K0-K5 and dashed line; K0 = contact between B1 and B3; K1 = contact between B1 and B2; K2 = contact between B1 and B4; K3 = contact between B1 and B5; K4 = contact between B1 and B6; K5 = contact between B5 and B3. Fractures: 01-90 and continuous line (thick lines represent water bearing fractures). Water: A-Q and v = damp-minor seepage, occasional drops; vv = wet-seepage, drops or minor flow; vvv = flow.

Table summarises the occurrence of the rock types. It is shown as the estimated area of rock type exposure and in percentage of total mapped area. About 50% of the contacts are tight and sharp. These are the ones between Äspö diorite and pegmatite, Äspö diorite and the fine-grained granite (in its "pure" state) and Äspö diorite and greenstone xenoliths (without any admixture of Äspö diorite or pegmatite). The boundaries between Äspö diorite and the impure greenstone xenolites, the Äspö diorite and the hybrid variety of fine-grained granite as well as the boundaries between the latter and the "pure" variety are on the other hand diffuse.

Rock type	Area (m²)	% of mapped area (hole wall and bottom 48 m²)
Äspö diorite	40.8	85
Greenstone	3.36	7
Fine grained granite	2.4	5
Pegmatite	1.44	3
Total	48	100

Table 1 Rock type distribution in deposition hole DA3147G01.

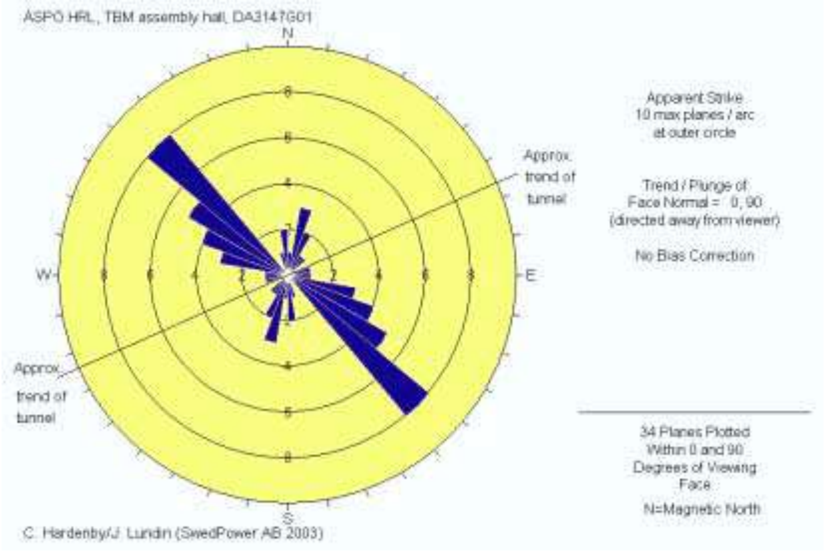


Figure 2 Fracture orientations (partly compass readings and partly graphical interpretation) from DA3147G01 presented in Schmidt net and joint rosette diagrams.

The fracture orientations are presented in Schmidt net and joint rosette diagrams in Figure 2, which shows two major fracture sets. One of them is rather steeply dipping and has a mean orientation of approximately 120˚/75˚ (strike/dip right). The other is gently dipping with a mean orientation of 195˚/20˚. Most of the fractures (57%) in the deposition hole were found to be natural, most probably formerly healed and tight fractures, that now are more or less re-opened due to the drilling of the hole. Twenty-nine percent were healed and tight fractures and 14% were truly open natural fractures. **More information on geology, fracture connectivity, borehole edz properties and inflow rates to the hole can be found in Cuss et al. (2008).**

The deposition hole, buffer and canister are equipped with instrumentation to measure the total stress, porewater pressure and relative humidity in 32, 26 and 7 positions respectively. Additional instrumentation continually monitors variations in temperature, relative displacement of the lid and the restraining forces on the rock anchors. The emplacement hole has been capped by a conical concrete plug retained by a reinforced steel lid capable of withstanding over 5000 tonnes of force. Figure Fel**! Ingen text med angivet format i dokumentet.** shows a photograph of the test site following the installation stage.

Figure ***Fel! Ingen text med angivet format i dokumentet.*** *A panoramic view of the Large-scale gas injection test (Lasgit) 420m below ground at the Äspö Hard Rock Laboratory in Sweden.*

Lid and retaining system

The pressure that would be exerted by the backfill as the tunnel gallery was closed is generated using a heavy 2600 mm diameter SS2172 carbon steel lid; this also prevents an uncontrolled expansion of the bentonite. At the top of the buffer a waterproof and sealed rubber mat is placed, upon which a conical shaped concrete plug was poured using K40 quality concrete (Bäck, 2003) to close the deposition hole, the top of which was level with the TBM assemble floor. On top of this plug, the steel lid was anchored to the rock by 10 anchor cables, Figure **Fel! Ingen text med angivet format i dokumentet.**.

The retaining system (i.e. concrete plug, steel lid and anchoring cables) is designed for a maximum operating pressure of 20 MPa. The rationale in using a conically shaped concrete plug is to (a) ensure that the plug can move upwards when subject to high axial pressures and (b) can be readily dismantled at the end of testing. The anchor system comprises cables of type VSL 19-15, which are secured using a low-pH cementitious injection grout within ten holes of 162 mm diameter, 11 m length, and angled at 21.8° from the deposition hole. Each cable is grouted for 8 m length of the cable to ensure the anchors can accommodate the forces which will be generated during testing. The retaining system is also design to allow small vertical deformations of the concrete plug and steel lid when subject to high axial forces. The anchor cables holding the lid were pre-tensioned to 1300 kN using two hydraulic jacks in parallel. Three of the anchors include Glötzel load cells of type kN 5000 A160 M/DKV6, with a maximum load 5500 kN. These are used to log load on the rock anchors, and thus the load exerted by the buffer, during the operation of the test.

Canister and filter array

The canister used in Lasgit is a standard KBS-3 design, with additional filters. This design consists of a 50mm thick outer copper skin, which acts as a corrosion barrier in the oxygen-poor groundwater of the crystalline rock selected for disposal, and a nodular iron insert to provide strength and rigidity. Each canister weighs up to 27 tonnes (including the fuel rod assemblies), is 4.835 metres long and has a diameter of 1.05 metre.

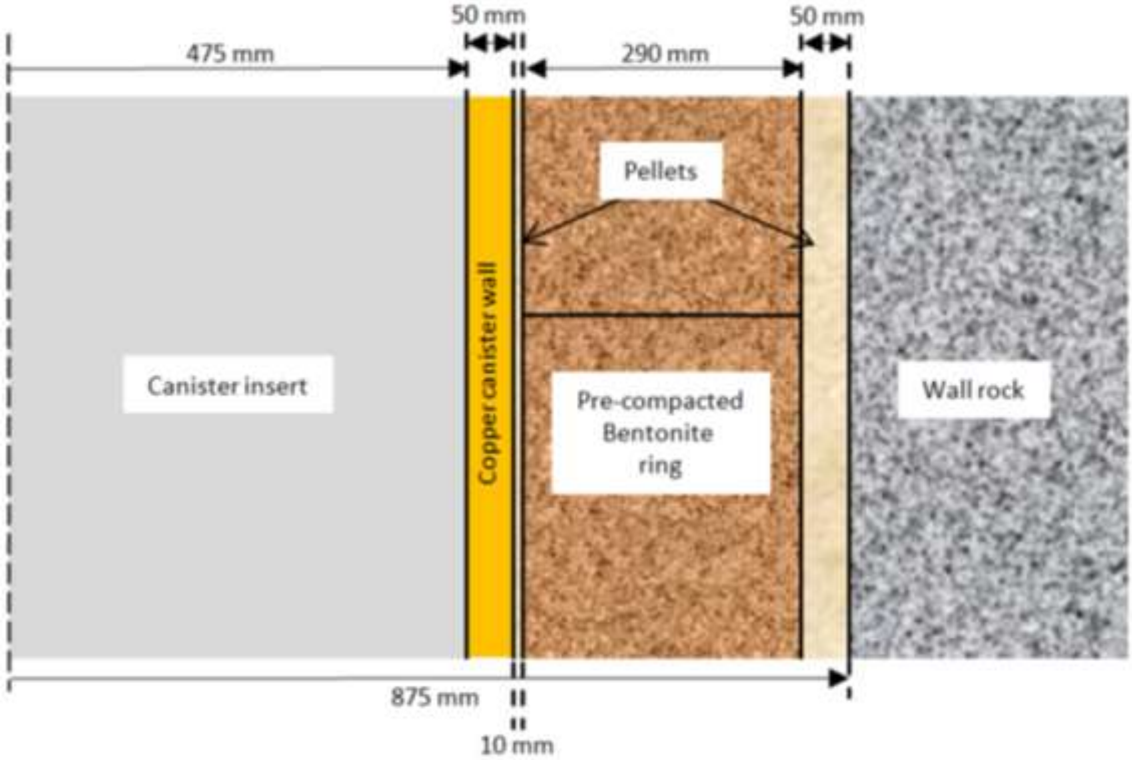


Figure 4 Cross-section sketch through the Lasgit deposition hole. Surrounding the copper canister is a 290 mm thick annulus of pre-compacted bentonite. This leaves a 10 mm gap on the inside between the bentonite and canister and a 50 mm gap between the bentonite and the wallrock, which is filled with bentonite pellets.

Figure shows a sketch cross-section through the deposition hole, giving dimensions of the individual elements of the KBS-3V concept. The space around the canister is filled with pre-compacted bentonite blocks, which, once hydrated, acts as a low permeability diffusional barrier. The bentonite used is MX-80 (Johannesson, 2003) with a water content of 22 % (for the ring-shaped blocks) and 26 % (for the cylindrical blocks). The space between the bentonite rings and wall-rock was in-filled using bentonite pellets, manufactured by Saut-Conreursin in France. Each pellet is pressed from bentonite and has dimensions of 16.3 × 16.3 × 8.3 mm, a water content of about 17 % and an expected density of a single pellet of about 2050 kg.m^{-3}. The expected bulk density of the fillings is approximately 1230 kg.m^{-3}. Table 2 shows the dimensions and starting physical properties of the pre-compacted bentonite rings. As shown, a high degree of saturation (between 95.1 % and 99.7 %) was achieved, with bulk densities ranging between 2018 kg.m^{-3} and 2061 kg.m^{-3}.

A series of filters were added to the canister surface in order to simulate a point defect perforation of the canister. A filter was also added to the bottom of the canister to look at the impact of the energy stored within a large volume of gas and its impact on the mechanisms of gas entry and movement. To help maintain structural integrity and strength of the canister, the diameter of the filter assemblies were minimised, in order to retain as much of the original canister material as possible. The rigidity of the canister was enhanced by securing each filter assembly with 8 Monel cap-screws, tensioned uniformly to apply an even load. Each filter array was designed with dual ports to facilitate the removal of test permeants and "sweeping" of the sintered filter. The size of the filter discs installed in each housing have been varied to examine the effect of gas pressure gradient on the gas entry pressure (Table Fel**! Ingen text med angivet format i dokumentet.**). Figure 5 shows a schematic layout of instrumentation at each horizon along the deposition hole. Also shown are the positions (marked in blue) of the artificial filter mats used to increase the rate of hydration.

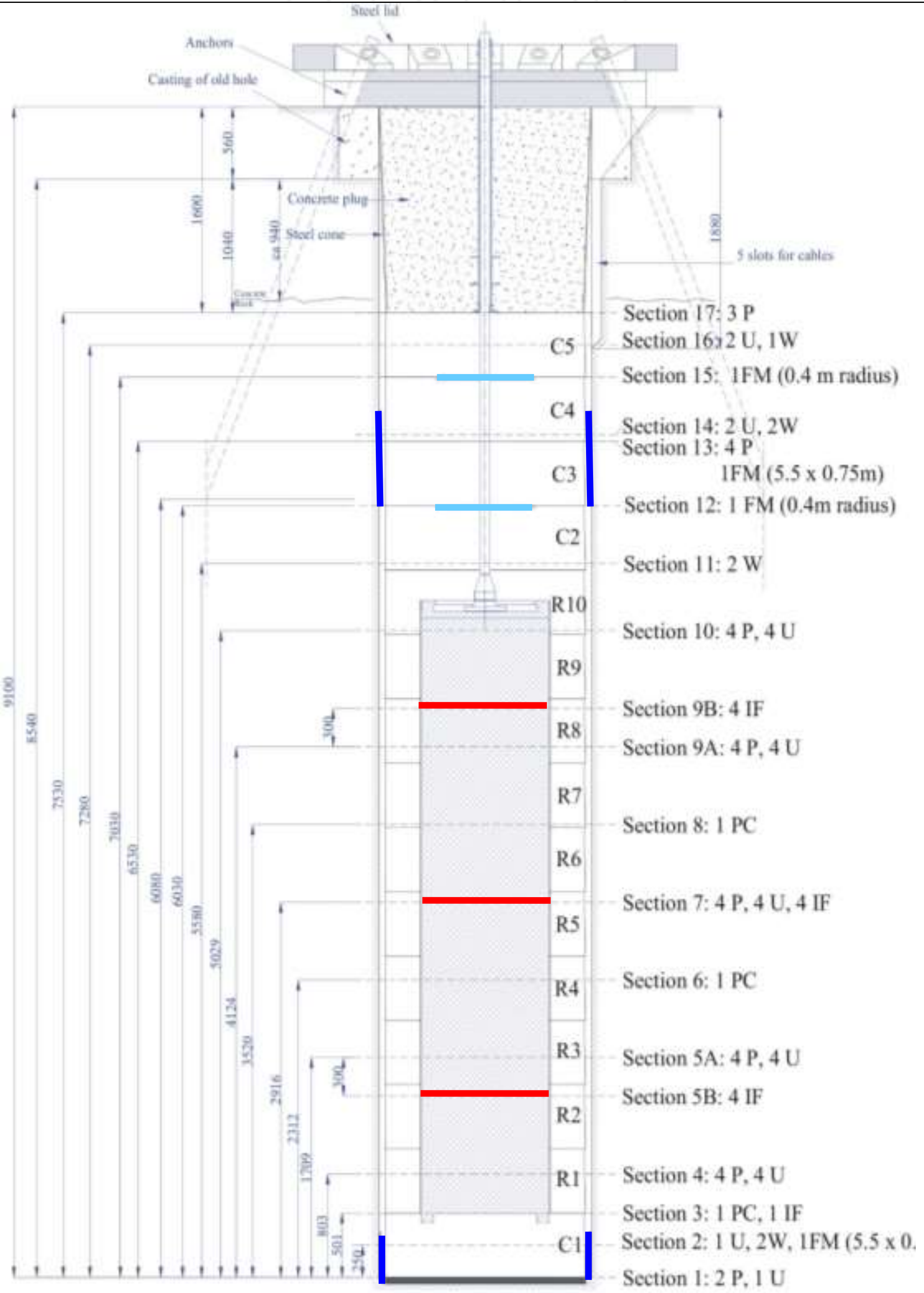


Figure 5 Schematic representation of borehole infrastructure taken from the R4 Report by Sandén (2003). Cartesian coordinates and a description of each sensor is included in the R4 report ("P" signifies a total pressure cell, "U" a pore pressure cell, "W" a relative humidity sensor, "PC" a total pressure on canister, "FM" a filter mat and "IF" an injection filter). The dark and light blue lines respectively highlight the position of filter mats bolted to the rock surface and those located between bentonite blocks. The red lines show the planes along which the canister filters are positioned.

Block No.	Date at Comp.	Block No In deposition hole	Moisture content	Bulk density (kg/m3)	Degree of Saturation	Void ratio	Dry density (kg/m3)	Dens at sat (kg/m3)	Weight (kg)	Height (mm)	Diam. D1 (mm)	Diam. D2 (mm)	Diam. D3 (mm)
LASC1	16/09/2003	Extra block	0.265	2018.1	0.993	0.743	1594.9	2021.2	2140.0	507.4	1623.3	1639.3	0
LASC2	17/09/2003	C1	0.264	2015.2	0.986	0.743	1594.8	2021.2	2112.0	501.4	1623.5	1639.35	0
LASC3	17/09/2003	C2	0.262	2020.4	0.989	0.736	1601.2	2025.2	2116.0	501.0	1623.45	1639.4	0
LASC4	18/09/2003	C3	0.261	2017.4	0.984	0.738	1599.9	2024.4	2096.0	496.9	1623.75	1639.45	0
LASC5	18/09/2003	C4	0.268	2017.9	0.997	0.746	1592.0	2019.3	2116.0	501.6	1623.7	1639.45	0
LASC6	19/09/2003	C5	0.260	2020.9	0.986	0.733	1604.0	2027.0	2114.0	500.5	1623.45	1639.3	0
LASR1	23/09/2003	Extra block	0.225	2055.5	0.951	0.656	1678.6	2074.8	1268.0	516.7	1625.25	1639.65	1070
LASR2	25/09/2003	R1	0.230	2050.2	0.958	0.668	1666.6	2067.1	1248.0	509.4	1625.6	1639.65	1069.6
LASR3	25/09/2003	R2	0.226	2054.1	0.953	0.659	1675.2	2072.6	1236.0	504.3	1624.8	1639.7	1070
LASR4	25/09/2003	R3	0.227	2059.6	0.962	0.656	1678.6	2074.8	1234.0	501.9	1624.75	1639.65	1069.7
LASR5	26/09/2003	R4	0.232	2057.0	0.970	0.665	1669.8	2069.2	1234.0	502.5	1624.95	1639.4	1069.5
LASR6	26/09/2003	R5	0.228	2059.7	0.964	0.657	1677.6	2074.2	1236.0	502.6	1624.9	1639.6	1069.6
LASR7	29/09/2003	R6	0.233	2058.4	0.974	0.665	1669.3	2068.9	1236.0	502.6	1625	1639.5	1069.2
LASR8	29/09/2003	R7	0.228	2050.8	0.953	0.664	1670.3	2069.5	1224.0	499.8	1625	1639.6	1069.5
LASR9	29/09/2003	Extra block	0.224	2060.6	0.956	0.651	1683.4	2077.9	1246.0	506.1	1624.75	1639.6	1069
LASR10	30/09/2003	R8	0.228	2054.1	0.957	0.661	1673.4	2071.4	1228.0	500.3	1624.85	1639.7	1069
LASR11	30/09/2003	R9	0.227	2061.4	0.964	0.655	1679.9	2075.6	1238.0	502.7	1625.25	1639.45	1069.3
LASR12	30/09/2003	R10	0.227	2061.1	0.964	0.655	1679.5	2075.3	1236.0	502.3	1625	1639.5	1069.2
Average LASC			0.263	2018.3					2115.7	501.4	1623.5	1639.4	0.0
Average LASR			0.228	2056.9					1238.7	504.3	1625.0	1639.6	1069.5

Table 2 Properties and dimensions of the bentonite buffer.

Device name	Location	Units	Description	Dimensions (mm)		
				Height	Width	Radius
AXG0FR901	Rock wall	kPa	Pressure in filter mat 1	350	5500	

Main learning points concerning bentonite homogenization / mechanical evolution and relevance for the project

The development of water pressure, stress and saturation do not evolve in a similar manner, even under ambient thermal conditions. Because of the stiffness of the bentonite, the localised development of stress can be transmitted through the clay generating reflected stresses. The development of porewater pressure within the clay, significantly lags behind that of stress indicating the system, even after 12 years of operation, remains in hydraulic disequilibrium, resulting in the heterogeneous development of swelling pressure. Because of the level of information, from the hydrogeological description of the hole and its fractures, to the high level of instrumentation and careful experimental activities, Lasgit represents a unique isothermal dataset against which models can be verified and or developed.

How could this work inform a new experimental or modelling study in BEACON?

See box above. The high level of instrumentation combined with detailed initial characterisation of the host rock and bentonite fill, allow boundary conditions to be well-defined prior to the start of hydration. The isothermal (ambient) nature of Lasgit also removes the thermal component of the hydromechanical response which will simply modelling and provide a way to benchmark/verify numerical codes before moving to more complex tests involving heated phases.

References (ideally with web links)

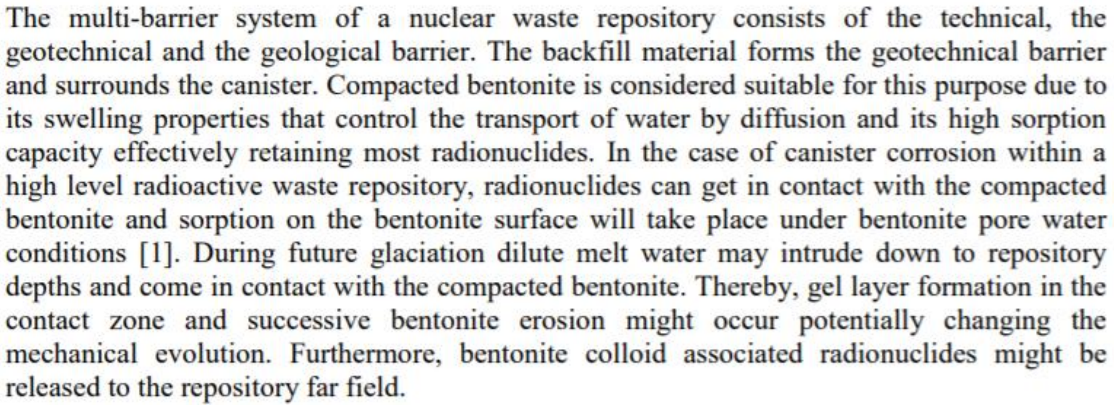
1. Cuss, R.J., **Harrington, J.F.**, and Noy, D.J. (2008) Large scale gas injection test (Lasgit) performed at the Äspö Hard Rock Laboratory: Summary report 2008. *British Geological Survey Commissioned Report,* CR/08/173. 123p.

Recommendations for BEACON project

The processes observed in the Lasgit experiment have also been seen in other field tests and smaller scale laboratory tests. Significant modelling work has already been undertaken to tackle these complex dataset with only limited success. At present the underlying physics of the problem remain poor understood, and benchmark/calibration tests are therefore required to further elucidate these processes. Without this information, it is difficult to see how meaningful development of the numerical codes, based on the phenomenology of the hydration process, can occur.

Project Acronym LIT (Long-term In-situ Test)	**Location** Grimsel Test Site	**Type** In situ
Lead organiser KIT/INE, NAGRA, Fracture Systems Ltd.	**Start date** May 2014	**End date**
Main partners involved in the project	**Characteristics of swelling clay** 12 pure Febex bentonite rings, 4 rings admixed with synthetic Zn-bearing montmorillonite	**Water Saturation** natural
Instrumentation pH, conductivity, swelling pressure, fluorescence of conservative tracer, volumetric flow velocity	**Main elements related to homogenization**	**Interfaces with other material**
Modelling Yes/no: Yes Groups/Codes :	**Main processes studied** ☐T ☒H ☒M ☐Swelling pressure ☐Gas transfer ☐Other	**Reference concept if pertinent**

Main objectives of the experiment



The multi-barrier system of a nuclear waste repository consists of the technical, the geotechnical and the geological barrier. The backfill material forms the geotechnical barrier and surrounds the canister. Compacted bentonite is considered suitable for this purpose due to its swelling properties that control the transport of water by diffusion and its high sorption capacity effectively retaining most radionuclides. In the case of canister corrosion within a high level radioactive waste repository, radionuclides can get in contact with the compacted bentonite and sorption on the bentonite surface will take place under bentonite pore water conditions [1]. During future glaciation dilute melt water may intrude down to repository depths and come in contact with the compacted bentonite. Thereby, gel layer formation in the contact zone and successive bentonite erosion might occur potentially changing the mechanical evolution. Furthermore, bentonite colloid associated radionuclides might be released to the repository far field.

General description

In the course of the Colloid Formation and Migration experiment (CFM) a bentonite source was emplaced in the migration shear zone at the Grimsel Test Site (GTS) in May 2014. The bentonite source consists of 12 pure Febex bentonite rings plus 4 rings that are admixed with synthetic Zn-bearing montmorillonite [2, 3] and located in the contact-zone with the fracture. Each ring has an inner and outer diameter of 43 and 82 mm, respectively. The ring height is 25 mm. The purpose of LIT is to investigate the evolution of a compacted bentonite source in-situ concerning bentonite swelling, erosion, interaction with radionuclides and mobility of the eroded material. Hydrogeological conditions are controlled and monitored constantly regarding volumetric flow velocity, pH, Eh, conductivity, swelling pressure of the bentonite source and fluorescence signal of a conservative tracer in the contact water. Water is sampled via surface packers from the outcrop of the shear zone at the tunnel wall (distance: ~ 5.7 m) as well as from observation boreholes close to the bentonite source (distance: ~5 cm, Figure 1).

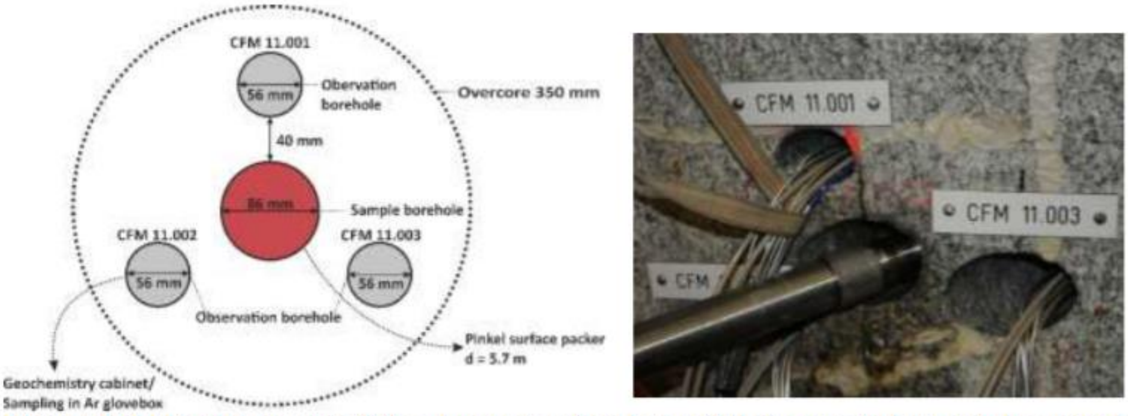


Figure 1: LIT arrangement of the observation boreholes (filled grey circles) and the central borehole (marked in red color. A schematic overview (left) and a picture of the site (right) is shown. The bentonite source is located in the central borehole and the surrounding boreholes (CFM 11.00X) are for near-field monitoring and sampling. Overcoring and retrieval of the source is currently planned for early 2018.

Four total pressure sensors are implemented in the source packer system to measure the swelling pressure evolution of the expanding bentonite source in contact with the water conducting feature of the MI shear-zone. Swelling pressure evolution is shown in Figure 2. Two sensors are installed on the lower interface between the packer and the bentonite source (TP_3 and TP_4) and two on the upper interface (TP_1 and TP_2) and two pore pressure sensors, one on each end of the packer. Total pressure rises immediately after the installation of the packer system and reaches steady state on all pressure sensors within 20 days. Values of 900 ± 100 kPa are obtained on both sensors at the lower end of the sample and stable over the total experimental duration of currently approx. 1200 days. Both pressure sensors measure very comparable values indicating homogeneous swelling in this region. Higher total pressure in the order of 1.4 (TP_2) to 1.9 MPa (TP_1) is obtained on the upper side of the packer. Both installed total pressure sensors give different values indicating inhomogeneous swelling or some kind of friction, preventing compensation of the swelling pressure between the sensors.

The values remain constant until a pressure release occurred at TP_1 after 520 days. Thereby part of the pressure is released and a new equilibrium is established within 25 days at 1.5 MPa. Total pressure on TP_2 remains constant during the drop on TP_1. Pore pressure is constant on both sensors at 300 kPa during the entire experimental time. Total pressure is the sum of pore pressure and swelling pressure, leading to swelling pressure values of 600 kPa on the lower packer end and 1.1 to 1.6 MPa on the upper packer end. Concerning the initial dry density of the bentonite source, which is 1.65 g/cm^3, one would expect much higher swelling pressure in the order of 6 MPa [4]. Swelling pressure in LIT is significantly lower as (a) the bentonite source is of limited size and (b) for radioprotection reasons a removable protective sleeve had to be installed leading to a gap between the bentonite and the tunnel wall of approximately 2-3 mm. The gap adds an additional volume of 16 to 21% to the compacted sample. Thereby, the effective dry density is decreasing to only 1.37 to 1.45 g/cm^3. Swelling pressures of 900 to 1100 kPa are expected according to Agus et al. [4] for this Febex bentonite dry density.

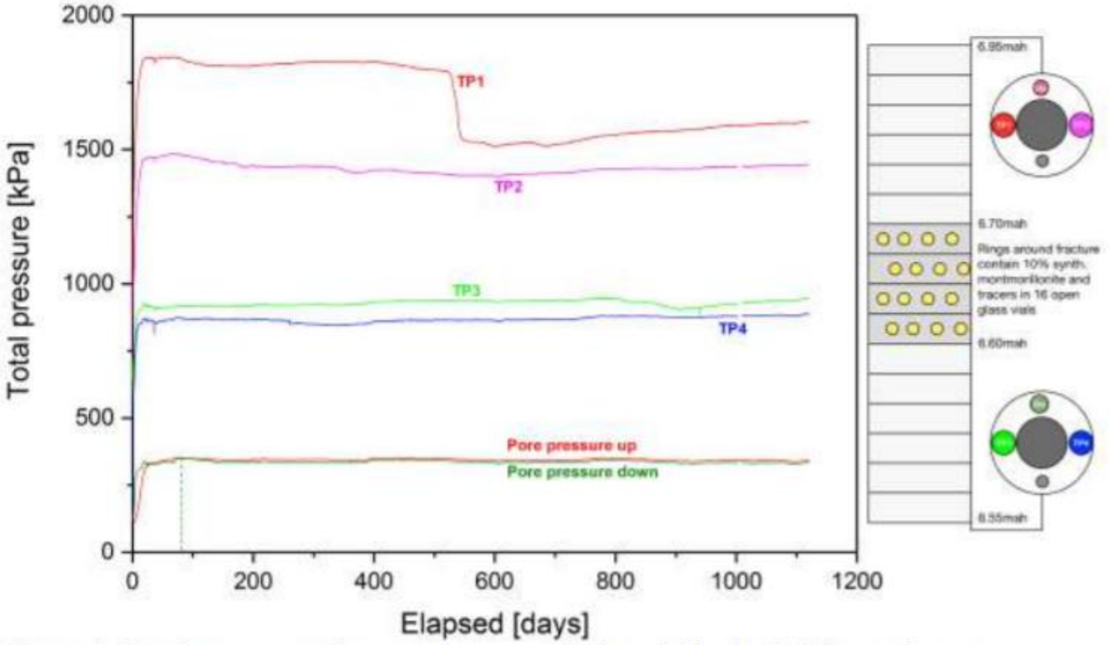


Figure 2: Total pressure and pore pressure evolution within the LIT bentonite source.

Complementary to LIT, bentonite erosion mock-up tests have been installed in the laboratory. The artificial horizontal parallel plate fracture set-up with a fracture height of 1 mm consists of an acrylic glass housing that can hold ring-shaped bentonite samples (Figure 3). Dimensions of the sample is identical to LIT but the artificial fracture set-up only holds one bentonite ring in comparison to the 16 rings within LIT. Tests were conducted with pure Febex bentonite at a dry density of 1.65 g/cm^3 and Zn-montmorillonite doped Febex bentonite identical to the rings installed in the LIT installation with an effective dry density of ~1.5 g/cm^3 because the sample was already broken and missing parts had to be filled with pulverized bentonite of the same composition. In contact with natural groundwater from GTS used for these experiments [5], the sample starts to expand into the fracture as it saturates.. Swelling distances and pressure evolution are depicted in Figure 4. Pressure is measured on top of the bentonite sample.

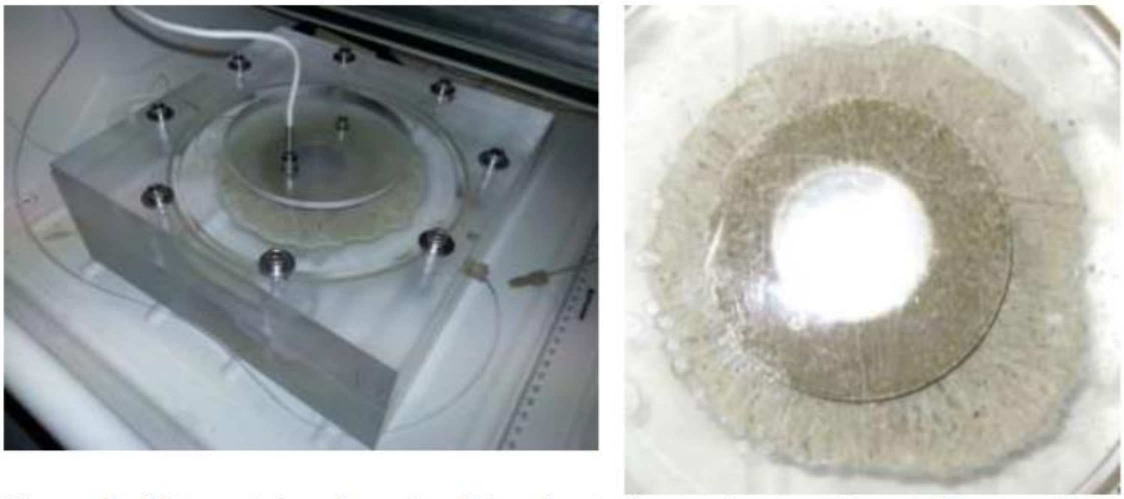


Figure 3: Pictures taken from the Febex bentonite erosion experiment. The experimental layout with the pressure sensor on top of the sample (left) and the swelling of the sample after ~20 days (right).

Under the given dry densities of 1.5 and 1.65 g/cm^3, swelling pressure of 2 MPa and 6 MPa is expected [4] for constant volume conditions, but only in the initial phase a peak swelling pressure of ~2.5MPa is measured for pure Febex bentonite. The swelling pressure decreases afterwards to constant values of only 0.4 and 1.7 MPa (Figure 4), respectively. The difference between the literature and experimental data can be explained by the swelling pressure release due to expansion to fill the sample mold and intrusion of the bentonite into the open 1mm fracture. Thereby the sample volume increases and the density reduces in return, leading to lower pressure values in comparison to the literature data which assume constant volume conditions. The swelling distance into the fracture is obtained by taking pictures regularly. The distance is proportional to the bentonite dry density. In the case of the pure Febex sample, the sample expanded over three weeks into the fracture to reach a steady state distance of 18.0 mm. The Zn-montmorillonite admixed sample with lower density reaches steady state swelling distances within two weeks at only 10.5 mm.

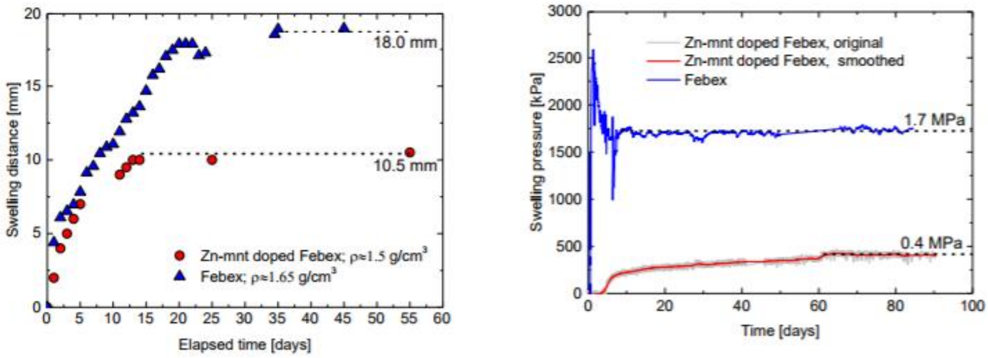


Figure 4: Swelling distance (left) and pressure evolution (right) in the artificial horizontal fracture experiments.

Currently, to overcome the rather low swelling pressures of the LIT (0.6-1.6 MPa), the small scale (86 mm borehole) and low flowrate likely to be dominated by a single fracture (gouge filled?) limiting extrusion/colloid generation the CFM consortium plans the I-BET experiment. The intention is to extend the CFM dataset and support integration with lab results by focusing on higher swelling pressure (higher effective density) and higher "erosion" rates.

Main learning points concerning bentonite homogenization / mechanical evolution and relevance for the project

How could this work inform a new experimental or modelling study in BEACON?

References (ideally with web links)

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3. Reinholdt, M., et al., *Hydrothermal Synthesis and Characterization of Ni-Al Montmorillonite-Like Phyllosilicates.* Nanomaterials, 2013. **3**(1): p. 48.
4. Agus, S.S. and T. Schanz, *A method for predicting swelling pressure of compacted bentonites.* Acta Geotechnica, 2008. **3**(2): p. 125-137.
5. Schäfer T., N.U., *Colloid/Nanaparticle formation and mobility in the context of deep geological nuclear waste disposal (Project KOLLORADO-1; Final Report)*, in *Wissenschaftliche Berichte*, F. Karlsruhe, Editor 2010, INE: Karlsruhe.

Recommendations for BEACON project

Mock-Up Josef

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Project Acronym MCJ (Mock-Up Josef)	**Location** Josef URL, Czech Republic (granodiorite)	**Type** Field-scale experiment Scale ½ (diameter 720mm, length 2230mm)
Lead organiser SÚRAO / CTU	**Start date** December 2012	**End date** In progress
Main partners involved in the project SÚRAO (Radioactive Waste Repository Authority, Czech Republic) CTU (Czech Technical University in Prague)	**Characteristics of swelling clay** B75 (Czech Ca-Mg bentonite from the Černý vrch deposit) - initial water content: 8% Pre-compacted blocks (dry density: 1.75Mg/m^3) Powder (dry density: 1.0Mg/m^3)	**Water Saturation** Natural (Josef URL groundwater)
Instrumentation 105 sensors • temperature • total pressure • relative humidity	**Main elements related to homogenization** Initial heterogeneity of density: • Zones filled with compacted bricks and zones filled with powder • Initial gaps	**Interfaces with other materials** Bentonite / granodiorite Bentonite / copper Bentonite / steel Bentonite / stainless steel
Modelling Yes/no: no modelling was performed Groups/Codes	**Main processes studied** ☒T ☒H ☐M ☒Swelling pressure ☐Gas transfer ☐Other	**Reference concept if pertinent**

Main objectives of the experiment or modelling study

The Mock-Up Josef project is the first in-situ experiment to simulate a vertical storage container surrounded by a bentonite barrier in a real natural environment made up of granitoid rocks to be conducted in the Czech Republic. The bentonite barrier in the experiment is exposed to the effects of groundwater and, simultaneously, thermal load is provided by a heating element simulating the emission of heat from spent nuclear fuel contained in a storage cask.

The main objective is to study the behavior of the bentonite barrier under repository conditions with particular concern to temperature development, hydration and changes in the various geotechnical and geochemical/mineralogical parameters (by means of sampling).

General description

The Mock-Up Josef experiment was built in the form of a supercontainer (see Figure 1) and consists of:

- Bentonite barrier: A total of around 280 bentonite segments each with a height of 67mm in 33 layers. The technological gap between the blocks and the heater (27.5mm) was filled with powdered bentonite and crushed blocks. The technological gap between the blocks and the stainless steel mesh was filled with powdered bentonite and crushed blocks (10mm) and the gap between the stainless steel mesh and the rock (15mm+/-10mm) was filled to approx. 30% with silica sand.
- Heater: the heater consists of a hollow high-grade steel cylinder with a diameter of 320mm and a height of 1300mm. The heater was covered with copper sheeting and positioned during model construction upon the sixth layer of bentonite blocks. Oil is used as the heat-transferring medium and heat is provided by two 2000W heating spirals installed inside the cylinder.
- Temperature of the heating medium: 100˚C (surface of the heater 90˚C)
- Instrumentation: 105 sensors were installed inside the bentonite body (65 thermometers, 37 hydraulic pressure cells and 3 relative humidity sensors) in 5 measuring profiles.

  Temperature sensors were also installed in the host rock.

  Data is collected at 10-minute intervals and is accessible online in both raw and graph forms. The data obtained provides immediate information on the behavior of the bentonite layer.
- Permanent construction elements employed to facilitate construction and transport: expanded metal casing, steel base and lid

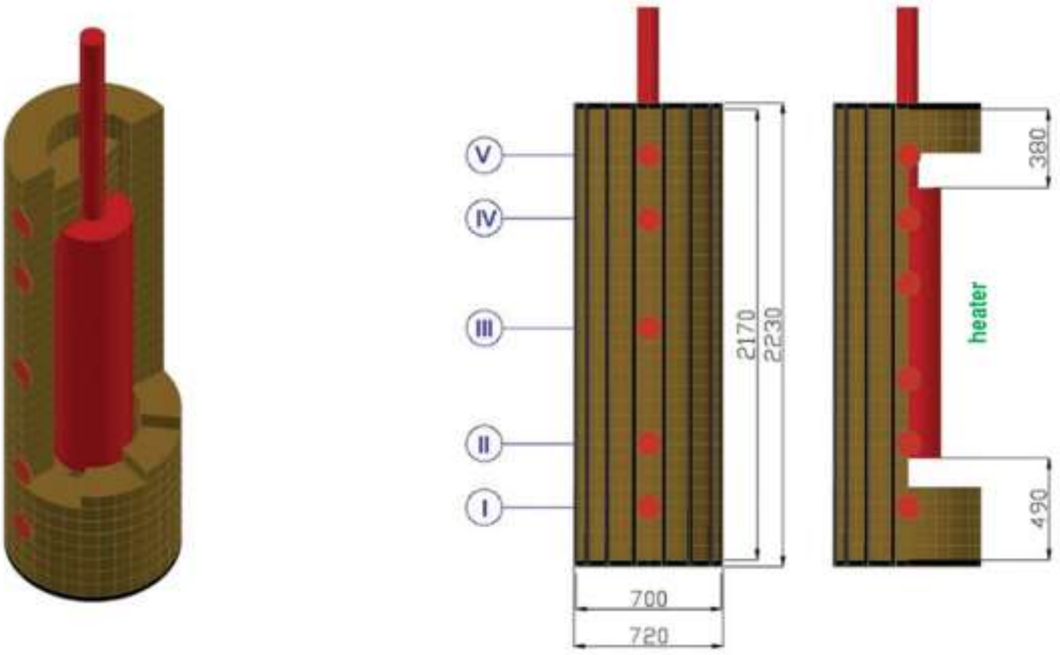

Figure 1 – Scheme of the Mock-Up Josef experiment indicating the profiles monitored (I - V), adapted from Šťástka (2014)

In addition to the monitoring system, the sampling of the bentonite barrier is performed every half year so as to provide an indication of changes in the bentonite material and the rate of saturation. The samples (see Figure 2) are obtained by means of drilling vertically through the steel lid (see Fig. 3). The samples help to provide a description of the saturation state of the bentonite via the evaluation of water content and density. In addition, the samples are studied for indications of mineralogical, hydraulic conductivity and swelling pressure changes brought about by heating and saturation.

Figure 2 – Core sample of the bentonite barrier extracted by means of vertical drilling

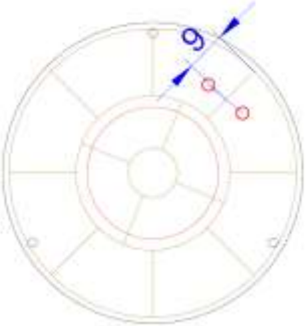

Figure 3 – Position of sampling locations (red circles)

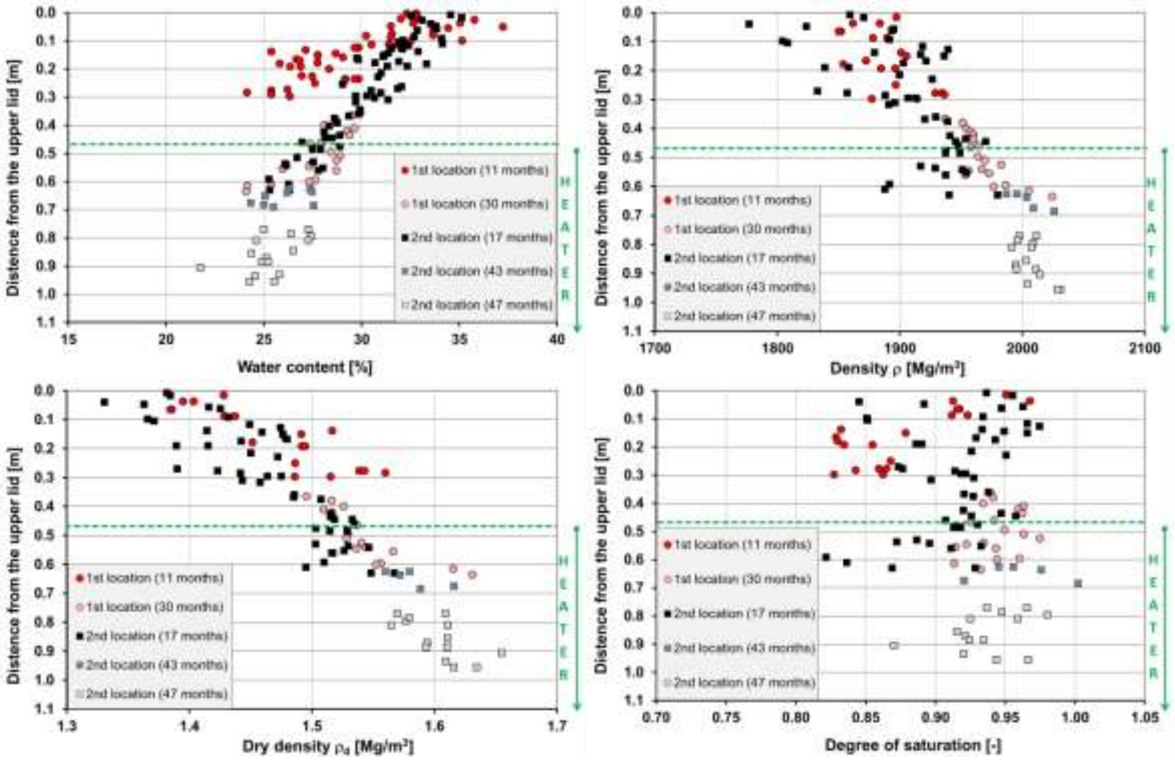

Figure 4 Water content, density, dry density and degree of saturation results obtained by sampling

The red circles reveal the results from the first sampling procedure at (1st location) after 11 months - depth 320mm (2 mineralogical samples were taken from depths of 15mm and 297mm). The black squares show the first sampling (2nd location) after 16 months - depth 640mm (4 mineralogical samples were taken from depths of 75mm, 242mm, 277mm and 580mm). The light red circles represent the second sampling procedure from (1st location) after 30 months - depth 660mm (4 mineralogical samples were obtained from depths of 160mm, 340mm, 480mm and 590mm). The dark grey squares show the results from the second sampling procedure (2nd location) after 43 months - depth 690mm (3 mineralogical samples were obtained from depths of 15mm, 270mm and 680mm). The light grey squares show the results from the third sampling session (2nd location) after 47 months - depth 960mm (2 mineralogical samples were taken from depths of 840mm and 950mm). The green line shows the level of the top of the heater (480mm).

Main learning points concerning bentonite homogenization / mechanical evolution and relevance for the project

- Swelling pressure developed almost immediately following the placement of the supercontainer in the well
- The saturation of the bentonite barrier is not homogeneous (observed from values measured by total pressure sensors and the evaluation of the bentonite core samples)
- The highest total pressure value was obtained from below the heater
- Heating immediately influenced total pressure within the barrier

How could this work inform a new experimental or modelling study in BEACON?

Mock-Up Josef is the first in-situ experiment to be performed at this scale using Czech Ca-Mg bentonite (Černý vrch deposit) with sampling availability throughout the experiment.

The data obtained from sampling might be used for the verification of mathematical models.

References (ideally with web links)

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Recommendations for BEACON project

Project Acronym NSC (Noyau de Scellement)	**Location** Bure URL, France (Callovo-Oxfordian claystone-COX)	**Type** Field scale experiment Scale ½ (diameter 4.5meters, length 5.1 meters
Lead organiser Andra (France)	**Start date** December 2012	**End date** In progress
Main partners involved in the project	**Characteristics of swelling clay** Pre-compacted bricks sand/MX-80 (60%/40%) Dry density: 2.05 g/cm^3 Initial water content : 6.5% MX80 powder/pellets: Dry density pellets (7mm) : 2.24g/cm^3	**Water Saturation** Artificial and natural
Instrumentation 420 sensors - pore pressure, - relative humidity, - total pressure, - temperature, - strain	**Main elements related to homogenization** Initial heterogeneity of density: - zones filled by compacted brick and zone filled with pellets/powder mixture - Initial gaps	**Interfaces with other material** Bentonite/COX claystone Bentonite/Concrete
Modelling Yes: scoping calculations Groups/Codes : Andra and UPC/Code Bright	**Main processes studied** ☐T ☒H ☐M ☒Swelling pressure ☐Gas transfer ☒Other Water transmissivity of the damaged zone	**Reference concept if pertinent** Tunnel seal in Andra reference concept for radioactive waste disposal

Main objectives of the experiment

To limit radionuclides migration along drifts and through the EDZ in radioactive waste disposal, seals will be implemented in drifts and shafts. These seals will be mainly composed of swelling clay core in between two concrete plugs. After natural hydration from the surrounding rock mass, the bentonite will swell and apply radial pressure against the drift wall. In this context, ANDRA designs and installs a large scale sealing experiment which is called NSC (French acronym for Noyau de SCellement) The main objective is to back analyze the equivalent permeability of the seal in place in order to check the efficiency of such seal. To reduce saturation time, artificial hydration is done and bentonite/sand mixture has been chosen to have high water permeability.

Before reaching full saturation state and starting hydraulic test program, a lot of data will be provided by this experiment on the effect of the hydration of the seal: evolution of the permeability (at the interface seal/claystone and in the surrounding rock mainly the damaged zone), the pressure build up on the concrete plug, water saturation propagation through the bentonite. After full saturation, water permeability of both EDZ and bentonite will be tested.

General description

The experiment is composed of 4 zones (figure 1): injection chamber (zone 1), seal (zone 2), concrete plug (zone 3) and water tight drift (zone 4). This seal is implemented in a drift with a 4.6 m diameter (see Figure 5).

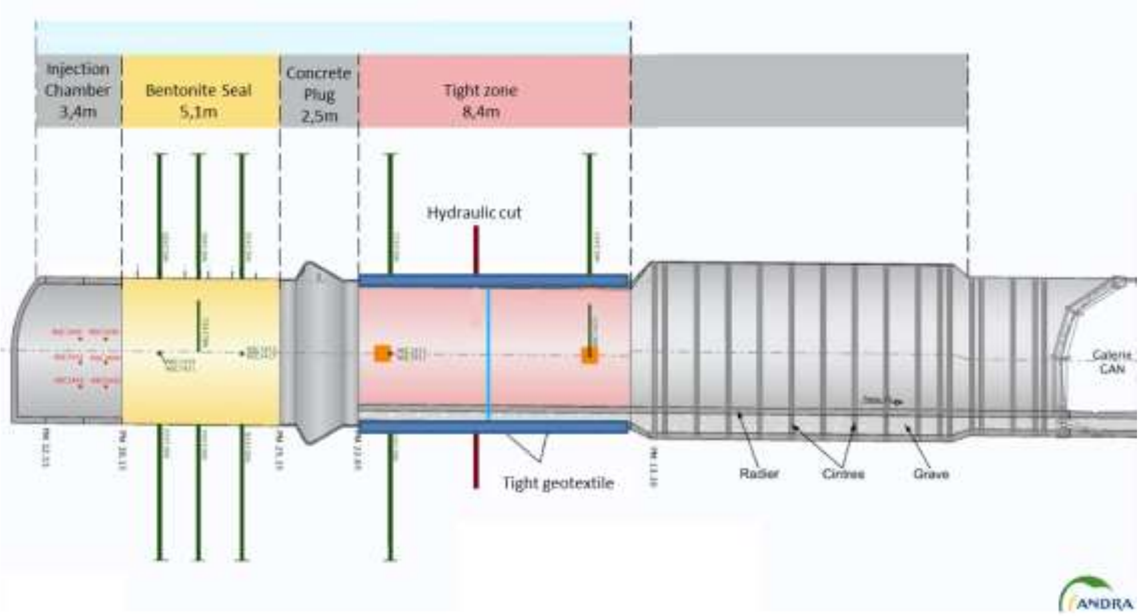


Figure 5 Scheme of NSC experiment

Hydration system: After installation hydration is done by 6 geotextile membrane. 4 of them have been installed directly inside the bentonite core, the two others are at the interface with the concrete plug and at the interface with the injection chamber.

The hydration membrane (Figure 6) at the interface between the concrete plug and the seal is divided into 12 independent areas. This specific design is for distinguish water fluxes from the near-field of the damaged zone, the interface between claystone and seal and water coming through the seal during the performance test.

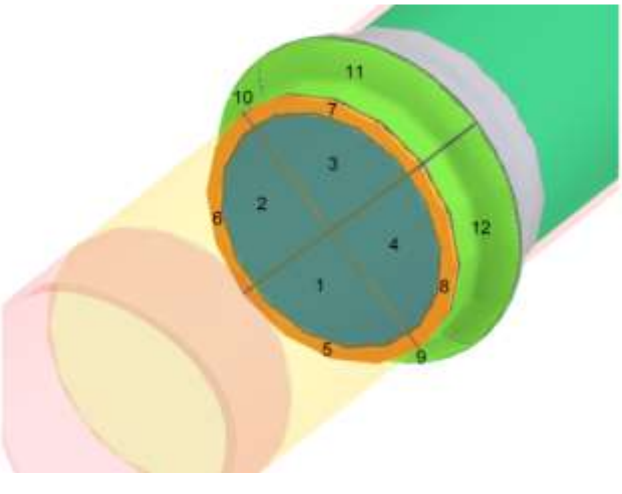


Figure 6 Detailed layout of the membrane at the interface with the concrete

plug (zone 3)

Concrete plug: The concrete plug (zone 3) will be monitored with deformation, displacement, temperature and acoustic sensors. Both concrete plugs of the zone 1 and 3 are dimensioned to a swelling pressure of 7 MPa. The chosen concrete is a low-heat concrete with no reinforcement.

Access gallery: The access gallery in GES (zone 4) is made watertight and a cut-off of 2.5 m. Indeed, scoping calculations were done with Bright code and showed that the ventilation into the access drift will desatured the damaged zone cross the seal. This desaturation will be harmful to get a full hydration of the S/B mixture. To counteract this effect, water will be injected into the cut-off.

Observation boreholes: Surrounding the GES drift (Figure 7), a total of 23 boreholes will be equipped with multi-packers systems to monitor pore pressure (19 boreholes) and the others (4) with extensometer. Into the multi-packers boreholes, hydraulic tests will be repeated to see the evolution of the hydraulic conductivity around the seal in respect to the swell of the S/B mixture.

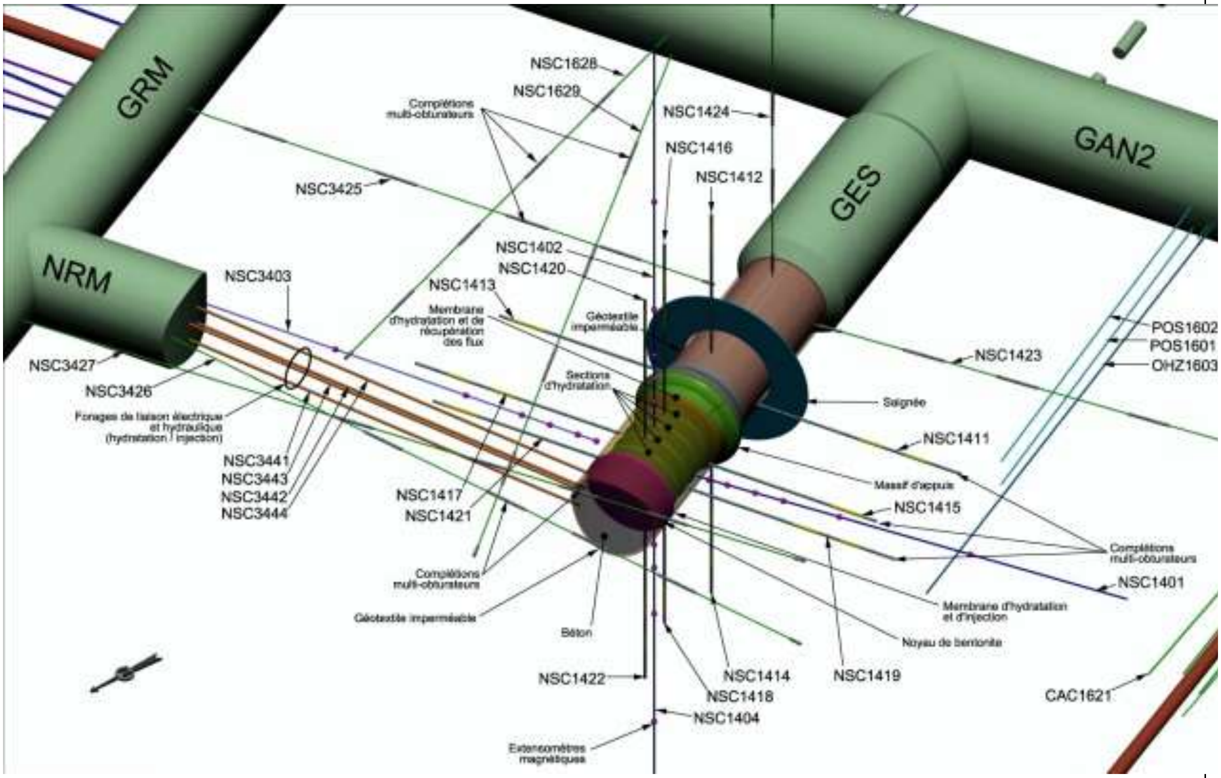


Figure 7 *NSC experiment in Bure URL- observation boreholes*

Bentonite core: The GES drift was excavated in 2012 and all the instrumentation inside GES drift and S/B mixture was installed during 2013. During the construction of the S/B seal, volume and mass of the S/B mixture was controlled. Those measurements were used to estimate the dry density of clay material in the seal and therefore estimate the swelling pressure. The estimated dry density of clay material and swelling pressure are closed to 1.45 kg/m^3 and 2.5 to 3.4 MPa respectively.

Bricks characteristics: Mass: 13.23 kg, dimensions 301 mm x 201 mm x 100 mm Mixture WH2/sand TH1000 - proportion 40/60 %.

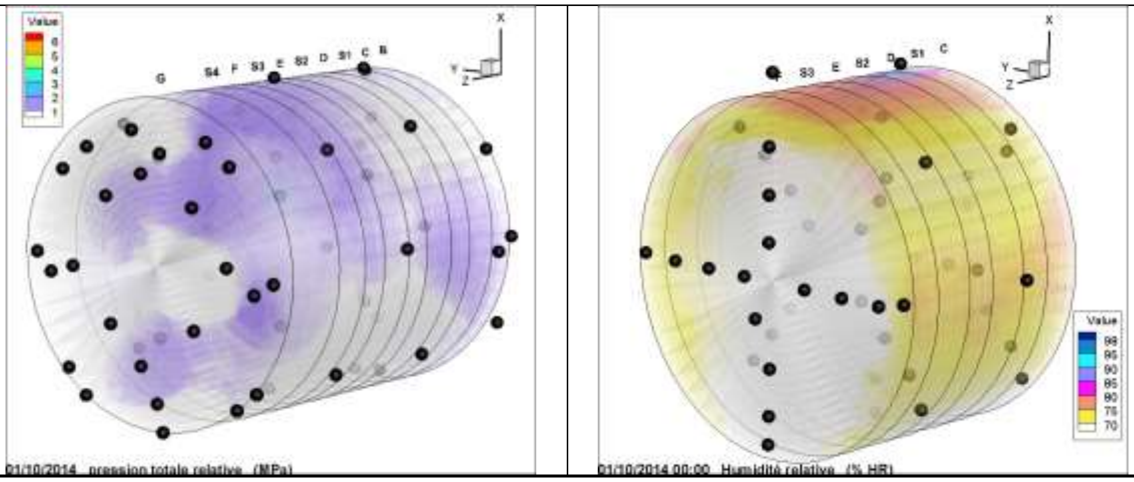
A total of about 80 tons of bricks, 8 m^3 of bentonite pellets and 3 m^3 of powder has been installed (Figure 8). All the gap and technologic voids are filled with pellets/powder mixture.

Figure 8 Installation of bentonite core, wall made with bricks, pellets/powder mixture between claystone and bentonite bricks. Background: hydration membrane

Monitoring: The monitoring instruments, which have been installed in the experiment, are divided in different cross sections. In the seal and at the interface with the concrete plugs (upstream and downstream), is composed of 319 sensors (humidity sensors: 64 capacitives, 64 psychrometers and 16 FDR; pore pressure sensors: 99; total pressure sensors: 76) and 6 hydration membranes. Between each hydration membrane, the thickness of the S/B seal is 1 m. The maximal distance inside the S/B mixture from hydration membrane is therefore equal to 50 cm.

The injection chamber is the upstream part during the performance test and the concrete plug will be the downstream part. To avoid leakage between the two faces of the seal, all instruments installed within the S/B sealing (sensors, hydration membranes and surrounding boreholes) must to be wired towards the injection chamber passing through the concrete plug in 2 tubes system that guarantees the test tightness. All the wires pass through 6 “instrumentation” boreholes between injection chamber and NRM niche.

Example of results: Despite artificial hydration of bentonite, water saturation and total pressure increase slowly. On Figure 9, both total pressure and relative humidity measured inside bentonite core indicate clearly that full saturation hasn’t been reached. All the measures are available (total pressure, relative humidity, pore pressure evolution in the boreholes surrounding…).



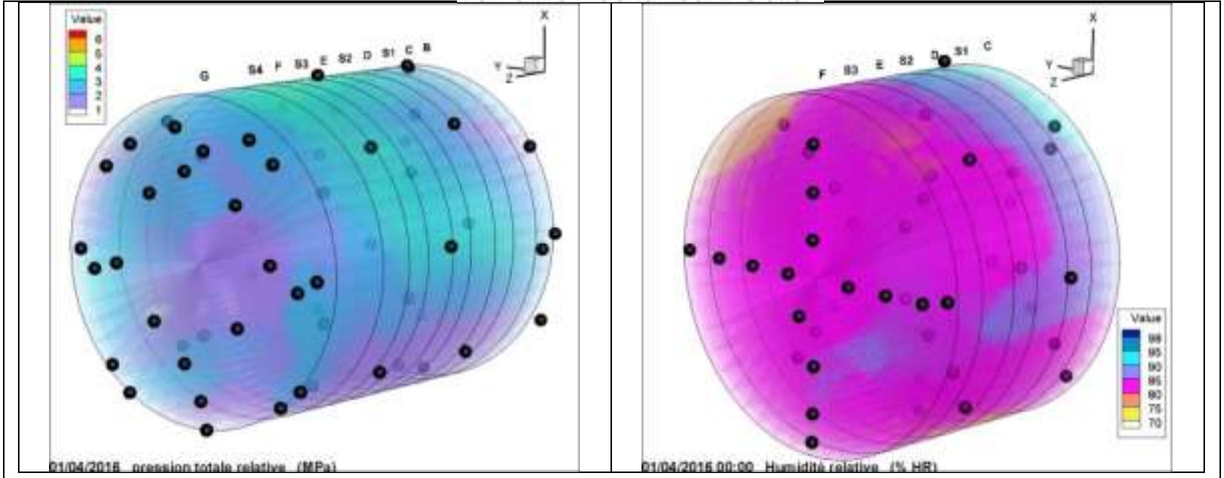


Figure 9 *Left: interpolation of total pressure; Right: interpolation of the relative humidity after 9 months (top) and 2.2 years (bottom)*

Main learning points concerning bentonite homogenization / mechanical evolution and relevance for the project

Water saturation and total pressure measured inside the bentonite don't evolve in a similar way in all the sections. This heterogeneous response during the transient phase needs to be investigated and especially the role of initial heterogeneities due to variation of density in brick arrangement or to the presence of pellets/powder mixture in gaps.

Hydro-mechanical evolution of a large structure equipped with a high density of sensors (about 420) give an interesting base of knowledge. Especially about how heterogeneities evolve in time and consequences on final performance or effect of heterogeneous water supply on final state of bentonite core.

How could this work inform a new experimental or modelling study in BEACON?

This experiment has a well-defined geometry. The initial characterization THM all the materials involved has been done. A large number of sensors allows to follow the hydromechanical evolution of the bentonite core and of all the material surrounding. Presence of heterogeneities in the system. This lead to consider this experiment as a good candidate to modelling test within WP 5. This experiment has not been proposed before for a benchmark or as a modelling exercise.

References (ideally with web links)

de La Vaissière, R., N. Conil, J. Morel, F. Leveau, C. Gatabin, J. L. Garcia-Sineriz, H. Habos, M. Rey, M. Piedevache, B. Helmlinger and C. Balland (2014). Design and construction of a Large-Scale sand-bentonite seal in the Meuse/Haute-Marne Underground Research Laboratory. International conference on the Performance of Engineered Barriers, Hannover, BGR.

Project Acronym PGZ2 (« Perturbation induite par les gaz »)	**Location** Bure URL, France (Callovo-Oxfordian claystone-COX)	**Type** Borehole experiment
Lead organiser Andra (France)	**Start date** August 2009	**End date** In progress
Main partners involved in the project	**Characteristics of swelling clay** Pre-compacted plugs sand/MX 80 (30%/70%) Dry density : ~1.6g/cm^3 MX80 powder/pellets: Dry density pellets (7mm) : 2.2 g/cm^3 Mean dry density ~1.55g/cm3	**Water Saturation** natural
Instrumentation sensors - pore pressure, , - total pressure, - temperature	**Main elements related to homogenization** Initial heterogeneity of density for pellets/powder mixtures Initial gaps due to breakout and technological voids	**Interfaces with other material** Bentonite/COX claystone
Modelling Yes Groups/Codes : ULG/Lagamine, Andra/Tough2, EDF/Code_Aster	**Main processes studied** ☐T ☒H ☒M ☒Swelling pressure ☒Gas transfer ☐Other	**Reference concept if pertinent**

Main objectives of the experiment

PGZ2 regroups a set of 5 boreholes where bentonite plugs have been installed. In three of them pre-compacted blocks made with sand/bentonite mixture have been placed. The other two plugs are made with powder/pellets mixture of pure bentonite.

The first objective of this experiment is to understand the consequences of gas percolation on bentonite plugs. The idea is to reproduce the situation of a seal closing a high level waste zone and submitted to gas pressure. Gas generation could perturb the hydration of the bentonite and increase the duration at which specified swelling pressure is reached. One other point of interest is the identification of gas pathways directly though the bentonite or via the interface between clay host rock and bentonite. In PGZ2 experiment, other issues are investigated as the difference of behaviour depending on how the seal has been built (mono block precompated or powder/pellets mixture). A lab test program has been developed in parallel to acquire fundamental parameters such as permeability and gas entry pressure and to evaluate the consequence on bentonite behaviour of different hydration scenarios.

General description

All the boreholes have been drilled between two drifts (GEX and GMR) (Figure 1). In this configuration; access is possible from both faces of bentonite cores and no sensor line go through the bentonite to avoid any perturbation. In three boreholes (PGZ1011, PGZ1012, PGZ1013) pre-compacted bentonite plugs have been installed, pellets/powder mixture have been put in 2 boreholes (PGZ1021, PGZ1022), one borehole is used to follow pore pressure evolution in the PGZ2 zone. The diameters of the boreholes are about 10cm and the lengths of the bentonite cores are about 40 cm for compacted plug and about 60cm for pellets/powder mixture.

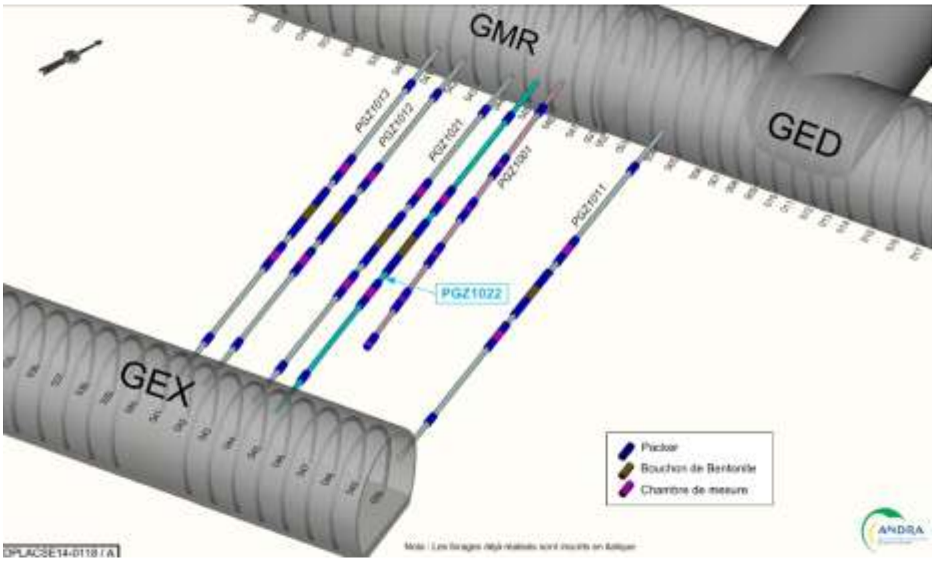
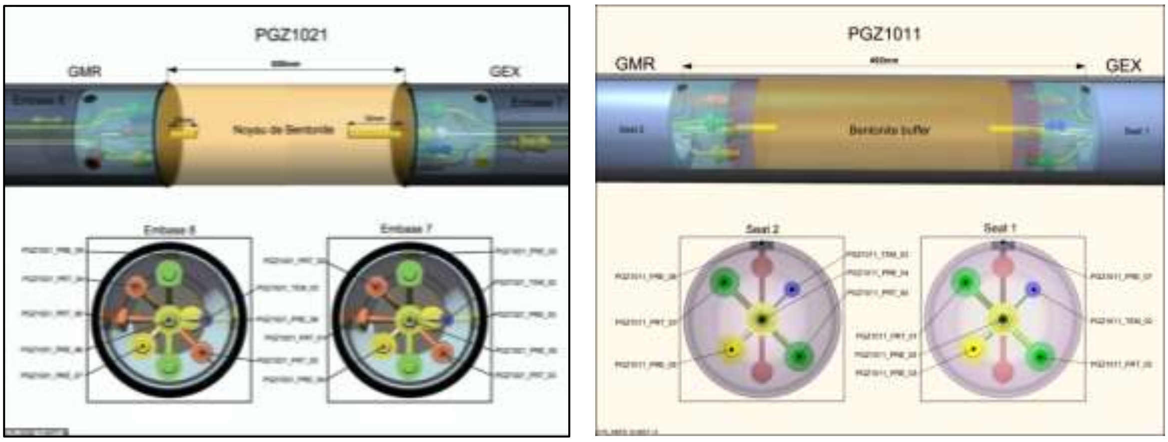


Figure 1 *PGZ2 design : 3 boreholes with compacted plugs (PGZ1011, PGZ1012, PGZ1013), 2 boreholes with pellets/powder mixture (PGZ1021, PGZ1022) and one borehole to monitor pore pressure (PGZ1001)*

Several sensors are in contact and around the bentonite plugs. As represented on Figure 2 total and pore pressure sensors are monitored on both face of the bentonite core and two sensors (pore pressure) have been introduced inside the bentonite.



(a) (b)

Figure 2 View of the bentonite section in borehole (a) PGZ1021 – pellets/powder mixture, (b) PGZ1011 - pre-compacted bentonite

Each borehole is equipped with several packers that isolate bentonite section and two intervals on each side of the bentonite plugs where the interstitial pressure is monitored (Figure 3). The objective is to be able to follow the potential fluid circulation along the borehole.

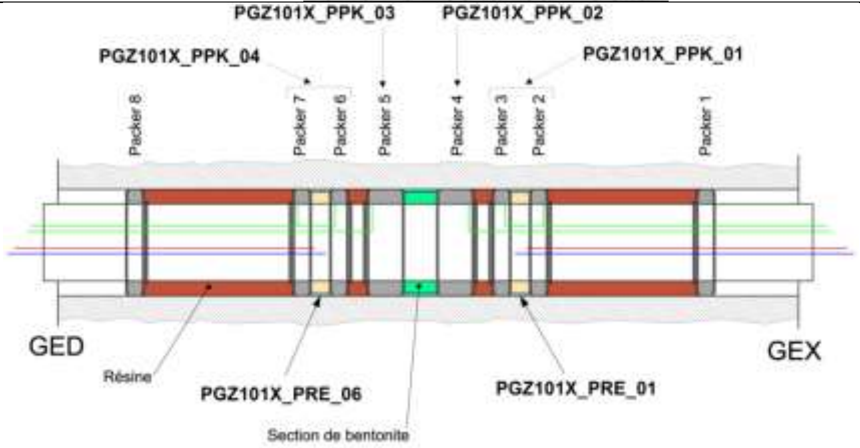


Figure 3 *Pressure measurements taken along the bentonite boreholes*

Characteristics of installed bentonite cores and estimated initial density are presented in table below:

Borehole	Water content by weight	Total length	Nominal diameter	Dry density	Estimated dry density *in situ*
	%	mm	mm	g/cm³	g/cm³
PGZ1011	8.84	400.1	93.9	2.07	1.62
PGZ1012	8.80	400.4	94.1	2.06	1.61
PGZ1013	8.72	400.3	93.9	2.06	1.61
PGZ1021	3.08	595	105	1.65	1.54
PGZ1022	2.35	582	106.6	1.59	1.55

Main stages:

- PGZ1011 and PGZ1012 : installation august 2009 – Natural saturation of bentonite
- PGZ1011 : gas injection during 70 days (from October 2009 to January 2010), gas injection stage was followed by natural saturation of bentonite
- PGZ1013 : installation February 2010 – Natural saturation of bentonite;
- PGZ1011, PGZ1012 and PGZ1013 : hydraulic tests (november 2011) ;
- PGZ1021 : installation April 2011. Gas injection at constant flow rate during 20 months on one face (GMR) of the bentonite plug till December 2012. Gas injection stage was followed by natural saturation of bentonite
- PGZ1013 and PGZ1021: Gas injection test at bentonite/Callovo-Oxfordian claystone interface in April 2014 and in September 2015 respectively
- PGZ1013: water permeability test at bentonite/Callovo-Oxfordian claystone interface in September 2015
- PGZ1022: installation February 2016 – Natural saturation of bentonite

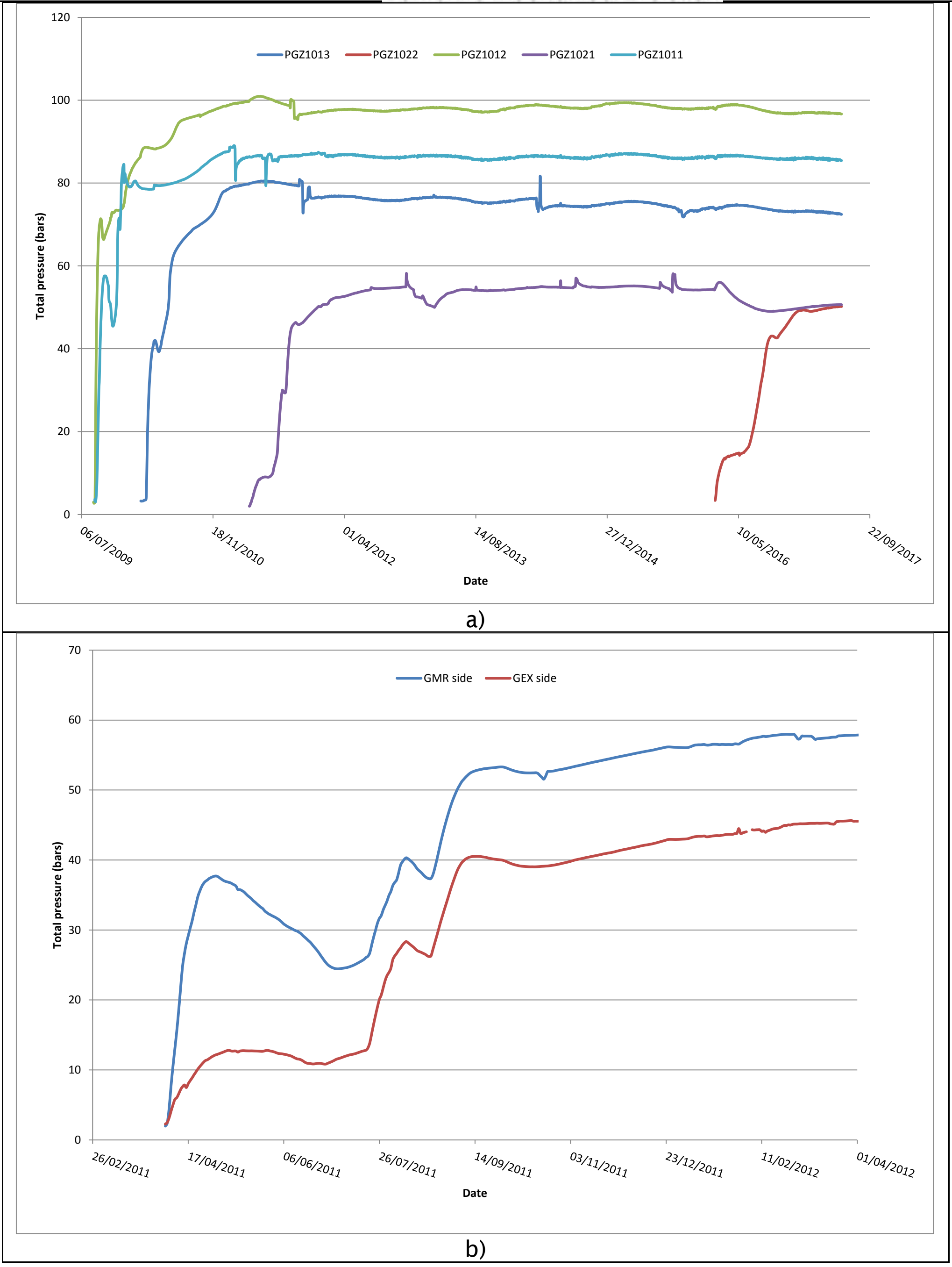


Figure 4 *(a) Total pressure recorded on GMR side till beginning of the PGZ2 experiment in 2009, (b) total pressure during saturation (PGZ1021)*

Main results:

- Core composed by pellets/powder mixture
  - ✓ Complex processes of saturation with heterogeneous responses of pore pressure and total pressure sensors. Mainly due to non-homogeneous distribution of pellets and powder. Some zones seem to be filled with powder only (see Figure 4b);
  - ✓ Consolidation effect from the saturated zone to the partially saturated one.
  - ✓ Bentonite core was able to sature despite a long gas injection phase (20 months).
- Pre-compacted bentonite cores :
  - ✓ Water saturation of the bentonite wasn’t modified by gas injection;
  - ✓ The main effect of gas is to increase the full saturation time ;
  - ✓ Swelling pressure and water saturation are similar in core with or without gas injection.
- Gas/water transfer
  - ✓ Water permeability of bentonite plug was not affected by a long gas injection phase.
  - ✓ Interfaces (including damaged zone around the bentonite plugs) in gas transfer play a major

role. Gas entry pressures in those zones are very low.

Main learning points concerning bentonite homogenization / mechanical evolution and relevance for the project

Evolution of total pressure (see for example Figure 4b) is quite different on both sides of bentonite plugs indicating non uniform development of swelling pressure. Those differences are mainly due to density variations in the bentonite when a pellet/powder mixture is concerned or to non-homogeneous distribution of initial voids (breakouts, technological voids…). If the influence of such heterogeneities can be important during the early stages of bentonite plug evolution, and mainly when the system is being saturated, long term evolution indicates a clear tendency to homogenization. In any cases, performances expected (in terms of hydraulic conductivity) are reached before a complete homogenization.

How could this work inform a new experimental or modelling study in BEACON?

Experimental confirmation of reaching performance at larger scale despite initial heterogeneities could be of interest within the BEACON project.

On PGZ2 set of experiments data are recorded for more than 7 years. The well characterization of the swelling clay uses in these experiments and the large quantity of measures could be interesting for modelling. Previous modelling work has been performed without introducing initial variability in the bentonite properties.

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Gerard, P., Radu, J.-P., Talandier, J., De La Vaissière, R., Charlier, R., & Collin, F. (2010). Numerical modelling of the resaturation of swelling clay with gas injection. In E., Alonso & A., Gens (Eds.), *Unsaturated Soils* (pp. 1383-1388). London, UK: Taylor and Francis Group.

Gerard, P., Charlier, R., Radu, J.-P., De La Vaissière, R., Talandier, J., & Collin, F. (2010). HM modelling of in-situ gas injection tests in bentonite and argillite: the PGZ experiment. *Clays in Natural and Engineered Barriers for Radioactive Waste Confinement* (pp. 545-546).

Project Acronym PRACLAY SEAL	**Location** HADES URL, Mol, Belgium	**Type** Field scale, 1.05 m-length, 2.5 m diameter
Lead organiser EURIDICE	**Start date** 2010-01	**End date** In progress till after 2025
Main partners involved in the project ONDRAF/NIRAS, SCK	**Characteristics of swelling clay** MX80 bentonite with	**Water Saturation** Artificial/natural
Instrumentation 104 sensors - Temperature - Pore water pressure - Total pressure - Relative humidity - Extensometer - Strain gauge	**Main elements related to homogenization** Between the inner and outer bentonite block layers, between inner bentonite block layer and steel cylinder, there is an initial technological gap of 10 mm respectively	**Interfaces with other material** Bentonite/Boom Clay Bentonite/steel
Modelling Yes/no: Yes Groups/Codes : EURIDICE/Code_Bright	**Main processes studied** ☒T ☒H ☒M ☒Swelling pressure ☐Gas transfer ☐Other	**Reference concept if pertinent** Seal for large scale in-situ PRACLAY heater test

Main objectives of the experiment

The main purpose of the seal is to hydraulically cut off the heated part of the PRACLAY gallery and surrounding clay from the non-heated part of the gallery. The seal consists of a steel cylinder, surrounded by a ring of bentonite. The steel cylinder physically closes off the gallery. Bentonite was used as a sealing material because of its intrinsically low permeability (when compacted to a suitable dry density) and its swelling capacity upon hydration by Boom Clay water, which helps to seal the excavation-induced zone around the seal. In this way, an almost impermeable zone is created at the intersection between the two parts of the gallery, helping to keep the pressure high inside the heated part of the PRACLAY gallery and consequently providing the quasi-undrained hydraulic boundary conditions for the PRACLAY Heater test.

The bentonite ring of the seal was instrumented to study the thermo-hydro-mechanical (THM) behaviour of the bentonite ring, more specifically its hydration and swelling behaviour.

The hydraulic seal is purpose-built for the PRACLAY Heater test and is not representative of seals in a real repository. However, the Seal test is an opportunity for studying the possibility of closing off galleries using bentonite.
Finally, the hydraulic seal has to allow watertight feed-through of the heater cables and the instrumentation cables that are placed in the heated part of the PRACLAY gallery.

General description

Background

In 2007, the 45 m long PRACLAY gallery was constructed in the HADES URL to host the large-scale PRACLAY Heater test (Figure 1). With this test, scientists want to study the impact of heat, produced by high-level radioactive waste, on the thermo-hydro-mechanical (THM) behaviour of the Boom Clay in conditions that are representative of an actual waste repository. The goal is to confirm on a large scale and refine existing knowledge from past small-scale heating experiments, performed both in HADES and in surface laboratories.

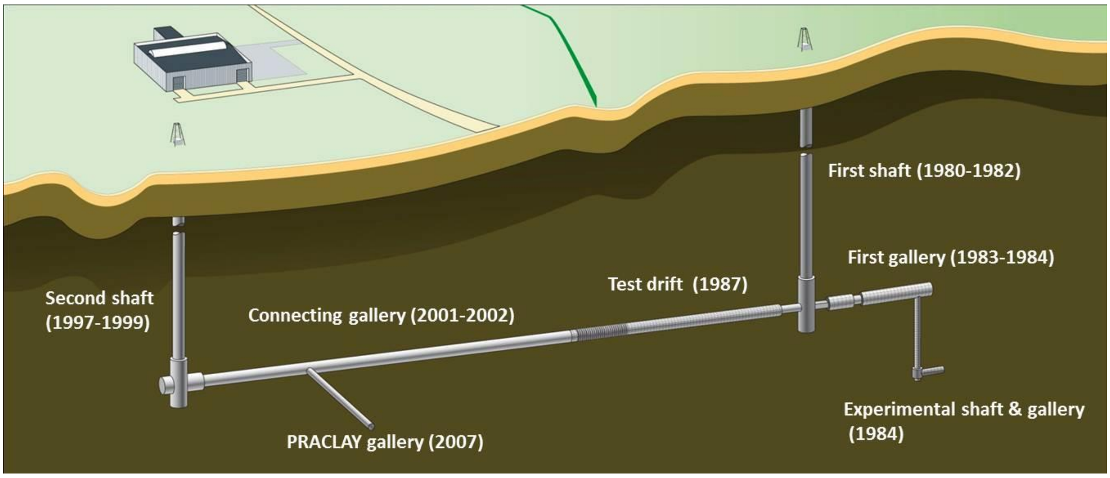

Figure 1 - Layout of the construction of the HADES underground research laboratory

The PRACLAY Heater test was conceived to be conducted under a well-controlled and reasonably conservative combination of thermal, hydraulic and mechanical boundary conditions. This implies, among other requirements, quasi-undrained conditions. These conditions are achieved by introducing water-saturated backfill sand into the heated part of the gallery and installing a hydraulic seal at the intersection between the heated and the non-heated parts of the gallery (Figure 2). The **PRACLAY Seal test** is focusing on the design, installation and functioning of this seal.

Together, the construction of the gallery, the Seal test and the Heater test make up the **PRACLAY In-Situ Experiment**.

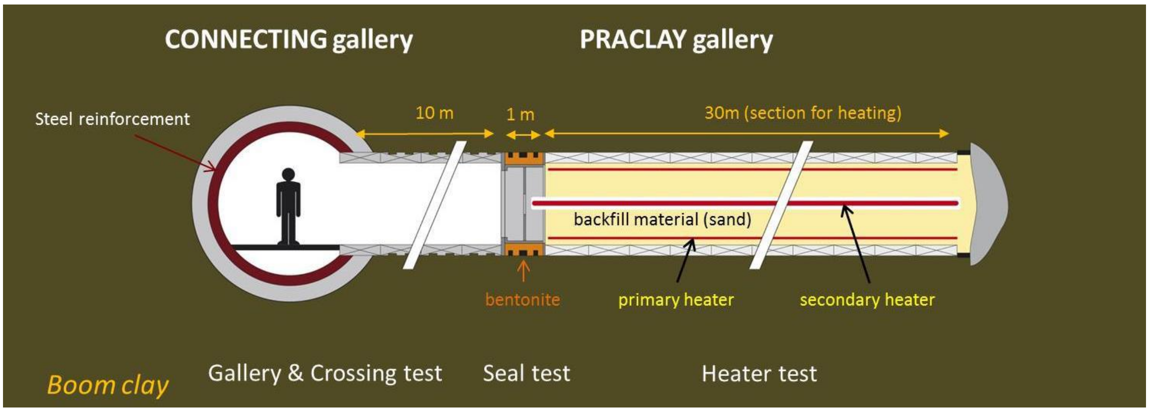

Figure 2 - The set-up of the PRACLAY In-Situ Experiment

Heating under undrained boundary condition implies that a higher pore water pressure (PWP) at the interface between the concrete gallery lining and the clay is expected. This expected high PWP is achieved indirectly by introducing the water-saturated backfill sand into the heated part of the gallery: upon heating, a homogeneous high PWP is generated in this saturated backfill material due to its high thermal dilation properties. However, this high PWP has to be maintained. This is the main purpose of the seal: it has to hydraulically cut off the heated part of

the PRACLAY gallery and surrounding clay from the non-heated part of the gallery and thus maintain the high pressure inside the heated section of the gallery.
The seal consists of a steel cylinder, surrounded by a ring of bentonite. Bentonite was used as a sealing material because of its intrinsically low permeability (when compacted to a suitable dry density) and its swelling capacity upon hydration by Boom Clay water, which helps to seal the excavation-induced zone around the seal. In this way, an almost impermeable zone is created at the intersection between the two parts of the gallery, helping to keep the pressure high inside the heated part of the PRACLAY gallery and consequently providing the quasi-undrained hydraulic boundary conditions for the PRACLAY Heater test (Figure 3).

Such an undrained boundary is chosen to achieve the conservative conditions that are reasonably achievable during the Heater test.

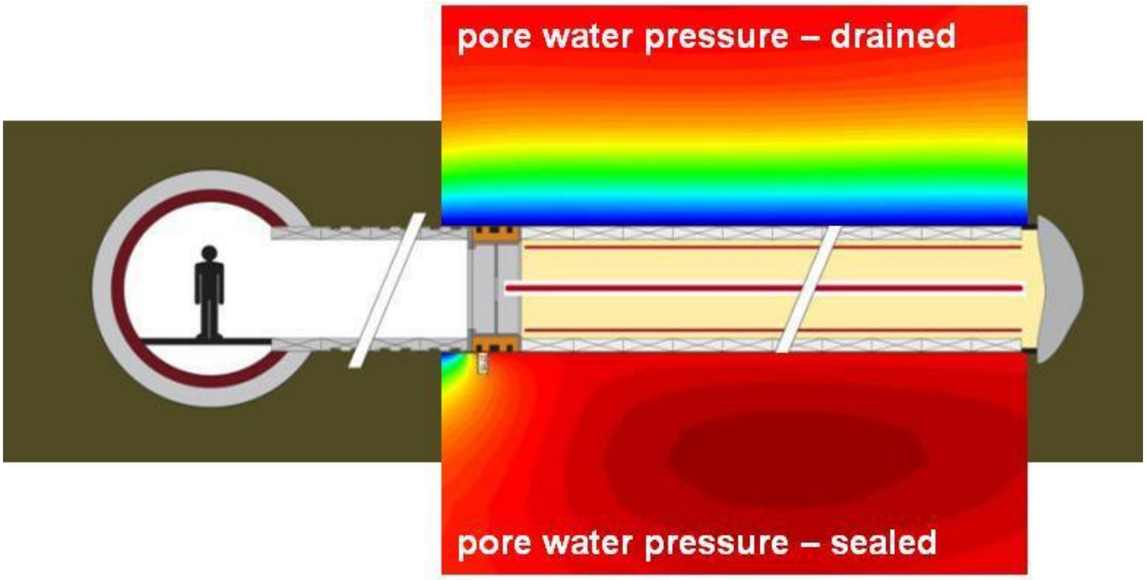

Figure 3 - Modelled pore water pressures in the clay around the Heater test, with a seal (undrained conditions) and without a seal (drained conditions)

Together with the design and installation of the seal, studying the swelling behaviour of the bentonite ring since its installation are the main objectives of the **PRACLAY Seal test**.
The hydraulic seal is purpose-built for the PRACLAY Heater test and is not representative of seals in a real repository. However, the Seal test is a unique opportunity to gather additional information on the in-situ behaviour of bentonite-based repository structures and thus for studying the possibility of closing off galleries.

Finally, the hydraulic seal has to allow watertight feed-through of the instrumentation cables placed in the heated part of the PRACLAY gallery and watertight feed-through of the heater cables.

DESIGN and INSTALLATION of the seal

The seal consists of a stainless steel structure and an annular ring of compacted bentonite placed against the clay (Figure 4). The steel cylinder physically closes off the gallery. Bentonite was chosen

as a sealing material because of its intrinsically low permeability (when compacted to a suitable dry density) and its swelling capacity upon hydration by Boom Clay water.

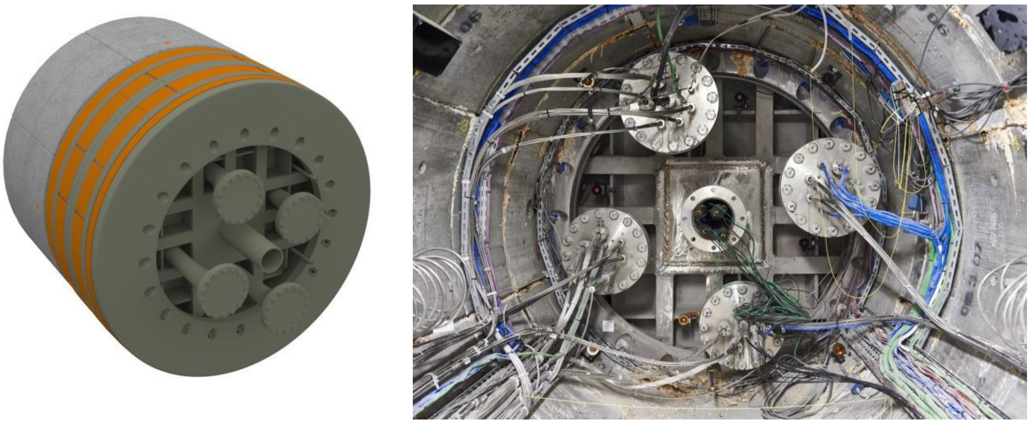

Figure 4 - 3D view of the seal with a central steel cylinder and an annular ring of bentonite (orange) against the clay (left) and front view of the seal from the non-heated part of the PRACLAY gallery (right)

The seal is installed 10 m from the Connecting gallery to limit the mutual interactions between the Heater test and the Connecting gallery. Scoping calculations indicate that a seal length of 1 m is sufficiently effective and that no significant gain was derived by further increasing its length. A bentonite-based hydraulic seal was chosen instead of, for example, a technical seal consisting of inflatable packers, as bentonite is generally considered to be a potentially suitable material for seals in repository designs for the disposal of radioactive waste. Although the design of the seal is primarily driven by the requirements of the Heater test and does not mimic the design of a repository seal, it can provide lessons on the feasibility of installing such a seal and on the behaviour of the bentonite.

The bentonite has to meet the following specifications:

- its swelling pressure (this is the pressure the bentonite exerts on the clay when the bentonite is completely hydrated) is larger than 2.5 MPa to avoid the creation of negative effective stresses around the hydraulic seal during the Heater test (the maximum pore water pressures in the Boom Clay around the hydraulic seal during the Heater test are estimated at 2.5 MPa);

- its maximum swelling pressure is 6 MPa to avoid fracturing the clay and not jeopardising the integrity of the stainless steel structure of the hydraulic seal;

- its hydraulic conductivity at saturated state is as low as possible (at least lower than the conductivity of undisturbed Boom Clay (≈ 10^{-12} m/s) and preferably one order of magnitude lower).

It was decided to use MX80 bentonite compacted into blocks. Relevant experience with this type of bentonite has been gained from its use in other experiments in underground research facilities (Mont Terri, Bure, ASPO and AECL's URL) and in the laboratory (by CEA, CIEMAT, CERMES and SKB). Furthermore, it is an Na-bentonite, which makes it chemically compatible with Boom Clay water. The initial dry density of the bentonite (1.8 t/m³), which affects its swelling pressure and saturated permeability, was determined by scoping calculations, taking into account the interaction between bentonite and Boom Clay.

The bentonite is naturally hydrated by pore water coming from the Boom Clay, and artificially by water injected through filters at the outside of the cylinder of the seal.

Instrumentation was placed in the bentonite blocks to gain information on the bentonite hydration and to be able to evaluate the performance of the hydraulic seal (Figure 5).

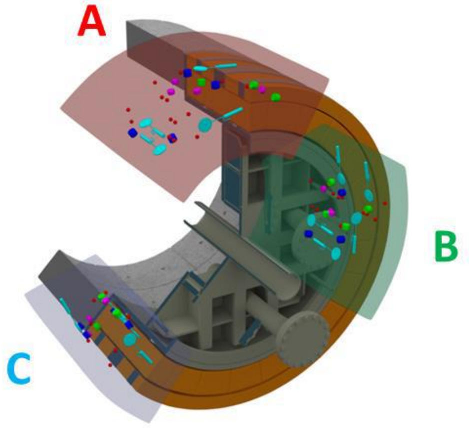

Figure 5 - Various instruments inside the bentonite, grouped into sections A, B and C

TIMING

The double layer of bentonite blocks and incorporated sensors for monitoring bentonite behaviour were installed between 13 January 2010 and 11 February 2010, followed by the installation of the stainless steel structure. As a consequence of direct contact between the Boom Clay and the bentonite ring, the natural hydration of the latter began immediately. When the stainless steel cylinder structure was installed, artificial hydration by water injection was started in April 2010.

After installation of the heating system and backfilling of the gallery with sand, the stainless steel structure was sealed on 13 October 2011 by welding a closing plate in position.

The PRACLAY Heater test started on 3 November 2014 after a detailed analysis and evaluation of the status and performance of the seal.

RESULTS

Figure 6 shows the radial pressure at the bentonite/Boom Clay interface in sections A and B of the seal. This pressure results from the equilibrium between the radial pressure exerted by the Boom Clay and the swelling pressure of the bentonite ring. It is observed that the pressure immediately started to increase upon contact with the saturated Boom Clay. The combination of the swelling pressure and the radial pressure generated a continuous increase in pressure with time. At the end of 2013, a series of characterisation tests took place and it was concluded that the pressure required to start the Heater test had been reached. The Heater test has caused a general increase in pressure since the start of the heating phase. Since the target temperature of 80°C was reached, the pressure has continued to increase, but at a slower rate.

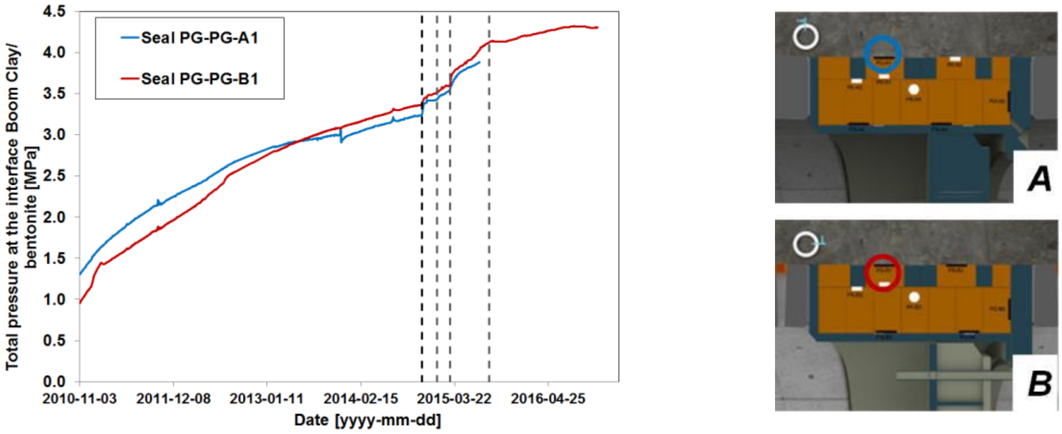

Figure 6 - Radial pressure measured at the Boom Clay/bentonite interface sidewall, for sections A and B. The dotted lines mark the phases of the heater experiment.

The pore water pressure is also monitored at the bentonite/Boom Clay interface, as can be seen in Figure 7 where a general increase in PWP with heating is observed. In addition to the PWP at the interface between both clays, the PWP inside the heated part of the PRACLAY gallery is also shown.

The measurements at different locations of the seal clearly show that the seal performs well as a hydraulic cut-off, maintaining a high PWP inside the gallery. Indeed, a high PWP gradient over the seal length is observed. More specifically, a pressure difference of approximately 1.3 MPa is observed between the heated part and the pressure sensor close to the non-heated part (*Seal PP-A3*). The PWP around the top of the seal, in section A, is shown in Figure 8. Between the heated (*Ring 21 S8*) and the non-heated part (*Ring 20 S8*) of the gallery, a difference of 2 MPa exists. This once again confirms that the seal is fulfilling its role as a hydraulic cut-off between the two different parts of the experiment.

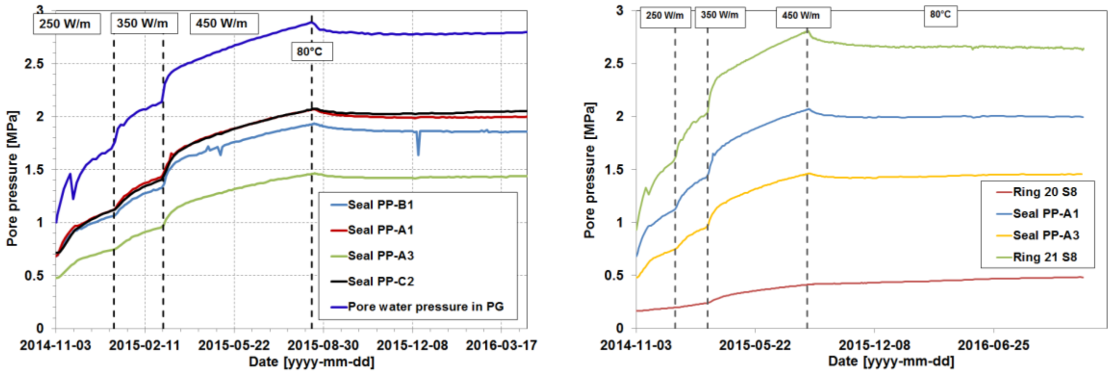

Figure 7 - Evolution of the pore water pressure at the Boom Clay/bentonite interface

CONCLUSION

To obtain the required quasi-undrained hydraulic boundary conditions for the Heater test, a steel structure was installed, surrounded by a bentonite ring in direct contact with the Boom Clay. The results show that the seal is very effective in creating quasi-undrained hydraulic boundary conditions and helps to keep the pressure high inside the heated part of the experiment.

After the installation of the seal in 2010, swelling of the bentonite began due to artificial (injection) and natural (Boom Clay) hydration. This swelling created the minimal pressure conditions to start the Heater test in November 2014.

Since the target temperature of 80°C has been reached, the pore water pressure inside the PRACLAY gallery has stabilised at 2.7 MPa. The seal structure (steel cylinder and bentonite ring) closes off the gallery as intended and maintains the pressure high inside the heated section of the gallery. The high pore water pressure gradient over the seal (from non-heated to heated section) indicates that the seal is fulfilling its role in creating quasi-undrained hydraulic boundary conditions for the Heater test.

Main learning points concerning bentonite homogenization / mechanical evolution and relevance for the project

Two 10 mm-gaps existed after the seal installation, soon after water was artificially injected from the filters integrated in the extrados of the steel cylinder into the seal, bentonite close to the gaps and joints was hydrated and swelled first, the gaps closed very quickly, and such hydration process induced the heterogeneity of the hydration and swelling at the early stage of the seal test. Meanwhile bentonite is hydrated by the natural water from the host Boom Clay with intrinsic permeability of the order of 10^{-19} m^{2}. Steel ribs exist partly along the interface between host Boom Clay and bentonite blocks.

The measured swelling pressure and pore water pressure in the seal presented nonhomogeneous evolution, which needs to be investigated by considering the heterogeneities due to initial techmological gaps, artificial injection, and steel ribs etc.

How could this work inform a new experimental or modelling study in BEACON?

Compacted MX80 bentonite is used as the main material of the seal, and this kind of bentonite is well characterized. A lot of sensors are measuring total swelling pressure and pore water pressure. The bentonite is being heated with strong THM coupling effect. Bentonite is in perfect contact with the Boom Clay.

Therefore PRACLAY seal test could be considered as a special in-situ test by taking into account all the above conditions.

References (ideally with web links)

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Recommendations for BEACON project

Project Acronym Prototype repository/outer section	**Location** Äspö URL	**Type** URL
Lead organiser SKB	**Start date** 2003	**End date** 2011
Main partners involved in the project Clay Technology, SKB	**Characteristics of swelling clay** Wyoming MX-80 Buffer, bentonite/crushed rock (30/70) tunnel backfill	**Water Saturation** Natural (partly drained)
Instrumentation The canister, buffer, backfill, rock and plug were instrumented for recording the influential processes during the evolution of the barriers in the transient water saturation phase. More than 1,000 instruments were installed in the buffer and the backfill, of which 401 were installed in the outer section (Börgesson and Sandén 2003).	**Main elements related to homogenization** On-line measurement of THM parameters during the operation phase Dry density and degree of saturation after excavation	**Interfaces with other material** Copper heater Buffer/backfill interface Crystalline host rock
Modelling Yes/no: Yes Groups/Codes : Abaqus, code_bright	**Main processes studied** ☒T ☒H ☒M ☒Swelling pressure ☐Gas transfer ☐Other	**Reference concept if pertinent** KBS-3

Main objectives of the experiment or modelling study

The Prototype Repository is a full-scale field experiment in crystalline rock at a depth of 450 m in the Äspö Hard Rock Laboratory (Äspö HRL) (Figure 3) (Svemar et al 2016). The experiment aims to simulate conditions that are largely relevant to the Swedish/Finnish KBS-3V disposal concept for spent nuclear fuel. The original intentions for the Prototype Repository were to operate the inner section for approximately 20 years in order to support the operational permit for the final repository for spent fuel with as accurate information and data as possible, and to operate the outer section for approximately five years in order to demonstrate the feasibility of the KBS-3V method in conjunction with the license application.

General description

The 64m long experimental tunnel at the very end of the main access ramp of the Äspö HRL contains six deposition holes and as many full-scale copper canisters surrounded by MX-80 bentonite buffer. This part of the access ramp was excavated by a tunnel boring machine (TBM) and the test-tunnel was divided into two separate sections. The inner section, with four deposition holes, has been operated since 2001 and the outer section, with two deposition holes, since 2003. Each section was backfilled with a mixture of bentonite (30% by weight) and crushed rock (70% by weight) and finally sealed by reinforced concrete dome plugs. One inner plug separates the inner section from the outer section and one outer plug separates the Prototype Repository from the rest of the Äspö HRL. The canisters contain electrical heaters to simulate the decay heat from spent nuclear fuel.

In accordance to the intents the outer plug was opened and the outer section (23 meter long) was retrieved after about seven years of operation. The overall objective with the retrieval was to study the actual conditions of canister, buffer, backfill and the surrounding rock after being subjected to natural groundwater inflow and heating for a considerable time. The work commenced in 2010 by a joint venture between SKB/Sweden and Posiva/Finland. Later six additional international parties joined the project's organization: NDA (RMW)/United Kingdom, Andra/France, NUMO/Japan, BMWi/Germany, NWMO/Canada and Nagra/Switzerland.

The outcome of the Project confirms that both the originally addressed experimental purposes and the specific objectives of the retrieval of the outer section have been successfully completed. The overall scientific result can be summarized into that the engineered barrier systems (plug, backfill, buffer and canister) have performed as expected and evolved consistently with the established understanding and available modeling capabilities.

Main learning points concerning bentonite homogenization / mechanical evolution and relevance for the project

The samples taken during removal of the backfill and buffer 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 both the backfill and the buffer 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.

Tunnel backfill

Dry density and degree of saturation of the backfill in the tunnel were calculated with the data from the measurement of water content and densityAbout 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 1 for section No 9. The data from all eleven sections have been presented by Johannesson (2014). 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.

This can be explained by the fact that the backfill material at removal was rather heterogeneous and the degree of saturation was calculated from the measurement of water content and density, which were etermined on two different samples although they both were taken from the same spot in the backfill. From the measurements on the investigated sections average density, water content and degree of saturation were calculated. The data from these calculations are shown in Figure 2. They indicate that the backfill was fully saturated on average and that there was a tendency of increased dry density towards the outer plug, which also was observed during the installation (Johannesson et al. 2004). Furthermore, the average dry densities were significantly lower than the density measured at the installation (Johannesson et al. 2004). A probable explanation to this is that the density was not measured directly at the installation. Instead a nuclear gauge probe and a penetrometer were used for interpretation of the density of the filling. These instruments and how they were used have been described by Johannesson et al. (2004). The dry densities measured close to the roof were low (< 1,000 kg/m3), see the example in Figure 1. 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.

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/m3 for providing a sufficiently low hydraulic conductivity (for this particular backfill composition). The margin to the acceptable level is too large for any other interpretation of the result obtained by the Project.

Buffer in deposition holes

The measurements of the water content and density of the buffer in the two deposition holes have been described in detail by Johannesson (2014) and Wieczorek et al. (2014). Johannesson (2014) carried through analyses of samples taken in eight radial directions at a distance of approximately 10 to 50 mm in all blocks, smaller distance close to the canister and the pellets filling and larger in the central parts. Along two of these directions samples were also taken from five different depths in the blocks. Wieczorek et al. (2014) analyzed samples taken in the vicinity of the geoelectric sensors.

Johannesson (2014) suggests that the data from the measurements of the water content he has presented show that the buffer in deposition hole No 6 had on average taken up more water compared to the buffer in deposition hole No 5. Furthermore, the water uptake had been more axisymmetric in deposition hole No 6, see Figure 4, where the water content of respective block R6 in the two deposition holes are plotted and compared. Figure 4 shows that there were large differences in the water content between the two blocks but also within the blocks. Johannesson (2014) further concludes that the measurements show that the uppermost blocks in both two deposition holes have taken up water from the backfill above. The degree of saturation and the water content in these blocks were higher than in the rest of the blocks, resulting in lower dry density.

The material used for the hydro-mechanical tests was taken from one profile in each of the two deposition holes. The location of these profiles was in the warmest part of the buffer in the two deposition holes, i.e. close to the mid-height of the canister. The judgment during planning of the Project was that changes in the buffer would most likely occur in the warmest part of the buffer. For the deposition hole No 6, a profile in block R5 was chosen (direction 165°, see explanation of profile location in Figure 6) and in deposition hole No 5 a profile in block R6 was chosen (direction 50°, see explanation of profile location in Figure 6). The dry density and water content of the bentonite in the investigated buffer profile at the retrieval are shown in Figure 5 and Figure 6.

It is clear that the deposition hole where the wetting was more even (deposition hole 6) also had a more homogenous dry density distribution.

How could this work inform a new experimental or modelling study in BEACON?

The deposition holes in the Prototype repository could very well serve as test cases for modelling in the Beacon project. Both the surrounding rock and the bentonite are well characterized. The difference in dry density distribution between the two deposition holes emphasizes the importance of the wetting history.

References (ideally with web links)

Johannesson L-E, 2014. Prototype Repository. Measurements of water content and density of the excavated buffer material form deposition hole 5 and 6 and the backfill in the outer section of the Prototype Repository. SKB P-13-14, Svensk Kärnbränslehantering AB. (http://www.skb.se/publikation/2713631/)

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Recommendations for BEACON project/ What would I do differently, were I to repeat my earlier study?

Not really appropriate.

The main purpose of the Prototype Repository was not the study the mechanical evolution. However, in a sense, this part of the experiment was actually rather successful.

Project Acronym RESEAL II	**Location** Hades URF	**Type** In situ
Lead organiser SCK-CEN	**Start date**	**End date** 2007
Main partners involved in the project ANDRA, CEA, CIEMAT, UPC	**Characteristics of swelling clay** 50% powder, 50% pellets	**Water Saturation** Artificial
Instrumentation Pore water pressure, total stress, displacement, relative humidity	**Main elements related to homogenization**	**Interfaces with other material**
Modelling Yes/no: Yes Groups/Codes :	**Main processes studied** ☐T ☒H ☒M ☐Swelling pressure ☐Gas transfer ☐Other	**Reference concept if pertinent**

Main objectives of the experiment

To ensure the long-term safety of a repository, the backfill material must have enough swelling potential upon hydration to perform the sealing function satisfactorily. As swelling potential depends essentially on the dry density of the sealing material, it may be necessary to apply a significant compaction effort in order to achieve an adequate density value. Often, this causes operational difficulties.

An interesting alternative is to use, as sealing material, a mixture of bentonite powder and highly compacted bentonite pellets. The resulting material is obviously highly heterogeneous. The behavior of such a material upon hydration is likely to be complex and must be understood if a sufficient degree of confidence in the design and performance of the seal is to be achieved.

General description

A large-scale sealing test (named the shaft sealing test) has been performed in the Hades underground research facility (URF). The URF is located in Mol (Belgium) and it has been excavated to a depth of 220 m in Boom Clay. The sealing test has been performed in an experimental shaft located at the end of the main test drift. The sealing material is a mixture of 50% powder and 50% highly compacted pellets of FoCa clay.

A large number of sensors measuring pore water pressure, total stress, displacement and relative humidity were installed to follow the hydromechanical evolution of the seal and the surrounding host rock.

After backfilling the shaft and closing the seal, a 7-month period was allowed to elapse to achieve steady-state conditions in the zone around the test. Afterwards, artificial hydration was applied

during 6 years.
Main learning points concerning bentonite homogenization / mechanical evolution and relevance for the project
How could this work inform a new experimental or modelling study in BEACON?
References (ideally with web links) Gens A. et al. (2011). Hydromechanical behaviour of a heterogeneous compacted soil: experimental observations and modelling. *Géotechnique* **61**, No. 5, 367-386 [**doi**: 10.1680/geot.SIP11.P.015] Gens A. et al. (2009). RESEAL II PROJECT: Final report on modelling (WP4). SCK-CEN External Report SCK-CEN-ER-80.
Recommendations for BEACON project

Project Acronym SB (in situ test)	**Location** Mont Terri rock lab, CH	**Type** In situ test
Lead organiser GRS	**Start date** January 1995	**End date** December 2007
Main partners involved in the project Nagra	**Characteristics of swelling clay** Sand/bentonite mixtures (calcigel)	**Water Saturation** artificial
Instrumentation Fluid and total pressure sensors	**Main elements related to homogenization**	**Interfaces with other material**
Modelling Yes Groups/Codes : GRS, Code_Bright	**Main processes studied** ☐T ☒H ☒M ☐Swelling pressure ☐Gas transfer ☐Other:	**Reference concept if pertinent**

Main objectives of the experiment or modelling study

Qualify sand/bentonite mixtures as material for engineered barriers with reduced cohesion and gas entry pressure to allow for discharge of corrosion gases while maintaining sufficiently low permeability to water and sufficiently high swelling pressure

General description

This text follows closely the respective section of a publication for the Mont Terri 20th anniversary (Wieczorek et al. 2017).

2 In-situ setup and results

After successful completion of the mock-up tests, the in-situ experiment was set up at the Mont Terri rock laboratory in 2005/2006 (Fig. 2). Four boreholes were installed and instrumented similarly to the mock-up tests:

- Boreholes SB1 and SB2 are equipped with 1 m long seal sections of 65/35 sand/bentonite mixture
- Borehole SB15 is equipped with an 0.5 m long seal section of 50/50 sand/bentonite mixture (sealing length was reduced due to an expected slower re-saturation with the higher bentonite content)
- Borehole SB13 is equipped with 0.5 m long seal section of pure granular sodium bentonite for comparison

The bulk densities of the seals achieved at construction were somewhat lower than those obtained in the laboratory (1.64 – 1.72 g/cm³) except for SB2 (1.91 g/cm³).

The experimental procedure followed the one described for the mock-up tests. The test procedure was to

- Instrument the test tubes
- Determine initial installation density of the granular sand/bentonite mixture
- Determine the initial gas permeability
- Inject water from the bottom to re-saturate the seal
- Determine seal permeability to water at full saturation
- Inject gas and determine gas entry pressure and permeability after break-through
- Determine the final water content in the seal by post-mortem sampling and analysis

During re-saturation of the seals it was, however, found that in both boreholes SB1 and SB15 water bypassed the seal element. This can be due to a pronounced borehole disturbed zone around the boreholes and is aided by the low installation density in these boreholes – the swelling pressure is not high enough to re-compact the EDZ. Since the swelling pressure sensors in these boreholes failed, too, they could not be evaluated further.

The test in SB2 ran more successful. Between February and April 2006 the injection pressure was increased stepwise to 0.38 MPa. Swelling pressure showed a quick response and reached final values between 0.15 and 0.19 MPa within less than one year after start of injection. No outflow of water could, however, be observed even after more than 5½ years of re-saturation.

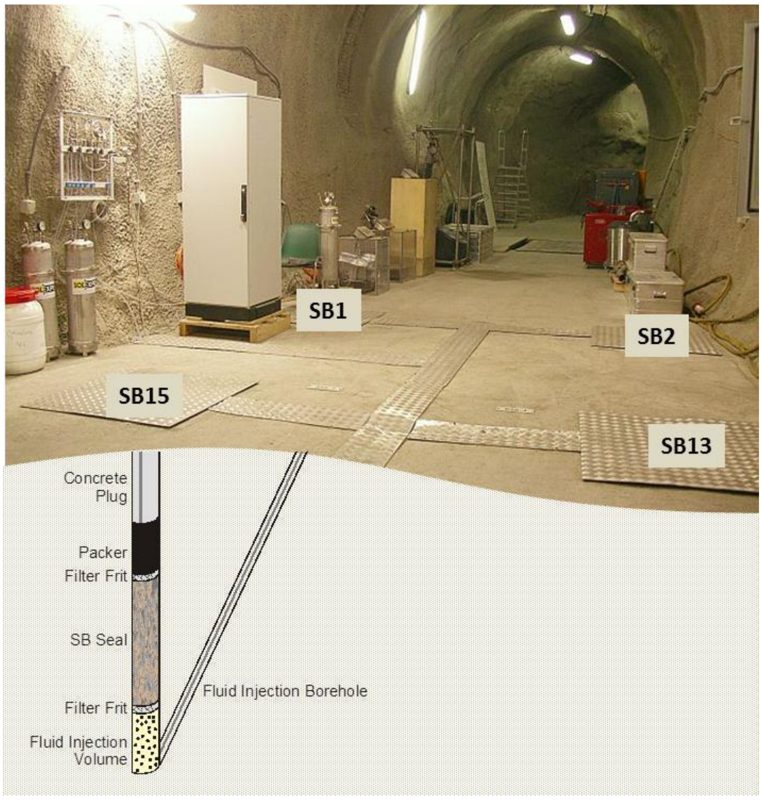

Fig 2. Overview of SB in-situ configuration. SB1 and SB2: boreholes with 65/35 sand/bentonite seal, SB15: borehole with 50/50 sand/bentonite seal, SB13: borehole with pure bentonite seal.

In order to investigate this problem and find a way to successfully complete the experiment, a new model simulation was performed taking into account a desaturation/pore pressure reduction in the gallery near-field which could be quantified by adjacent pore pressure measurements. The result was that the applied injection pressure was not sufficient to induce an outflow at the top of the borehole. Increasing the injection pressure to 1.1 MPa led to measureable outflow at the seal top, and a water permeability of 4.2×10^{-18} m^2 was determined. Afterwards, gas injection resulted in a gas entry pressure of 0.45 MPa and a gas permeability at break-through around 10^{-16} m^2. The results of this test were quite in line with the preceding laboratory and mock-up tests, showing that the sand/bentonite mixture fulfilled the requirements.

The fourth test, SB13, involved pure granular bentonite as sealing material. As could be expected, much higher swelling pressures (>3 MPa) were obtained here, although it was not possible to completely re-saturate the sealing element within the experiment time.

After finishing the experiment, samples were taken from all boreholes between November 2011 and March 2012. This involved retrieving of the concrete plug and the packer and drilling core holes into the seal and the surrounding rock. The samples were evaluated in terms of water content. For the samples from SB2, the water content ranges between 16.1% and 20.5%. This is in good agreement with the mock-up test. For SB1 and SB15, the water content values are much higher (23% – 35%), as a consequence of their low emplacement density. Water content measurement of SB13 (29.8% in average) showed that the pure bentonite seal was close to full saturation.

Main learning points concerning bentonite homogenization / mechanical evolution and relevance for the project

The focus of the experiment was on sand-bentonite mixtures. The data from the borehole with pure bentonite are meagre, since swelling pressure exceeded the sensor range. Relevance for Beacon sems limited.

How could this work inform a new experimental or modelling study in BEACON?

The in-situ experiment does not provide enough data for a modelling case.

References (ideally with web links)

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Wieczorek, K., I. Gaus, J.C. Mayor, K. Schuster, J.-L. García- Sineriz, T. Sakaki (2017). In-situ experiments on bentonite-based buffer and sealing materials at the Mont Terri rock laboratory (Switzerland). Swiss Journal of Geosciences, 110.

Recommendations for BEACON project/ What would I do differently, were I to repeat my earlier study?

Better characterize the rock around the test boreholes, put more sensors there.

Project Acronym SEALEX (field tests)	**Location** Tournemire URL	**Type** Field test
Lead organiser IRSN	**Start date** Autumn 2012	**End date** Ongoing
Main partners involved in the project	**Characteristics of swelling clay** MX-80 70/30 bentonite/sand	**Water Saturation** Artificial
Instrumentation RH, axial and radial stress	**Main elements related to homogenization** Technological void between bentonite seal and host rock.	**Interfaces with other material**
Modelling Yes/no: Yes Groups/Codes : Decovalex-2015	**Main processes studied** ☐T ☒H ☒M ☒Swelling pressure ☐Gas transfer ☐Other	**Reference concept if pertinent** ANDRA

Main objectives of the experiment

- Three large scale sealing experiments have been installed in the Tournemire URL.

-The in-situ tests are analysed specifically focusing on the impact of technological voids on the long-term performance of bentonite-based seals.

- The important role of the technological gap, on the saturation and swelling pressure kinetics is demonstrated.

- Observed differences in axial and radial swelling pressure measured in each in-situ test, suggests a heterogeneous distribution of bentonite dry density which might lead to a remaining gradient after full saturation.

General description

In the framework of SEALEX project, three in-situ performance tests have been installed in the Tournemire URL to investigate the impact of technological voids on the long term performance of the bentonite-based seals. These tests are still in progress, but the collected set of data provides already valuable information on the hydro-mechanical behaviour of the tested seals. The swelling cores consisted of pre-compacted blocks of a natural sodic Wyoming bentonite (MX80 type) mixed with quartz sand in a ratio of 70/30 (in dry mass) with different geometries (monolithic disks or four jointed disks). Two types of technological gaps existed within the experiments: annular gaps between the bentonite-based blocks and the rock and gaps between the blocks. Artificially injected water volume, relative humidity, and swelling pressure in both radial and axial directions were monitored. Comparison of the results showed that the presence of technological gaps constituted new hydration sources (annular gaps) and flow paths (gaps between the blocks) that changed the saturation kinetics. The effect of technological gaps was also evidenced when comparing the swelling pressure kinetics. The existence of an additional gap for one SEALEX test between the packer and the host-rock greatly influenced the axial swelling pressure evolution, since it constituted a free volume into which the bentonite could extrude. Compared to monolithic discs, the evolution rates of radial swelling pressure were significantly lower in case of four jointed discs. For each test, different evolution of radial swelling pressure was observed, suggesting a heterogeneous structural distribution of bentonite/sand mixture within the blocks.

Main learning points concerning bentonite homogenization / mechanical evolution and relevance for the project

How could this work inform a new experimental or modelling study in BEACON?

References (ideally with web links)

Mokni N, Barnichon J-D, Dick P, Nguyen TS, 2016. Effect of technological macro voids on the performance of compacted bentonite/sand seals for deep geological repositories. International Journal of Rock Mechanics and Mining Sciences, 88, 87-97.

Recommendations for BEACON project

Project Acronym Temperature Buffer Test (TBT)	**Location** Äspö HRL	**Type** URL
Lead organiser ANDRA/SKB/Clay Technology AB	**Start date** Spring 2003 (installation)	**End date** Winter 2009/2010 (dismantling)
Main partners involved in the project Supported by ENRESA and DBE	**Characteristics of swelling clay** MX-80 bentonite	**Water Saturation** Artificial
Instrumentation Sensors for measurement of temperature, relative humidity, total pressure, pore pressure, cable force and lid displacements.	**Main elements related to homogenization** High density bentonite blocks installed together with compressible sand-filled slots.	**Interfaces with other material** Sand fillings in filter and shield; Heaters of carbon steel.
Modelling Clay Technology/Code_Bright Clay Technology/Abaqus UPC/Code_Bright	**Main processes studied** ☒T ☒H ☒M ☒Swelling pressure ☐Gas transfer ☒Other Chemical/mineralogical characterizations Retrievability of heaters	**Reference concept if pertinent** No

Main objectives of the experiment

The Temperature Buffer Test (TBT) was a joint project between SKB and ANDRA, with support from ENRESA (modelling) and DBE (instrumentation). The project aimed at improving the understanding and to model the thermo-hydro-mechanical (THM) behaviour of buffers made of swelling clay exposed to high temperatures (over 100˚C) during the water saturation process.

General description

The ***installation*** of the test was performed in the beginning of 2003, and consisted of different components (Figure 1): the depositions hole (8.5 m deep, Ø 1.76 m); the heating system with two heaters (3 m long, Ø 0.61 m); the bentonite blocks (0.5 m thick; water content: ~17.5 %; void ratio: ~0.63 or ~0.57); slots filled with sand (in filter towards the rock wall, and in shield towards the upper heater) or pellets; the retaining construction with the plug, lid and anchor cables; the system for artificial saturation through the sand filter; and the instrumentation.

The ***operational conditions*** evolved during the course of the test (Figure 1). During the first ~1700 days the power output was 1500 W (1600 W during a limited period) from each heater. This was subsequently changed to 1000 and 2000 W, for the upper and lower heater respectively, and was kept at these levels during the last ~600 days. The second phase implied that the temperature in the innermost part of the bentonite around the lower heater reached approx. 155 ˚C. The hydration of the bentonite was initially made with a groundwater from a nearby bore-hole, but this groundwater was replaced with de-ionized water after ~1500 days, due to the high flow resistance of the injections points in the filter, which implied that a high filter pressure couldn't be sustained. The sand shield around the upper heater was hydrated from day ~1500 to day ~1800. The ***sensors data*** consisted of evolutions and distributions of temperature (Figure 2), relative humidity, total pressure, pore pressure, cable force and lid displacements.

*The **dismantling operation*** was performed during a period from the end of October 2009 to the end of April 2010. One important goal with the dismantling operation was to obtain different types of samples: i) bentonite cores devoted for the so-called base program. These Ø 50 mm cores spanned over the entire height of the bentonite blocks and were taken in four directions at 50 mm intervals (Figure 3); ii) large pieces of bentonite, so-called big sectors, were devoted for the hydro-mechanical and chemical (HM&C) characterization program and represented the entire radial distribution; and iii) so-called end sectors, i.e. pieces taken close to the rock or the lower heater. A second goal was to investigate the retrievability of the upper heater, as facilitated by the possibility to remove the surrounding sand shield. The experiment was also documented in different aspects: by measurements of the coordinate of different joints and interfaces; verification of sensor positions and retrieval of sensors for subsequent function control; and by documentation of the operation through photography.

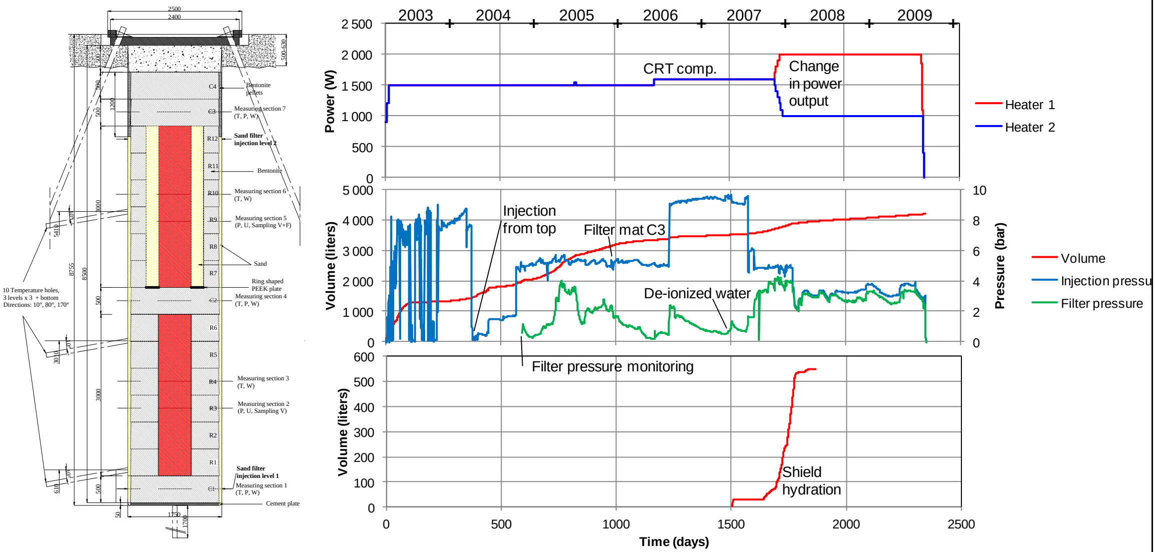

Figure 1. *Design of the TBT experiment (left). Timeline of major events regarding power output (upper right), filter injection system with total injected volume and pressures (middle right); and shield hydration with total injected volume (lower right).*

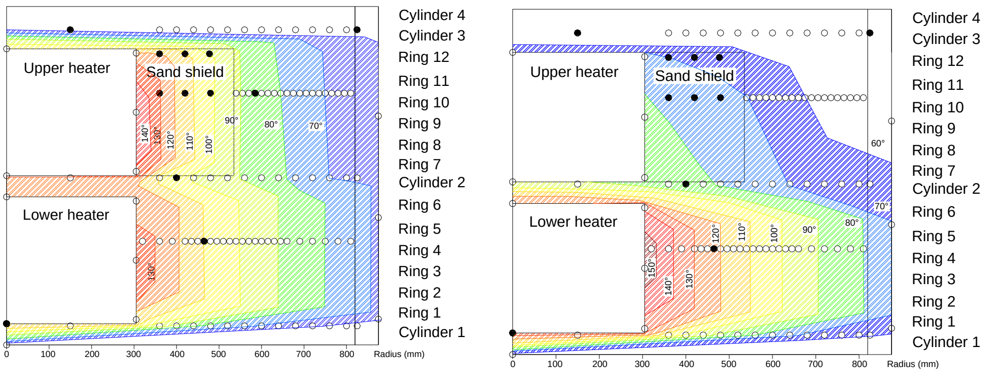

Figure 2. *Temperature distribution on January 1, 2007 (left) and August 16, 2009 (right).*

*The **base program***, i.e. the determination of water content and density, was performed in parallel to the dismantling operation. The cores and end-sectors taken from the bentonite blocks were cut in smaller samples before the analysis. These analyses resulted in detailed distributions and contour plots of the determined properties (Figure 4).

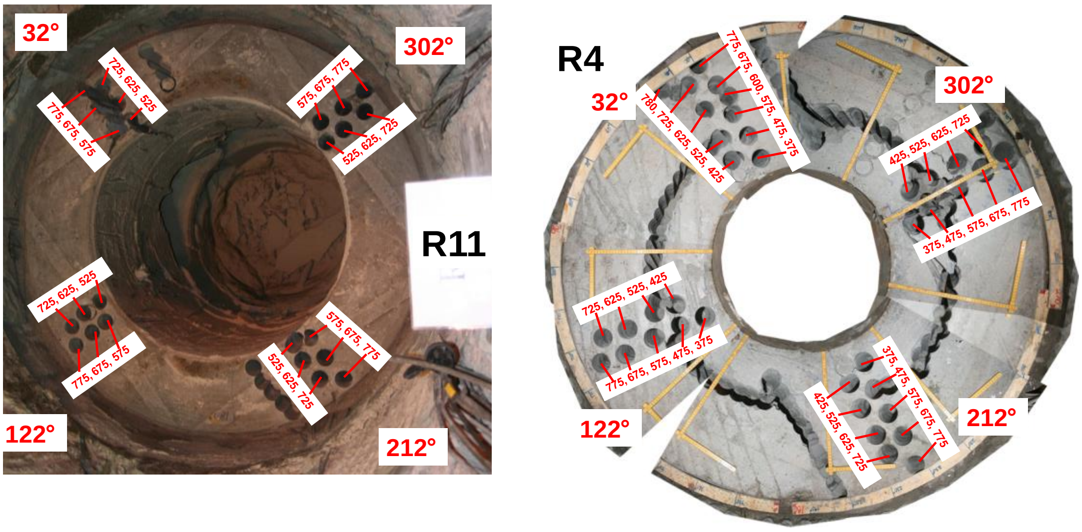

__Figure 3__. Cores of Ring 11 (left) and Ring 4 (right) sampled during the dismantling.

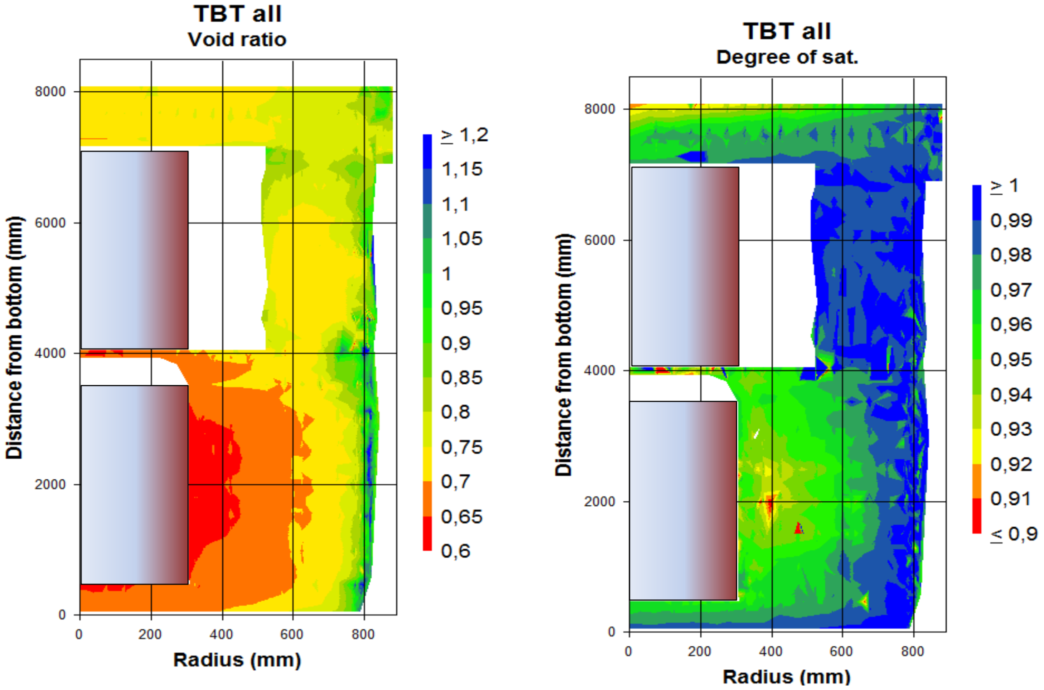

***Figure 4.** Results from measurements of density and water content. Distributions of void ratio (left) and degree of saturation (right) at the end of the test.*

*The **HM&C characterization program*** was launched subsequent to the dismantling operation. The main goal was to investigate if any significant differences could be observed between the field test material and the reference material. The following hydro-mechanical properties were determined for the materials: hydraulic conductivity, swelling pressure (Figure 5), unconfined compression strength, shear strength and retention properties. The following chemical/mineralogical properties were determined: anion concentration of water leachates, chemical composition, cation exchange capacity and exchangeable cations, mineralogical composition, element distribution and microstructure, iron oxidation state. The analyses were performed on bulk samples, and in some cases also on Na-converted fine fraction (< 0.5 μm).

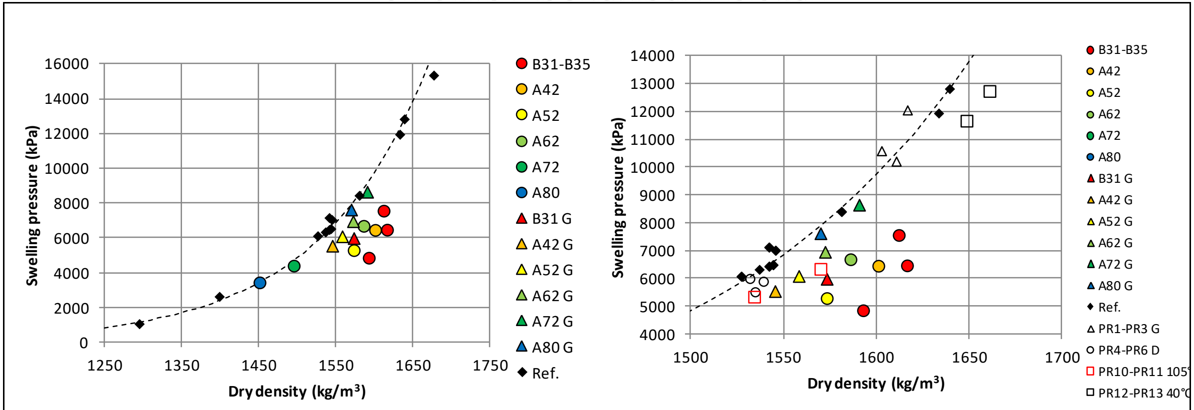

Figure 5. *Swelling pressure as a function of dry density. Field samples are denoted with colored markers: circles and triangles denote trimmed, and ground and re-compacted samples, respectively. References samples are denoted with black or unfilled markers.*

Several ***THM modelling*** tasks have been carried out since the beginning of the project: initial scoping calculations, predictions and first evaluations of the field test; as well as predictions and evaluations of two parallel mock-up tests. The final modelling task of the field test was resumed after the dismantling operation. The main part of this work consisted of numerical modelling of the field test. Three modelling teams presented several model cases for different geometries and different degree of process complexity. Two codes, Code_Bright and Abaqus, were used (see example in Figure 6). The work also included different evaluations of experimental results with the aim to validate a number of data sets (Figure 7), and to assess the conditions in the tests prior to the dismantling operation. Finally, the validity of the material models was assessed. This task was a test of the different parts of the material models, especially for the bentonite, for their ability to reproduce the experimental data (see example in Figure 8).

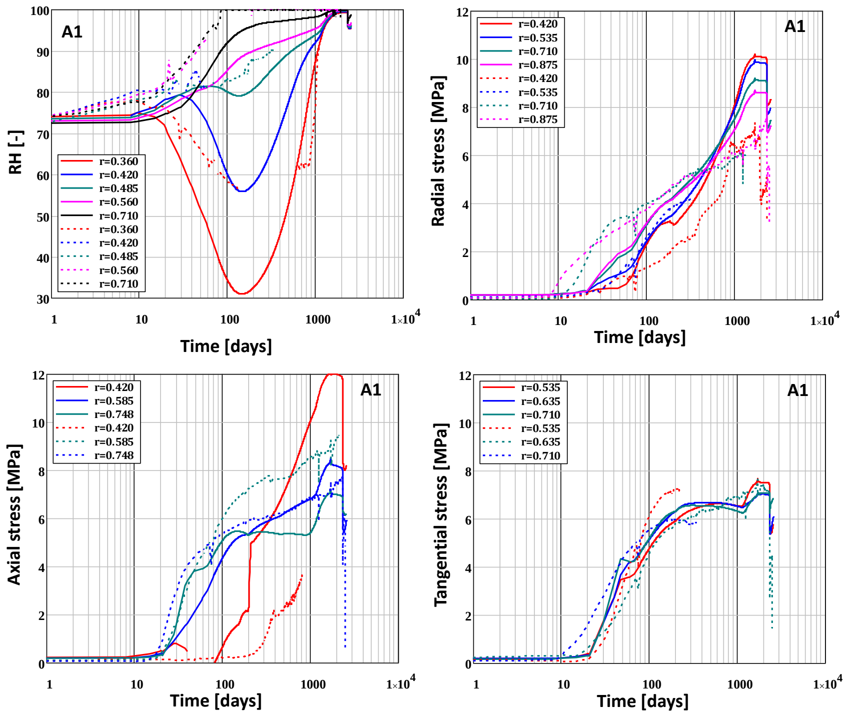

Figure 6. *Evolution of relative humidity as well as radial, axial and tangential stresses seen in one numerical THMg Code_Bright model (solid lines) compared with the actual evolution in Ring 3 and 4 (dashed lines).*

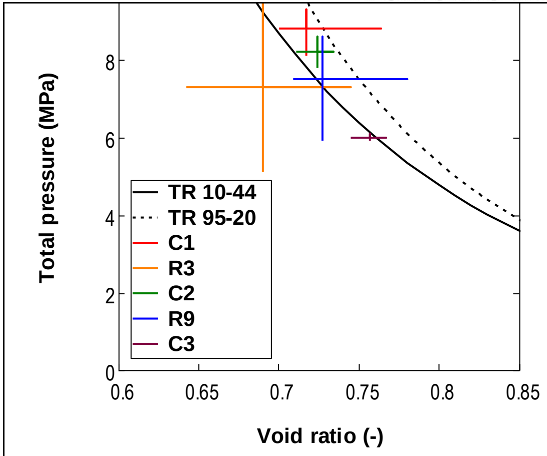

Figure 7. Compilation of final pressures (minimum, mean, maximum) for each instrumented block versus the corresponding void ratios at dismantling (minimum, mean, maximum). Two swelling pressure curves shown for comparison.

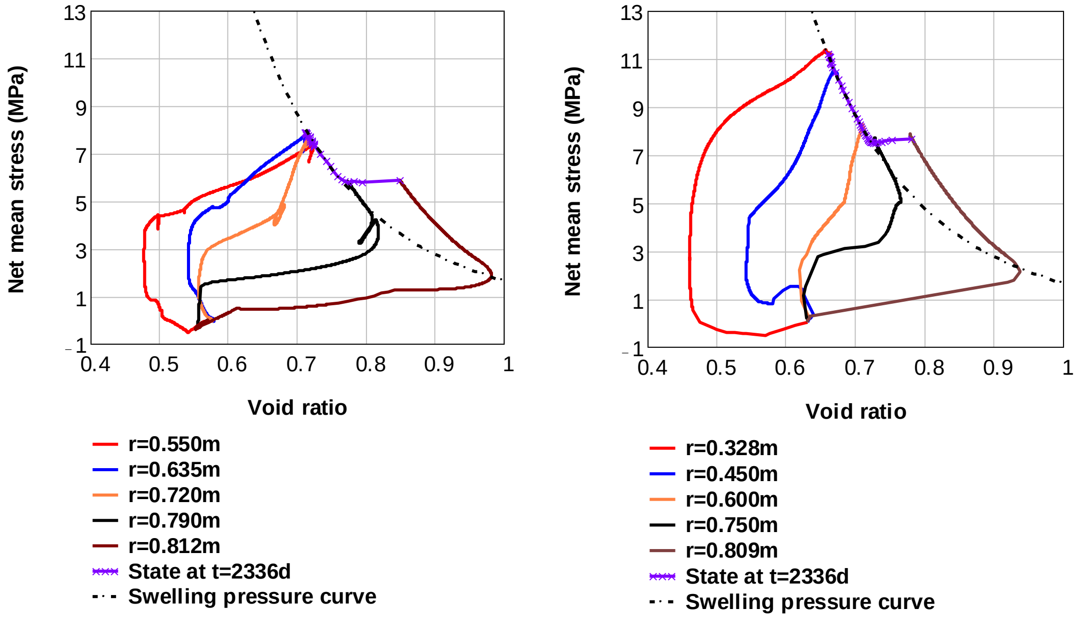

Figure 8. *Stress paths for different radii and final state in two Code_Bright models together with adopted swelling pressure curve. Results for model of the upper package (left), and lower package (right).*

Main learning points concerning bentonite homogenization / mechanical evolution and relevance for the project

The following observations were made from the assessment of the validity of the hydro-mechanical material model:

- Swelling pressures, i.e. the relation between the void ratio and net mean stress during the final state, could be well reproduced with the material model developed for the SR-Site (Figure 8). This was facilitated by the inbuilt swelling pressure relation in the kappa_s function.
- The plastic parameters describing the yield surface was highly related to the void ratio. The yield surface is however (according to the BBM) unaffected during swelling at fairly isotropic stress states. The current approach to adopt plastic parameters for swelling materials (i.e. highly compacted blocks) has therefore been to set the parameter values for a target void ratio representing totally homogenized conditions. This approach was improved in this modelling task, through the adoption of a LC-curve included in the BBM. The void ratio

dependence of the yield surface could in this way be mimicked by a suction dependence of the yield surface.

- Calculated von Mises stresses were in some cases significantly lower than the experimental data. This suggests that the shape of the actual yield surface was different than the shape implied by the modified Cam-Clay surface included in the BBM.

How could this work inform a new experimental or modelling study in BEACON?

The objective of the project was to improve the understanding and to model the THM behaviour of a bentonite buffer at high temperature. The experiment was generally well defined, densely instrumented, and has been used for several modelling tasks.

Nevertheless, the high temperature level has complicated the processes, since this means that it is necessary to include the transport of gas in a model of this test. High temperature also means that the temperature dependence of the density of water is quite important. Together with the quite long time needed for the dismantling (almost 6 months), the high temperature level also meant that the saturation profiles and void ratio profiles were affected by the dismantling operation. The test is therefore not considered to be suitable as a modelling study in BEACON.

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Johannesson L-E, Sandén T, Åkesson M, Bárcena I, García-Siñeriz J L 2010. Temperature Buffer Test. Installation of buffer, heaters and instruments in the deposition hole. SKB P-12-02. Svensk Kärnbränslehantering AB.

Johannesson L-E, 2010. Temperature Buffer Test. Measurements of water content and density of the excavated buffer material. SKB P-12-05. Svensk Kärnbränslehantering AB.

Recommendations for BEACON project

Appendix B 4: Modelling studies

INPUT to Beacon Work Package 2 - Collection and compilation of existing data and available models

Project Acronym **BÅT**	**Location** Äspö HRL	**Type** URL
Lead organiser SKB	**Start date** 2013-05-01	**End date** 2013-05-20
Main partners involved in the project SKB, Posiva	**Characteristics of swelling clay** N.A.	**Water Saturation** N.A.
Instrumentation No	**Main elements related to homogenization** ***Compression of block and pellets tunnel backfill***	**Interfaces with other material** Buffer/tunnel backfill and rock
Modelling Yes/no: Yes Groups/Codes : Claytech/Abacus Wesi Geotecnica Srl / PLAXIS 2D and 3D	**Main processes studied** ☒T ☒H ☒M ☒Swelling pressure ☐Gas transfer ☐Other	**Reference concept if pertinent** KBS3-V

Main objectives of the experiment

Developing models of buffer upward swelling and block and pellet tunnel backfill compression.

The experiment as such was focused on the deformation of the tunnel backfill. The modelling of the experiment is presented in /TR 17-03/. The model of buffer saturation, expansion and the coupled compression of the backfill was further developed and used for sensitivity analyses /TR 16-08/

General description

A tunnel with deposition tunnel dimensions was backfilled with bentonite blocks and pellets according to the current backfill design. The upward swelling of the buffer was simulated by four hydraulic cylinders in contact with a steel plate and a bentonite block. The force, displacement and the pressure on the rock walls were measured .

The modelled results agreed well with the measured up to about 8 cm displacement when the backfill blocks started to crack, which confirmed the backfill model. The backfill model has been used for performing a sensitivity analyses of the consequences of bentonite swelling on a dry backfill for different cases /Börgesson and Hernelind 2016/. In this work the models and techniques that were used for SR-Site /SKB 2011/ have been further developed and tested.

A few cases were also simulated using a 3D model. The comparison with the 2D model showed that the 2D model gives more pessimistic results, i.e. larger upward swelling.

Main learning points concerning bentonite homogenization / mechanical evolution and relevance for the project

General conclusions from the work:

- The tested models could simulate the deformation of the backfill until diffused failure of the blocks occurred
- The reference design results in acceptable upward swelling
- The stiffness and thickness of the pellet filling in the floor and roof are the factors most sensitive to changes
- Only low density buffer (starting values close to the limit) causes problems for the buffer.

Relevance for the Beacon project:

This is an example of how THM models are used for designing buffer and backfill and describing the evolution.

How could this work inform a new experimental or modelling study in BEACON?

It is necessary to develop and verify the models for buffer/backfill interaction. To do this lab tests and full scale tests are probably necessary. An iterative approach to model development is recommended. SKB is planning to start a project including this during autumn 2017.

References (ideally with web links)

In prep:

Börgesson L, Hernelind J, 2016. Modelling of the mechanical interaction between The buffer and the backfill in KBS-3V Modelling results 2015. SKB report TR-16-08. Svensk Kärnbränslehantering AB.

Leoni M, Börgesson L, Keto P, 2017. Modelling of the buffer swelling test in Äspö HRL - Validation of numerical models with the ÅSKAR test data. SKB report TR-17-03. Svensk Kärnbränslehantering AB.

Recommendations for BEACON project

There is a need to develop the basic understanding and modelling capabilities of bentonite swelling and Beacon is focused on this. However the implementation of models for the full scale EBS will run in parallel and it will give a more complete picture of also this is taken into consideration.

Project Acronym Development of thermo-hydro-mechanical model for expansive soils and simulation of nuclear waste repository	**Location**	**Type** Research grant project
Lead organiser Charles University & Czech Technical University (Czech Republic)	**Start date** January 2015	**End date** December 2017
Main partners involved in the project	**Characteristics of swelling clay**	**Water Saturation** Artificial/natural
Instrumentation	**Main elements related to homogenization**	**Interfaces with other material**
Modelling Yes Groups/Codes : Charles University, Czech Technical University/Code SIFEL	**Main processes studied** ☐T ☐H ☐M ☐Swelling pressure ☐Gas transfer ☐Other	**Reference concept if pertinent**

Main objectives of the experiment or modelling study

The main task of the project is development and evaluation of an advanced thermo-hydro-mechanical model for partially saturated expansive double structure soils. The model is based on the theory of hypoplasticity. Thermal effects are incorporated into the model by defining new formulation for water retention behaviour of macrostructure and microstructure. The model has been implemented into a coupled thermo-hydro-mechanical finite element code SIFEL. An accurate explicit time-integration scheme has been be utilized to ensure robustness and accuracy of the simulations. Finally, the model has been be evaluated on the boundary value problem level by means of simulations of large-scale mock-up experiments of nuclear waste repositories. To calibrate the model, laboratory experiments have been performed in the soil mechanics laboratory. Simulation results have been be compared with the monitoring data to reveal advantages as well as shortcomings of the approach.

The main objective of the research project is development and evaluation of an advanced thermo-hydro-mechanical model for partially saturated expansive double structure soils. The model is based on the theory of hypoplasticity. Expansive soil model by Mašín (2013), enhanced by a novel hypoplasticity formulation with the explicit state boundary surface by Mašín (2012, 2013, 2014) has been adopted for predicting expansive soil behaviour at constant temperature. Thermal effects have been incorporated into the model by defining new formulation for water retention behaviour of macrostructure and microstructure. Thermal behaviour of macrostructure has been modelled by means of an approach developed by Mašín and Khalili (2012). The model has been implemented into the single-element driver developed at Charles University, and it will has been evaluated on the single-element level using experimental data available from the literature.

The second main objective of the project is the implementation of the model into a coupled thermo-hydro-mechanical finite element code SIFEL developed by the research group of the Department of

Mechanics of the Faculty of Civil Engineering of the Czech Technical University. The implementation will takes into consideration highly-nonlinear structure of the constitutive model. An accurate explicit time-integration scheme has been utilised to ensure robustness and accuracy of the simulations. Finally, the model has been be evaluated on the boundary value problem level by means of simulations of large-scale mock-up experiments. To this aim, laboratory experiments have been performed in the soil mechanics laboratory for calibration of parameters of the newly developed model.

General description

The double structure model consists of two parts (two individual models): model for the behaviour of macrostructure and model for the behaviour of microstructure. While the thermal behaviour of macrostructure is relatively well understood, at least from the conceptual point of view, a number of aspects related to the behaviour of microstructure remain unclear. In particular, we need to answer the question how temperature influences inter-platelet force status (London van der Walls forces and diffuse double layer forces), and thus how it influences compressibility of microstructure. We also need to study how temperature influences water retention of microstructure.

An advantage of the formulation of hypoplastic models is its “hierarchical structure”. That is, advanced models (such as the model for unsaturated soils) are based on equivalent models for saturated soils, and for specific conditions (in the case of unsaturated model for zero suction) the advanced model reduces to the basic model. The hydro-mechanical hypoplastic model for expansive soils by Mašín (2013) is based on the saturated clay hypoplasticity model by Mašín (2005). While this model is reasonably accurate and robust in most cases, it has been replaced by the recently developed model with explicit formulation of the asymptotic state boundary surface (Mašín 2012, 2013b, 2014).

The aim of the project is the development of a complete thermo-hydro-mechanical model for materials with double structure. This will require incorporation of temperature into the model. The incorporation of temperature into the macrostructural model has been be performed using the approach by Mašín and Khalili (2012). This approach assumes the asymptotic state boundary surface size dependent on temperature, and it thus considers macrostructural collapse in the case of temperature increase in soils with the state close to the asymptotic state boundary surface. The model has been be combined with microstructural model and tested on the single-element level using data from literature.

Time integration of a constitutive model at an integration point is based on the Runge-Kutta method. The Butcher tables have advantageously been used because adaptivity is implicitly implied by them. The difference between various orders of the Runge-Kutta method serves as an error indicator. The constitutive relationships have been implemented in a single-element driver written in the Fortran programming language which is used by Charles University research group. With respect to future implementation of the material models to the open source computer code SIFEL, the Runge-Kutta method has been implemented there alongside the integration methods used for material models implemented earlier.

After validation of the constitutive relationships in a single-element driver, they have been transferred to the object oriented computer code SIFEL written in the C++ programming language. SIFEL is a open source computer code for solution of mechanical, transport and coupled thermo-hydro-mechanical problems. SIFEL enables one, two or three-dimensional analysis of stationary or non-stationary problems with linear or non-linear response. SIFEL contains one-dimensional, triangular, quarilateral, tetrahedral and hexahedral finite elements with linear and quadratic shape functions. SIFEL has been developped to solve multi-physics problems and therefore it is an ideal environment for the implementation of material models developed in this project.

The aim of this project is to develop a fully coupled thermo-hydro-mechanical approach applicable to expansive soils. Therefore, the set of governing equations has to be specified. The mechanical part is governed by the equilibrium conditions while the transport processes are governed by balance equations. Special attention has been devoted to the boundary conditions because they are an inseparable part of an analysis. The modified and full Newton-Raphson method is used on the structural level. The staggered and fully coupled approach has been used within this project. As the constitutive model developed is highly non-linear, we had to test robustness of the SIFEL solver to tackle this non-linear time-dependent problem.

With respect to relatively complex form of the constitutive models of a soil under thermo-hydro-mechanical conditions, the models can be transfered directly from the single-element computer code to the general computer code SIFEL. In the SIFEL code, an environment for arbitrary material model, is prepared in a separate class. Each instance of the class integration point contains all informations needed to determination of actual state. There are arrays for the strain, stresses and all internal parameters. A material model is responsible for the determination of correct stresses from trial strains.

Examples of predictions of the the hypoplastic model implemented in the SIFEL software are in Fig. 1. In this figure, results of constant hydraulic gradient permeability tests accompanied by measurement of vertical (swelling) pressure by Hausmannová (2017) are shown together with model predictions. Three initially unsaturated (suction of 100 MPa) compacted bentonite samples at three different dry densities have been tested under constant volume, they were subject to water pressure through their bottom, while they were open to the atmosphere at the top, where pressure cell was located. Bottom water pressure has been increased in steps, which led to an increase of hydraulic gradient and of the vertical stress. The model, calibrated using single element tests only, predicts accurately swelling pressures and their dependency on the initial dry density.

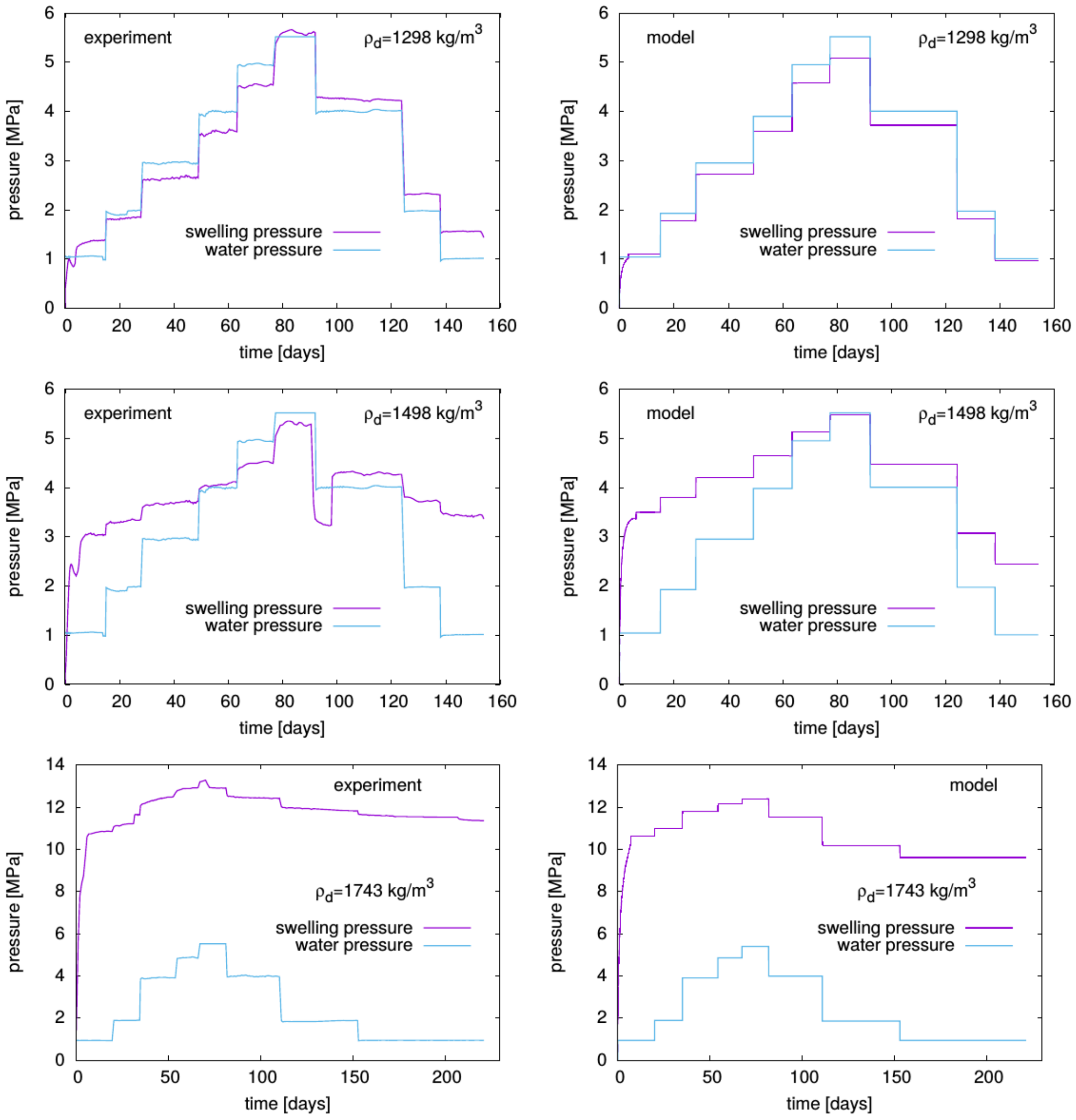

Figure 1: Swelling pressures during constant hydraulic gradient constant volume tests by Hausmannová (2017) predicted by hypoplastic model implemented in SIFEL finite element software.

Main learning points concerning bentonite homogenization / mechanical evolution and relevance for the project

The model of thermo-hydro-mechanical behaviour of bentonite, which is developing within the project, can be used for numerical simulations within the BEACON project. The model is being calibrated against the mock-up test performed by the Czech Technical University (Centre of Experimental Geotechnics).

How could this work inform a new experimental or modelling study in BEACON?

This project prepared a background needed for use within the BEACON project. Constitutive model and finite element implementations are ready to use within BEACON.

References (ideally with web links)

Hausmannová, L. (2017). The influence of water pressure on the hydraulic conductivity and swelling pressure of Czech bentonites. PhD thesis, Czech Technical University, Centre of Experimental Geotechnics

Mašín, D. (2005). A hypoplastic constitutive model for clays. International Journal for Numerical and Analytical Methods in Geomechanics 29, No. 4, 311-336.

Mašín, D. (2012). Hypoplastic Cam-clay model. Géotechnique 62, No. 6, 549-553.

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Mašín, D. (2013b). Clay hypoplasticity with explicitly defined asymptotic states. Acta Geotechnica 8, No. 5, 481-496.

Mašín, D. (2014). Clay hypoplasticity model including stiffness anisotropy. Géotechnique 64, No. 3, 232-238.

Mašín, D. and Khalili, N. (2012). A thermo-mechanical model for variably saturated soils based on hypoplasticity. International Journal for Numerical and Analytical Methods in Geomechanics 36, No. 12, 1461-1485.

SIFEL. http://mech.fsv.cvut.cz/~sifel/

Recommendations for BEACON project

To model B75 bentonite mechanical evolution, all material parameters needed by the hypoplastic model need to be calibrated. In particular, we need to focus on the parameter controlling the thermal behaviour (laboratory experiments will be performed as a part of the BEACON project). Subsequently, the model may need to be adjusted to predict as closely as possible the experimental data.

Project Acronym TF on EBS – Sensitivity and Code Comparison Task	**Location** Generic	**Type** Generic
Lead organiser SKB (TF on EBS) BGR (Sensitivity and Code Comparison Task)	**Start date**	**End date**
Main partners involved in the project BGR, UPC, Amec FW, Clay Technology, CRIEPI, EPFL, SKB	**Characteristics of swelling clay**	**Water Saturation** Natural
Instrumentation	**Main elements related to homogenization**	**Interfaces with other material**
Modelling Yes/no: Yes Groups/Codes: BGR / OpenGeoSys UPC / CodeBright Amec FW / Tough2-FLAC3D Clay Technology / Comsol CRIEPI / LOSTUF EPFL / Lagamin	**Main processes studied** ☒T ☒H ☒M ☐Swelling pressure ☐Gas transfer ☐Other	**Reference concept if pertinent** KBS-3V

Main objectives of the modelling study

To investigate the effects of value uncertainties on the modelling results, to improve the understanding of the coupled processes active in the repository near field and to increase confidence in the predictive capabilities of different numerical codes, a sensitivity analysis and code comparison of EBS simulations was chosen as one of the tasks within the project Task Force on Engineered Barrier Systems.

General description

Based on the Swedish disposal concept for spent nuclear fuel, the base case model of the sensitivity analysis and the code comparison is a simplified representation of a single KBS-3V deposition hole in a two-dimensional axisymmetric model (Figure 1 (left)). The sensitivity analysis included variations of material parameter values, boundary and initial conditions, considered physical processes and alternative model geometries amounting to about 60 different modelling cases (SCHÄFERS 2011).

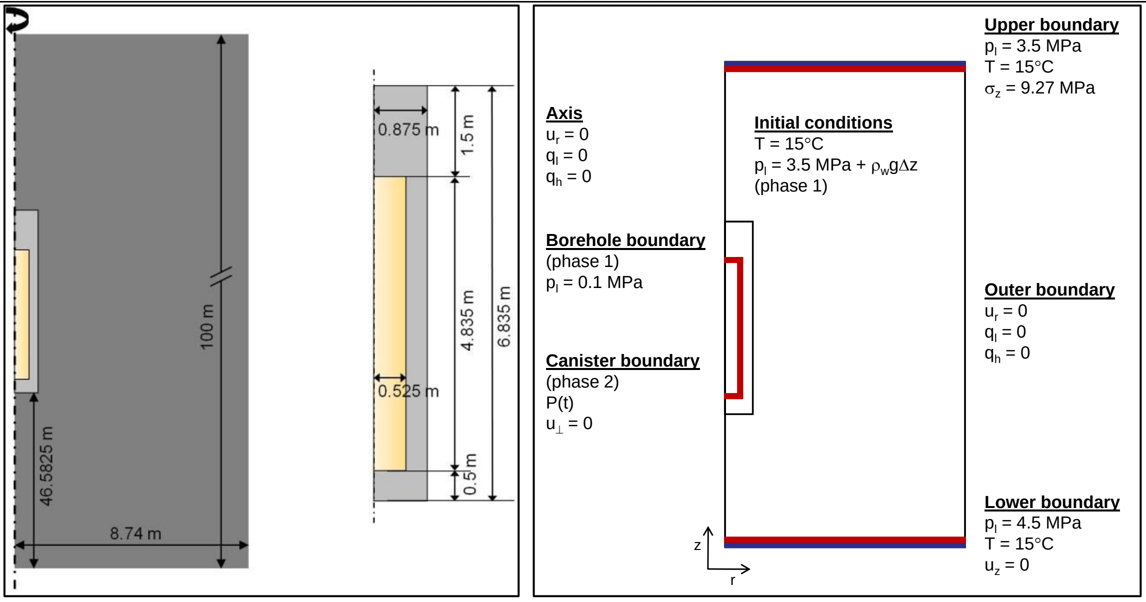

Figure 1: Axisymmetric base case model – dimensions (left) and boundary and initial conditions (right).

A sub-task of the sensitivity analysis was a code comparison, using the base case model as a benchmark example for coupled thermo-hydro-mechanical (THM) simulations of the near field. The input parameters such as material properties and boundary and initial conditions (Figure 1 (right)) were closely defined in the task description to avoid deviations in the modelling results. The code comparison was divided into different stages with increasing complexity:

- Stage 1 – thermo-hydraulic calculation applying Richard's approximation,
- Stage 2a – thermo-hydraulic calculation applying Richard's approximation with vapour diffusion,
- Stage 2b – thermo-hydraulic calculation applying Richard's approximation with vapour diffusion and temperature dependent fluid properties (density and viscosity),
- Stage 2c – thermo-hydraulic calculation applying a two-phase-flow approach with vapour diffusion,
- Stage 3a – thermo-hydro-mechanical calculation applying Richard's approximation with vapour diffusion,
- Stage 3b – thermo-hydro-mechanical calculation applying Richard's approximation with vapour diffusion and a simplified swelling law for the bentonite.

For the mechanical process, only elastic material behaviour is considered in Stage 3a. The effective stress increment in the rock and the buffer is calculated taking into account elastic and temperature induced stress changes. In Stage 3b a term for the swelling of the bentonite is introduced. In order to facilitate the comparison and to allow for a relatively easy implementation, a simplified swelling law is proposed. It defines the build-up of swelling pressure in linear dependence on the change of liquid saturation (Eq. (1)).

$$d\boldsymbol{\sigma}' = \mathbf{D}:(d\varepsilon - d\varepsilon_T) - \Delta S_l \sigma_{sw,\max}\mathbf{I} \qquad (1)$$

where the model parameter $\sigma_{\mathrm{sw,max}}$ corresponds to the maximum swelling pressure at a change of liquid saturation of $\Delta S_l = 1.0$. The total stress is defined according to Equation (2), with the sign convention of compressive stress and suction being negative.

$$\boldsymbol{\sigma} = \boldsymbol{\sigma}' - \chi\beta p_l \mathbf{I} \qquad (2)$$

For the calculation of effective stress the following was defined: $\beta = 1.0$ and

$$\chi = \begin{cases} 0.0 & \text{if } S_l < 1.0 \\ 1.0 & \text{if } S_l = 1.0 \end{cases}.$$

Six teams participated in the sub-task, providing results of six different numerical codes (Amec Foster Wheeler using Tough2-FLAC3D, BGR using OpenGeoSys, Clay Technology using Comsol, CRIEPI using LOSTUF, EPFL using Lagamine and UPC using Code_Bright). The results were compared in terms of evolution of temperature, pore pressure, saturation and stress components in different points in the bentonite buffer.

Main learning points concerning bentonite homogenization / mechanical evolution and relevance for the project

Figure 2 shows the evolution of radial stress in the point close to the heater for Stage 3b, applying the simplified swelling law for bentonite. For the coupled THM processes some quantitative deviations remain, while the overall qualitative agreement is good. For the remaining differences explanations were identified. Among these are differences in process couplings, as some codes used a unidirectional HM coupling and some a two-directional coupling.

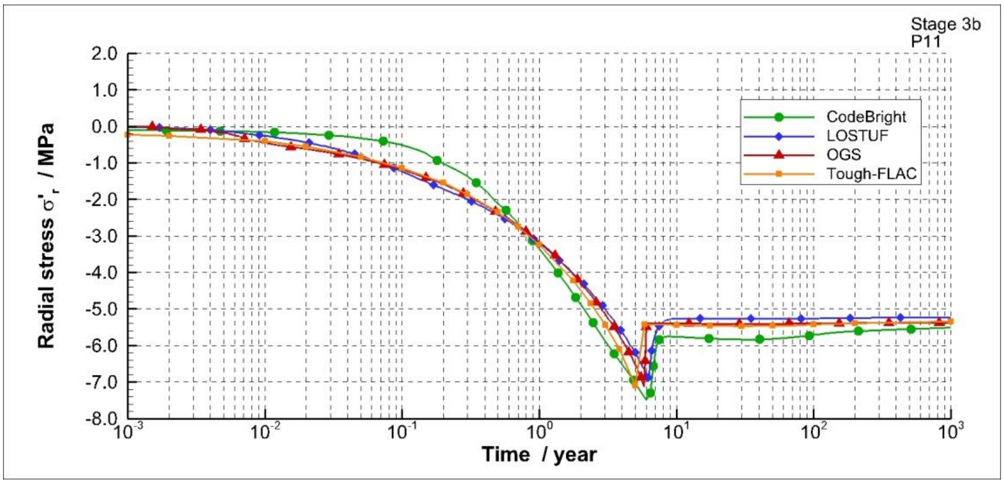

Figure 2: Evolution of radial stress in a point close to the heater - results of Stage 3b.

How could this work inform a new experimental or modelling study in BEACON?

References (ideally with web links)

SCHÄFERS, A. (2011): Task Force on Engineered Barrier Systems: Sensitivity Analysis – Task Description. Annual Report 2011. Internal Report. Bundesanstalt für Geowissenschaften und Rohstoffe, Hannover, Germany.

Schäfers, A.; Gens, A.; Rodriguez-Dono, A.; Carta, G.; Gordon, A.; Holton, D.; Malmberg, D.; Sawada, M.; Yafei, Q.; Ferrari, A.; Laloui, L.; Sjöland, A. (2017) Code

Comparison of coupled THM Processes in Engineered Barriers Performed within the Task Force on Engineered Barrier Systems. Beacon Initial Workshop, Kaunas, Lithuania.

Recommendations for BEACON project

The cross code comparison performed within the Task Force on Engineered Barrier Systems encouraged a fruitful exchange between modelling teams. In particular, the step-wise increase of complexity of the coupled simulation helped to provide in-depth insights into the individual behaviour of the codes when modelling the THM-coupled behaviour of EBS. Serving as a benchmark example for THM-coupled simulations of bentonite based EBS, the code comparison task helped to increase the confidence in the modelling capabilities of several codes used for safety evaluations of repositories for spent fuel and high level radioactive waste, some of which are also going to be used in the Beacon project.

Project Acronym Homogenization task in EBS Taskforce.	**Location** Clay Technology AB	**Type** Modelling study
Lead organiser Clay Technology/SKB	**Start date** 2011	**End date** 2016
Main partners involved in the project	**Characteristics of swelling clay** MX-80 Bentonite	**Water Saturation** Homogenisation cases with water saturated bentonite
Instrumentation No	**Main elements related to homogenization** Hydro-mechanical material model used for bentonite homogenisation	**Interfaces with other material** No
Modelling Development of hydro-mechanical material model	**Main processes studied** ☐T ☒H ☒M ☒Swelling pressure ☐Gas transfer ☐Other	**Reference concept if pertinent** No

Main objectives of the modelling study

Development of HM material model of relevance for water saturated homogenization tests.

General description

Engineered Barrier Systems are generally composed of different components with different initial dry density, for instance bentonite blocks, bentonite pellets-filled slots, or open slots. The homogenization process is a process through which these differences in dry density tend to decrease with time and is characterized by wide ranges of void ratios and water contents. Hydro-mechanical modelling of this process therefore requires a material model that can represent the behaviour of the bentonite for such wide ranges.

This process was investigated in the Homogenisation task within in the framework of the EBS Taskforce, in which among other things several well-defined laboratory-scale swelling tests were analysed (Dueck et al. 2014). These tests were performed with water saturated bentonite specimens and for different geometries (with axial, radial or isotropic swelling). This task motivated the development of a new hydro-mechanical material model, the Hysteresis Based Material model (HBM) (Åkesson 2017).

The model is defined for water saturated conditions and is based on a description for which a clay potential Ψ, defined as stress (σ) + suction (s), for a specific void ratio is assigned in an allowed interval bounded by two lines, for swelling ($\Psi_M - \Delta\Psi/2$) and consolidation ($\Psi_M + \Delta\Psi/2$), respectively. The actual state between these lines is controlled by a path function (f), with values between -0.5 and +0.5, which in turn is governed by the strain (ε) history. A stress-strain relation is defined for each principal direction (Figure 1). With this description, the void ratio and the suction are scalars, whereas the stress, the strain and the clay potential are tensors. The definition of the path function for different principal directions has been further refined so that the difference between f in different directions does not exceed 0.5. The only parameter, K, is a measure of the slope in the f-ε plane.

$$s+\sigma^k=\Psi^k=\Psi_M(e)+\Delta\Psi(e)\cdot f^k(\varepsilon^k(t))$$

$$\frac{df^k}{d\varepsilon^k}=-\left(\frac{1}{2}+\delta(\varepsilon^k)\cdot f^k\right)\cdot K$$

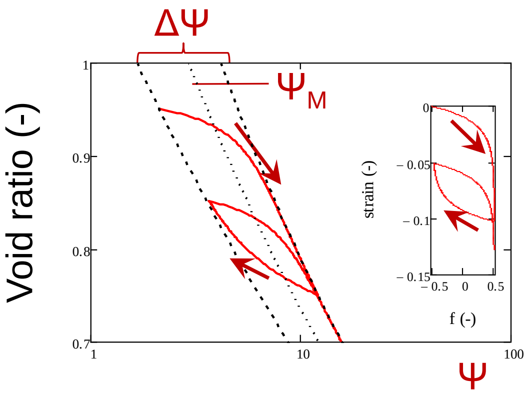

Figure 1. *HBM stress-strain relation for principal direction k (left). Ψ_M and ΔΨ denote the mid-line and the allowed span, respectively. δ denotes the sign of the time derivative dε /dt. Path function f varies between -0.5 and 0.5. Stress path in e-Ψ plane (right).*

Of vital importance for proper prediction of the mechanical evolution of bentonite is the capability to capture swelling pressure and shear strength at different dry densities. The HBM model was based on a body of empirical data, as well as a thermodynamic relation for the chemical potential of the clay water, which means that the fundamental properties, as well as the hysteresis behaviour, are at the core of the material model and that no parameter value adoption is needed for specific void ratios (Figure 2).

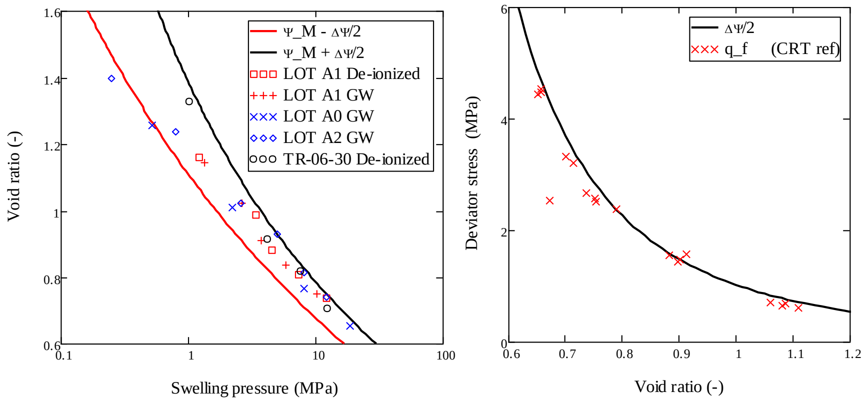

Figure 2. *Clay potential functions Ψ_M and Δ Ψ used in HBM consistent with swelling pressure data (left) and data from unconfined compression tests (right).*

Numerical solutions for homogenisation problems have so far been limited to simple 1D geometries (axial, radial and spherical) developed in an advanced spreadsheet software (MathCad). These solutions also included Darcy´s law (and water mass balance) together with a void ratio dependence of the hydraulic conductivity.

Stress paths for a 1D geometry of a homogenisation tests with axial swelling (into an open slot), showed that the (axial) clay potential in all parts of the specimen asymptotically followed the predefined swelling line until the slot was closed. Subsequently, the stress paths for the outer parts of the bentonite turned and asymptotically followed the consolidation line, which in effect gave rise to a heterogeneity (Figure 3). A comparison of model and measured evolution of stresses and final dry density distributions are shown in Figure 4.

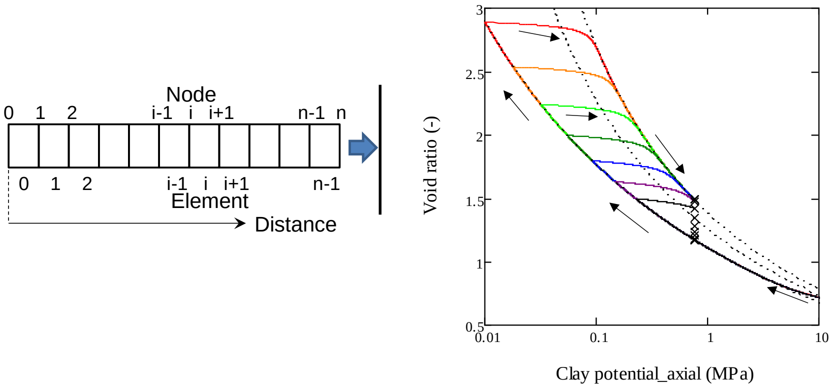

Figure 3. *Stress paths for 1D homogenisation lab test with axial swelling performed with the HBM: lines denote the 7 outer elements of a specimen discretized in 25 elements (red line denotes the outermost element). Crosses denote final state.*

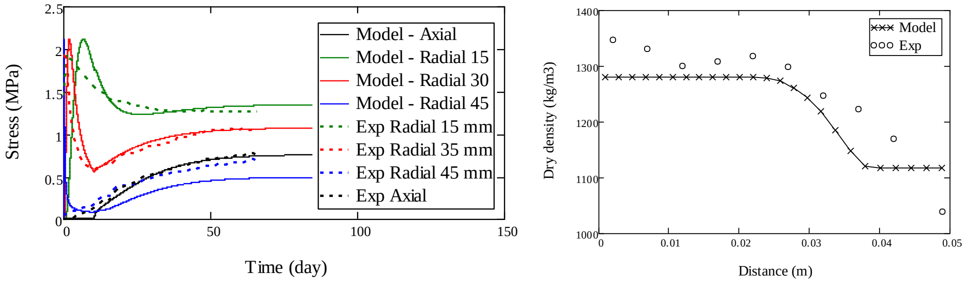

Figure 4. *Evolution of measured and modelled stresses for homogenization lab test with axial swelling (left). Modelled and measured final dry density distribution(right).*

Main learning points concerning bentonite homogenization / mechanical evolution and relevance for the project

The following observations can be regarded as the main learning points from the development of this material model.

The stress-stain relations. It was previously well known that the sum of suction and pressure equals suction at unconfined conditions, which in turn can be described as a function of the water content ($s + \alpha \bullet p = s_{free}(w)$) with the compressibility factor $\alpha=1$ for saturated conditions). The replacement of the s_{free} with a void ratio dependent interval ($\Psi_M(e) \pm \Delta\Psi(e)/2$), in which the actual state is determined by the strain history was however a quite novel description.

The implicit representation of shear strength. The hysteresis behaviour of the water retention curve and the results from oedometer tests were previously well known. The notion that the allowed span between the swelling line and the consolidation line appears to be related to the shear strength ($q_f \approx \Delta\Psi/2$, see Figure 2) was however a new observation. This mean that there is no need for any additional representation of the shear strength, as long as the difference between the path function (f) in different directions does not exceed 0.5.

Compressibility of water. For a general description of the HM process, it was found to be necessary to introduce an explicit relation between suction and the density of water, thereby generalizing the compressibility of water to “negative pore pressures”.

How could this work inform a new experimental or modelling study in BEACON?

In order to address more complex geometries, the HBM model is currently being implemented in the general finite element code COMSOL Multiphysics. The subsequent goal is to generalise the definition of the model for water unsaturated conditions as well, and this may be performed within WP3 of BEACON.

The HBM model could potentially be used for *scoping calculations for new experimental studies* in BEACON, and also as *a modelling tool for new modelling studies* in BEACON.

References

Åkesson M, 2017. EBS-TF Homogenization – Task 1. Report in progress.

Dueck A., Goudarzi R., Börgesson L., 2014. Buffer homogenisation, status report 2. SKB Technical Report TR-14-25. Svensk Kärnbränslehantering AB.

Recommendations for BEACON project

The planned work of model development (WP3) and, in particular, model validation (WP5) will inevitably involve comparisons and evaluations of the capabilities and limitations of the material models used by the participating modelling teams.

A commonly used procedure for such programs is to define one (or several) joint *modelling tasks*, which are subsequently carried out by the modelling teams. The modelling tasks may for instance address field experiments which can be quite complex and may therefore require a substantial amount of work. Once the contributing teams have completed their work, the *model results* are submitted to the evaluator of the task together with descriptions of the used *constitutive equations* and *parameter setting*. The evaluation of the material models are thus based on these sets of information.

An alternative procedure could be to define simple but selective tasks, or *validation problem*, designed to determine whether certain properties or behaviours can be simulated with the material models. For instance, such tests could address the final swelling pressure for different void ratios; the maximum deviator stress for different void ratios; or the evolution of suction during loading/unloading of a specimen with constant water content. The evaluation of the material models are in this case based on the capabilities to simulate these simple test conditions.

There should be several advantages with the procedure with validation problems:

i) **Assessment of model applicability.** The parameter setting adopted for a modelling task may be specific for the test conditions for that task, and the validity for other test conditions may be difficult to assess. In contrast, such limitations will be readily observed with the validation problem procedure.

ii) **Efficiency.** The information gained from a validation problem procedure is likely to exceed the corresponding information obtained from a procedure with modelling tasks, especially if these information sets are related to the costs of the procedures. In addition, if the validation problems are simple enough, then it should be possible to perform the calculations without any complicated numerical tools. The validation problem procedure may therefore be organized in such a way that the actual calculations are performed by only one (evaluation) team.

Project Acronym Homogenization task in EBS Taskforce.	**Location** Clay Technology AB	**Type** Modelling study
Lead organiser Clay Technology/SKB	**Start date** 2011	**End date** 2016
Main partners involved in the project	**Characteristics of swelling clay** MX-80 Bentonite	**Water Saturation** Homogenisation cases with water saturated bentonite
Instrumentation No	**Main elements related to homogenization** Hydro-mechanical material model used for bentonite homogenisation	**Interfaces with other material** No
Modelling Yes: Calibration/validation of hydro-mechanical material model Code: Abaqus	**Main processes studied** ☐T ☒H ☒M ☒Swelling pressure ☐Gas transfer ☐Other	**Reference concept if pertinent** No

Main objectives of the modelling study

SKB has been running a project with the objectives to increase the knowledge of the homogenization processes in the bentonite buffer and backfill. The project consist of four parts; theoretical studies, fundamental laboratory tests, laboratory study of the influence of friction and medium scale tests of the scenario involving swelling in complex geometries after loss of bentonite. Test and results of this program are described by e.g. Dueck et al (2014 and 2016).

This modelling was done as a task within the EBS Taskforce. This task involved two subtasks: 1) to model several well-defined laboratory scale swelling tests, and 2) to model a large laboratory scale test that simulates bentonite lost in a deposition hole.

General description

Material model

A material model that can be used for simulating the swelling process by the finite element simulations has been derived and implemented into the finite element code Abaqus. It is an elastic plastic cap model with a failure surface, a yield surface and non-associated flow surface (Claytech plastic cap model). It reminds of the Cam-clay model but has some substantial differences that make it more suitable for swelling bentonite.

The model is described in Figure 1, which shows the yield and failure surface in the q-p plane as well as flow surface. The behaviour in the q-p plane is controlled by two lines that limit the allowable Mises´stress: $q=ap^b$ and $q=cp^b$ where a>c. The upper line is a combined yield and failure surface (1) at the over-consolidated side (dry side) while the lower line is the failure surface (4) at the normally consolidated side (wet side) corresponding to the critical state line of the Cam Clay model. The lower line is also the top point of the yield surface at all states. The other parts of the yield surface are the elliptic cap (3) which intersects the p-axis at p_b and an elliptic transition surface between the other two parts.

The plastic behaviour at the yield surface is controlled by the flow surface (plastic potential). The flow surface consists of two ellipses. One ellipse for parts 1 and 2, where the flow is not associated since the tangent of the flow surface does not coincide with the tangent of the yield surface, and one for the cap (3), which coincides with the cap and where the flow in thus associated. By letting the ellipse at 1 and 2 be large, the inclination of the flow surface and thus the dilatancy can be made small. The model is described in Börgesson et al (1995 and 2014). The model includes 9 variables and a cap hardening function.

The elastic part of the model is a porous elastic model defined by a logarithmic relation between average stress and the void ratio $\Delta e = -\kappa \cdot \ln p$ where κ=porous bulk modulus.

The hydraulic conductivity is made a function of the void ratio. The contact with the confinements has been modelled by contact surfaces with a friction angle corresponding to about half the friction angle of the bentonite.

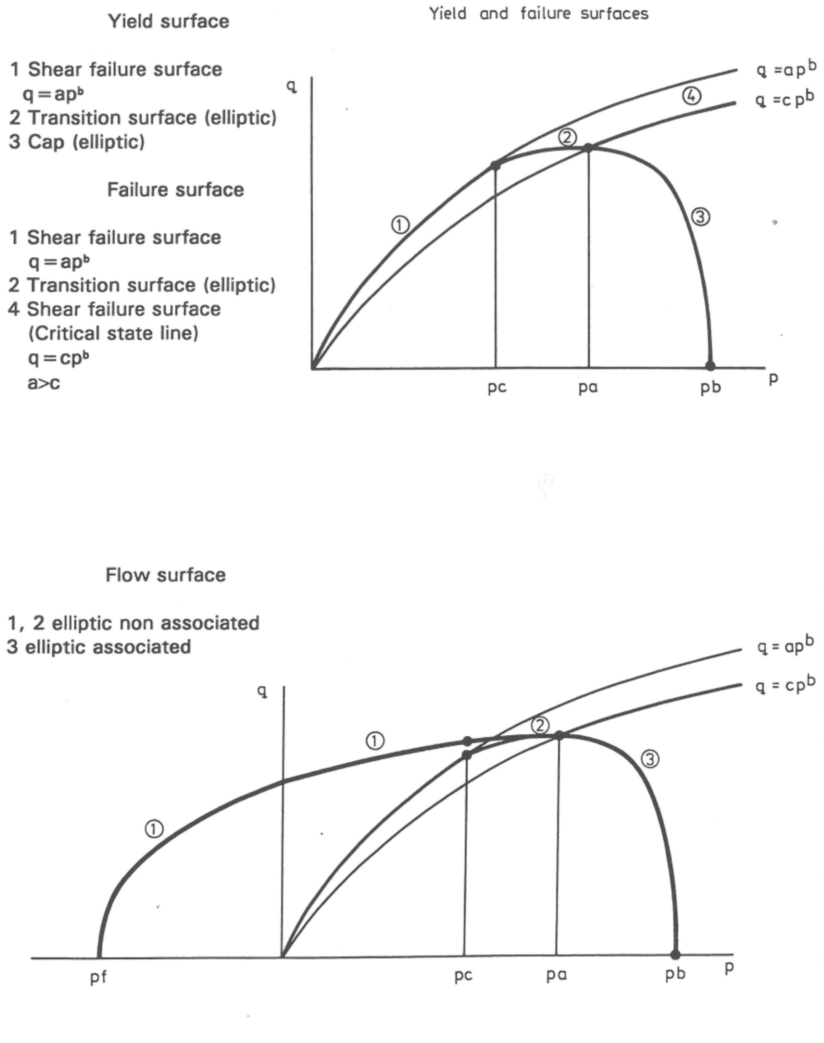

Figure 1. *Claytech plastic cap model. The yield surface, failure surface and plastic flow surface are shown in the q-p plane.*

The material used in the tests series was MX-80 bentonite. The swelling and homogenization of water saturated bentonite specimens with access of water were mainly studied with three tests types (Figure 2). These tests were done in two scales and the larger scale tests (HR tests with the diameter 100 mm with measurements of the radial stress in 4 locations and the axial total stress) were used for the material model calibration and validation.

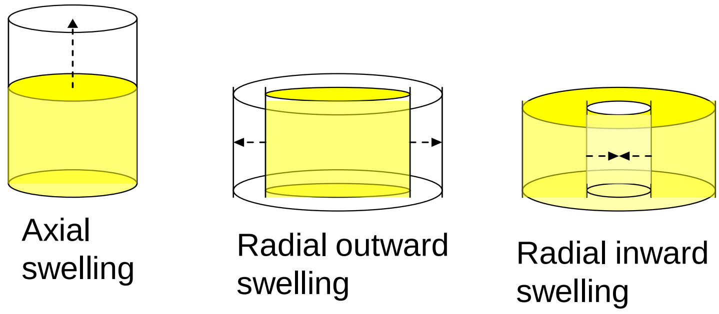

Figure 2. *Illustration of the geometry of the test types carried out.*

The parameters in the material model have been calibrated by modelling the axial swelling test (about 30% swelling) and validated afterwards by modelling the radial swelling tests and comparing the test results (Börgesson et al 2014). Figure 3 shows the element meshes. The calibration exercise have yielded a parameter set that gave the modelling results of the axial swelling tests as shown and compared with the measurements in Figure 4 (left). The models were then validated by modelling the radial swelling test (about 40 % swelling) as shown in Figure 4 (right). The results

ıe density distribution at the end of the test and the
t as good for the axial swelling test. Figure 5 illustrates
ıd the shrinkage of the yield surface as a result of the
envelope.

Clay Technology
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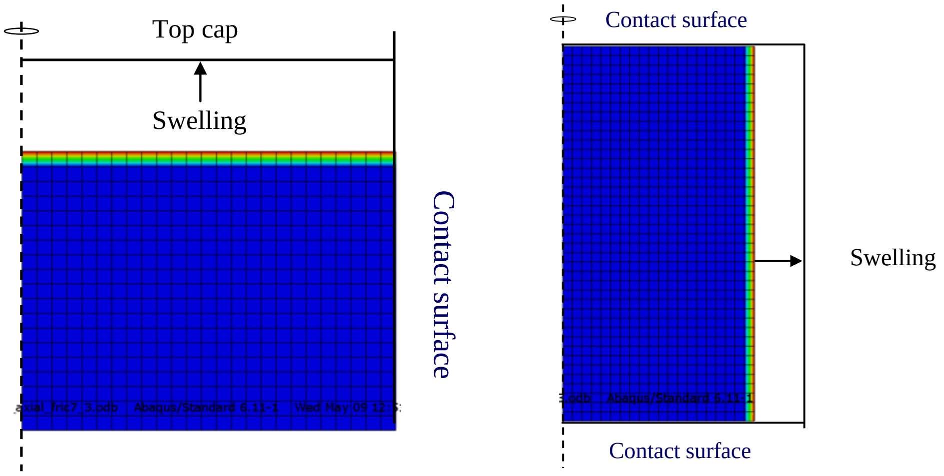

dial swelling tests. Axial symmetry at the left side and

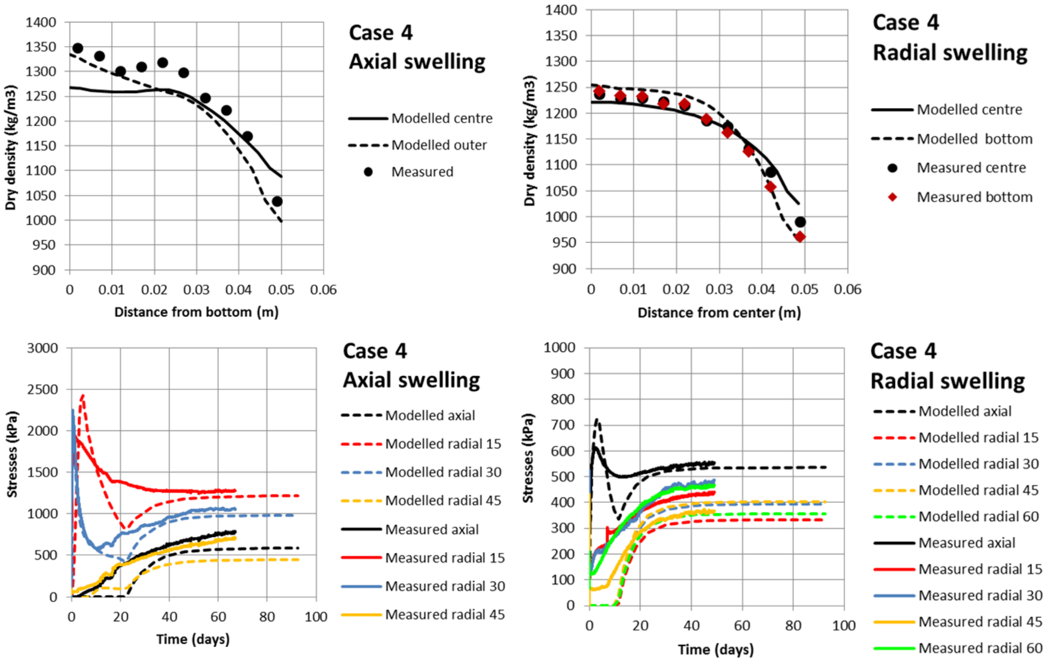

Figure 4. *Modelled and measured results of the axial (left) and radial (right) swelling test. Dry density distribution in the swelling direction after finished test (upper) and evolution of measured radial and axial stress are shown (lower). The radial stress is measured at different distances from the bottom.*

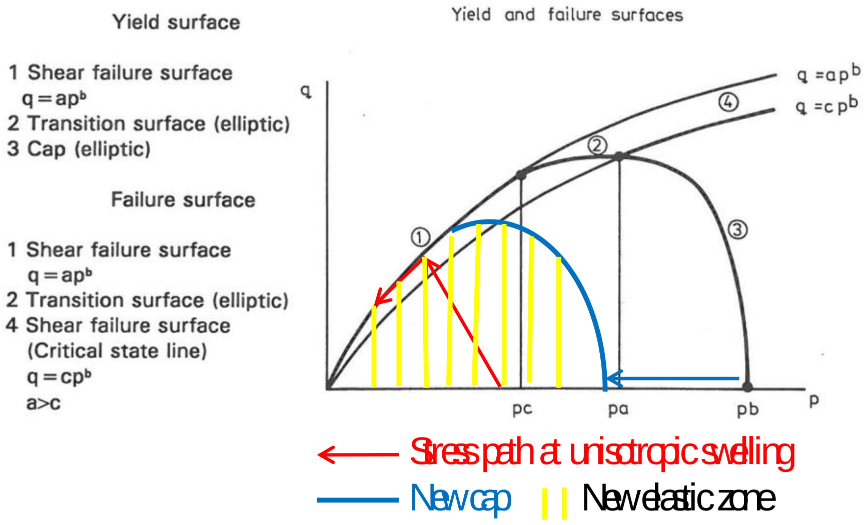

Figure 5. *Illustration of the yield and failure surfaces of the plastic cap model and a stress path (red arrows) of a point close to the swelling surface and its effect on the yield surface (3) that moves to the new position (blue arrow and curve).*

Subtask 2 - Modelling of the Self-healing Test

A laboratory experiment (Dueck et al. 2016) with very stiff and confined boundaries and a high density bentonite block has been used to simulate loss of bentonite in a part of a deposition hole. The block has a diameter of 30 cm and a height of 10 cm. Two diametrically located irregular voids of 35x50x70 mm^3 were cut in the block before installation. Measurements of the total stress (in 9 positions) and RH (in 2 positions) were performed during the operation. After the termination, the tests was sampled and analysed regarding the density distribution.

The test was modelled with a blind prediction before the start of the test. The element mesh and the modelled void ratio distribution at two times are shown in Figure 6. The spreading of the stresses in the measuring points was larger in the models than measured. Both the blind prediction yielded the highest stress 9.5 MPa in the measuring point located furthest away from the cavity and the lowest stress 2.0 MPa in the centre of the cavity while the measurements in corresponding places were 6.0 MPa and 3.3 MPa respectively. The blind prediction yielded higher void ratio e=1.2 in the centre of the cavity than the measured void ratio e=1.0. A general conclusion is thus that the Plastic Cap model underestimated the self-healing ability (or the homogenisation) of the bentonite in the test by yielding too high void ratio and too low stresses in the former cavity.

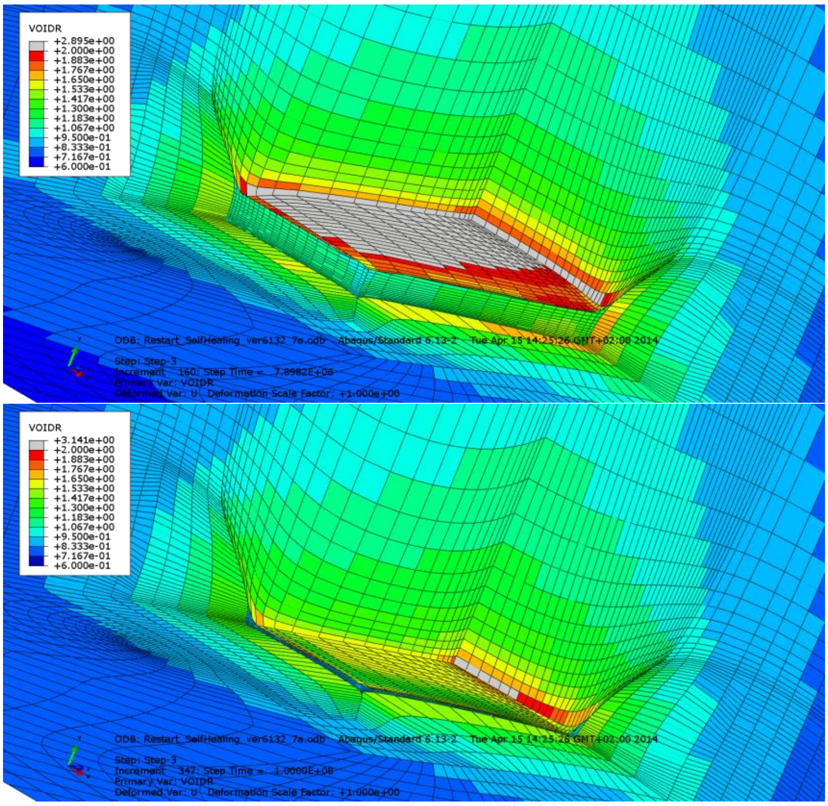

Figure 6 *.Void ratio after half way swelling and after completed swelling (updated calculation from Börgesson et al. 2016).*

Main learning points concerning bentonite homogenization / mechanical evolution and relevance for the project

A general conclusion from this task was that the Plastic Cap model underestimated the self-healing ability (or the homogenisation) of the bentonite in the test by yielding too high void ratio and too low stresses in the former cavity. The Drucker-Prager plastic model captured the homogenisation better with a void ratio distribution that agreed rather well with the measured and smaller remaining gaps in the former cavity. However, also this model yielded the same too low stresses in the cavity.

Subtask 2, with a large scale complicated geometry, thus yielded better results when the Drucker-Prager model was used while Subtask 1 (Börgesson et al, 2014) with small scale simple swelling models yielded much better results when the Plastic Cap model was used. The reason for the better homogenisation and better results of the Drucker-Prager model for Subtask 2 is judged to be that the material model is simpler and convergence much easier to obtain.

How could this work inform a new experimental or modelling study in BEACON?

For WP3, one of the alternatives is to modify the material model used in Abaqus, in particular for extending the validity of the porous elastic model and to enable plastic hardening for isotropic swelling in the Plastic Cap model.

The Plastic Cap model could potentially be used for scoping calculations for new experimental studies in BEACON, and also as a modelling tool for new modelling studies in BEACON.

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Recommendations for BEACON project

Project Acronym PhD research of G. Ghiadistri (Double structure framework for unsaturated, expansive clays)	**Location** Imperial College London	**Type** Constitutive model development (ICL1 form)
Lead organiser Imperial College London	**Start date** 2015	**End date** 2017
Main partners involved in the project Imperial College London, UK AMEC FW, UK RWM, UK	**Characteristics of swelling clay** - initial conditions following compaction; - swelling pressure - volumetric deformation upon wetting	**Water Saturation** Natural and artificial
Instrumentation NA	**Main elements related to homogenization** Evolution of double structure with wetting	**Interfaces with other material** None
Modelling Yes: HM modeling Groups/Codes: Geotechnics group at Imperial College London/ICFEP	**Main processes studied** ☐T ☒H ☒M ☒Swelling pressure ☐Gas transfer ☐Other	**Reference concept if pertinent**

Main objectives of the experiment

The behaviour of unsaturated expansive clays is of a particular interest in the design of buffers for nuclear waste storage. A number of modelling frameworks have been proposed to describe the complex hydro-mechanical phenomena that these materials undergo upon wetting, however this still remains a challenging task. This form summarises formulation and implementation of a new hydro-mechanical model for unsaturated, expansive clays into the Imperial College Finite Element Program, ICFEP (Potts & Zdravkovic, 1999, 2001). The framework takes into account the double porosity structure of dry-side compacted materials: it can be argued that such approach allows better understanding and reproduction of the hydro-mechanical (HM) interactions that are key to the re-hydration and subsequent swelling of the buffer. The new expansive model adopts, and further expands, the conceptual framework of the Barcelona Expansive Model (BExM, Gens et al., 1992; Alonso et al., 1999; Sanchez et al., 2005).

General description

The model assumes the existence of two levels of structure:

- *Macrostructure*, formed by groups of closely-packed clay aggregates with relatively large pore spaces between them, called macro-pores; the tensile pore pressure associated with the capillary water, which finds preferential flow patterns in the macro-pores, controls the behaviour;

- *Microstructure*, observable at the scale of a single aggregate, which is an alternation of thin layers of water and clay platelets; most physico-chemical phenomena that are responsible for the swelling capacity of the soil occur at this level.

The macrostructure is assumed to be unsaturated, hence its behaviour is described in net stress and equivalent suction, $s_{eq} = s - s_{air}$, where s_{air} is the air entry value of suction. The convenience of the choice of these two independent stress variables is debated in Georgiadis et al. (2005). From a constitutive standpoint, the macrostructure follows a Barcelona Basic Model (BBM)-type framework described in Georgiadis et al., 2003, 2005; Tsiampousi et al., 2013, which in itself is an expansion of the BBM framework of Alonso et al., 1990.

The microstructure is assumed to be elastic, volumetric and fully saturated (Alonso et al., 1999; Sanchez et al., 2005). Consequently, the effective stress principle holds and, therefore, the change in effective stress triggers volumetric, elastic micro-strains.

The two levels of structure are overlapping, but they are not independent: the macrostructure does not exercise any direct influence on the microstructure but the opposite is not true. In fact, a fundamental assumption for the model is that the microstructure is capable of contributing to macro-plasticity, despite being elastic. A multi-scale interaction is introduced that binds microstructural elastic strains, $\Delta\varepsilon_m^e$, to macrostructural plastic strains, $\Delta\varepsilon_\beta^e$:

$$\Delta\varepsilon_\beta^p = f_\beta \Delta\varepsilon_m^e$$

where f_β are the interaction functions: one function is used upon microstructural loading and one upon microstructural unloading. Their shapes are defined with coefficients c_{c1}, c_{c2}, c_{c3}; c_{s1}, c_{s2}, c_{s3}, and their value depends on the degree of openness of the structure (Gens and Alonso, 1999).

Because of the multi-scale interaction, the behaviour below the macrostructural yield surface is not elastic. As plasticity can be originated from both the macrostructure and microstructure, it is necessary to introduce a hardening parameter for each level of structure. According to the BBM framework, p_0^* is the hardening parameter for the macrostructure:

$$\Delta p_0^* = p_0^* \frac{\nu}{\lambda(0) - \kappa} \Delta\varepsilon_{vol}^p$$

where ν is the specific volume, λ(0) and κ are model parameters (more details can be found in the ICL2 Beacon form on oedometer tests), and $\Delta\varepsilon_{vol}^p$ is the total volumetric plastic strain, which is the sum of two contributions and, thus, effectively couples the macrostructure and the microstructure.

The void factor, VF, on the other hand, is introduced in order to express the evolution of the micro-structure. VF is defined as the ratio of the micro void ratio and the total void ratio. Hence, its value indicates whether the fabric resembles primarily the macro-structure, or whether the micro-structure is dominant.

Main learning points concerning bentonite homogenization / mechanical evolution and relevance for the project

The model has been assessed through numerical analyses of different forms of bentonite swelling tests, demonstrating very clearly the importance of the contribution of the microstructure to the overall behaviour of bentonite upon hydration.

How could this work inform a new experimental or modelling study in BEACON?

In certain cases the fabric of the material undergoes permanent changes upon hydration. A number of experimental studies on compacted clays have clearly shown that the double porosity structure disappears upon full saturation and that the material assumes a single porosity structure thereafter (Seiphoori et al., 2014; Monroy et al., 2010). Such change is irreversible. Unlike previous frameworks, the model accounts for this evolution and deactivates further contribution of the microstructure once suction has reduced below the air-entry value. It would be of great interest, though, to document the fabric evolution during different stages of the wetting process and not only in its initial and final phase: such information would allow more accurate definition of the interaction functions between the two levels of structure.

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Recommendations for BEACON project

Similar to others, the new expansive model is complex, making its calibration and derivation of model parameters equally complex. Its formulation has required a large number of parameters: those inherited from the BBM framework plus those introduced to characterise the microstructure.

The process of calibration can be broken down into three phases corresponding to three types of testing, each providing a source of information which is necessary to calibrate a sub-group of parameters:

1) *oedometric/isotropic studies*

   Firstly, the samples are wetted under constant axial load while being left free to swell axially, if it is an oedometer test, or axially and radially, if it is an isotropic test. Hence the behaviour with respect to purely hydraulic loads can be observed. For the constitutive model, this enables derivation of the parameter κ_s, which represents the elastic compressibility coefficient with respect to changes in suction. This parameter is of paramount importance because it contributes to quantifying the elastic strains that arise upon changes in suction.

Subsequently, the samples are loaded under constant suction, therefore the pre-yield and post-yield compressibility of the material are characterised. The former is independent of suction, while the latter is strongly dependant on it. It is thus useful to have several tests carried out at different levels of suction in order to assess how the yielded material behaves at different unsaturated states. Since the original BBM formulation (Alonso et al., 1990), the following law has been adopted: $\lambda(s_{eq}) = \lambda(0)[(1-r)e^{-\beta s_{eq}} + r]$

Therefore, the parameters r and β can be fitted with the aforementioned information. The pre-yield compressibility is expressed throughout the constant κ.

Overall the following parameters can be derived using oedometric or isotropic data: $\lambda(0)$; r; β; κ; κ_s.

2) *triaxial studies*

Characterising the triaxial behaviour of unsaturated clays is challenging because very little experimental evidence from triaxial tests is available, given the amount of time needed for such testing and the intrinsic difficulties in conducting such experiments. Consequently, the calibration of the strength parameter, i.e. the slope of the critical state line, M, is usually based on information collected on saturated samples. It is relevant to point out, though, that expansive clays generally have a very small friction angle, which can be tied to M through the relationship

$$\phi = sin^{-1}\left(\frac{3M}{6+M}\right)$$

It is reasonable to assume that this remains true for both saturated and unsaturated states.

Nevertheless, the definition of the shape of the yield surface, other than the Modified Cam Clay ellipse, is a more complicated issue: the lack of unsaturated triaxial tests prevents accurate calibration of various shape parameters of the yield and plastic potential surfaces, such as α_F and μ_F, and α_G and μ_G for the model described here. Therefore the choice of the yield surface is often arbitrary and in most cases the Modified Cam Clay ellipse is employed.

Overall the following parameters of the current model can be calibrated using triaxial data: M; α_F; μ_F; α_G; μ_G, where the subscript F refers to the yield function, and G refers to the plastic potential.

3) *microstructural studies*

Another rather challenging aspect of calibration concerns the definition of the behaviour of the microstructure, because investigating at such small scale proves difficult. Three microstructural parameters have been defined for the current model:

- *Elastic compressibility parameter,* κ_m. To the authors' knowledge, there is still no particular lab test that is designed to provide this information. Conceptually, the macro-structural compressibility coefficients, κ and κ_s, have similar roles with respect to κ_m. κ is measured by evaluating the slope of unloading-reloading paths during oedometer tests, whereas κ_s is estimated from suction-controlled tests. It is relevant to point out that the macrostructure reacts differently to $\Delta\sigma$ and Δs and that is fully justified by its unsaturated state, conversely, the microstructure, permanently saturated, is characterised by κ_m only.

- *Void Factor, VF*. Environmental Scanning Electron Microscopy (ESEM)-based studies are used to provide visual insights on the fabric, whereas Mercury Intrusion Porosimetry (MIP) investigations produce bimodal pore size distributions for compacted clays. Two examples are presented in Figure 1.

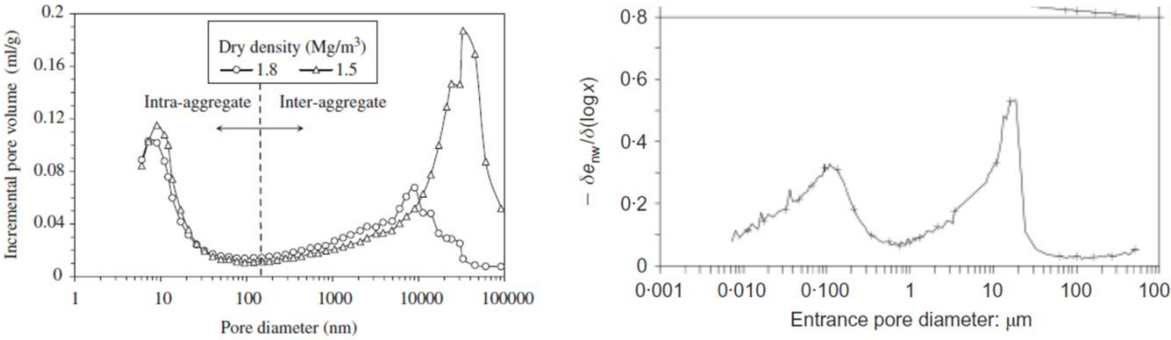


Figure 1: Pore size distributions of compacted clays highlight the double porosity structure throughout a bimodal distribution. The material on the left is Febex Bentonite (Sanchez et al., 2005), on the right London Clay (Monroy et al., 2010).

Both distributions show two peaks corresponding to macropores and micropores. Hence this type of experimental evidence can be quantitatively correlated to the void factor.

- *Interaction functions,* f_β. Calibrating the coefficients c_{c1}, c_{c2}, c_{c3} and c_{s1}, c_{s2}, c_{s3} is complicated as the intrinsic physical meaning of the functions is not obvious. Once the knowledge about the microstructure has improved, it would be foreseeable to conceptually re-interpret these interaction functions in order to assign them a more specific meaning.

Overall the following parameters will have to be calibrated using experimental evidence from microstructural investigations: $\kappa_m; VF;\ c_{c1}, c_{c2}, c_{c3};\ c_{s1}, c_{s2}, c_{s3}$.

An ICL2 Beacon form on oedometer data and ICL3 Beacon form on triaxial data have also been compiled. It is recommended to refer to those for further information about the delicate process of calibration of the expansive framework, briefly described in the present form. The microstructural investigation, however, is not discussed in further detail, as a better knowledge of the microstructure must be achieved in order to elaborate on the subject.

It is worth noticing that p_C, the characteristic pressure (Alonso et al., 1990), has been left out of the calibration of parameters, as no direct measurement provides an immediate estimation for it. Hence some engineering judgement is required when deriving this parameter for the constitutive model.

Project Acronym PhD research of G. Ghiadistri (Double structure framework for unsaturated, expansive clays)	**Location** Imperial College London	**Type** Laboratory test – oedometer (ICL2 form)
Lead organiser Imperial College London, reporting on oedometer experiments of: M.V. Villar (CIEMAT) A.M.Tang (ENPC)	**Start date** 2015	**End date** 2017 Publication date: 2005 2008
Main partners involved in the project Imperial College London, UK AMEC FW, UK RWM, UK	**Characteristics of swelling clay** Compacted MX-80 bentonite Dry density: $1.69\frac{Mg}{cm^3}$ (Villar, 2005); $1.78\frac{Mg}{cm^3}$ (Tang et al., 2008) Initial water content: 17% (Villar, 2005); $10 \pm 2\%$ (Tang et al., 2008)	**Water Saturation** Artificial
Instrumentation Measurements of: • suction • vertical load • total vertical strain (Villar, 2005); total pressure (Tang et al., 2008) • dry density	**Main elements related to homogenization** Initial suction, initial dry density and suction-controlled wetting	**Interfaces with other material**
Modelling Yes: calibration of constitutive models Groups/Codes: Geotechnics section at Imperial College London/ICFEP	**Main processes studied** ☐T ☒H ☒M ☐Swelling pressure ☐Gas transfer ☐Other	**Reference concept if pertinent**

Main objectives of the experiment

The tests of Tang et al. (2008) aim at investigating the behaviour of bentonite upon mechanical, hydraulic and thermal loads inside an isotropic cell. Thermal effects will not be discussed as only hydro-mechanical behaviour is studied.

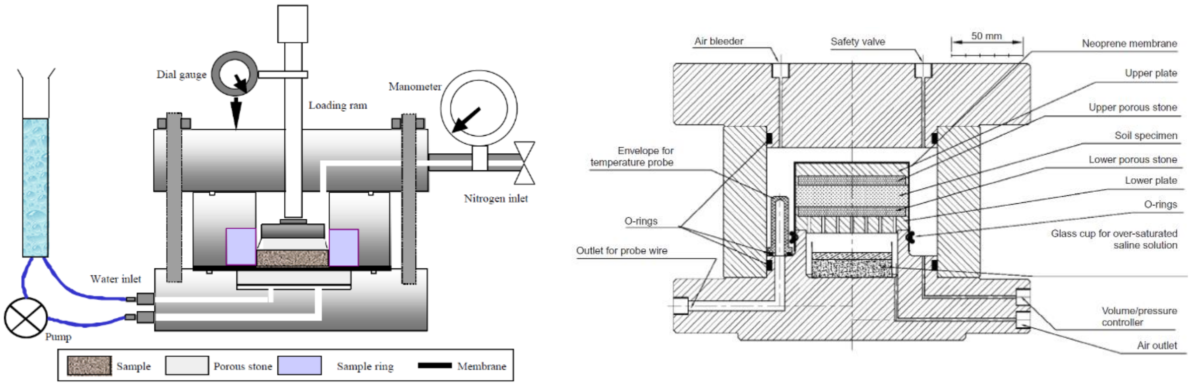
The work of Villar (2005) aims at providing characterisation for MX-80 bentonite as part of the Prototype repository project. Nevertheless, the oedometric study is of particular interest as it allows the study of the one-dimensional compressibility of bentonite.

General description

From Villar (2005) two oedometer tests are selected to be analysed. The bentonite sample is statically compacted at a compaction pressure between 32 and $38\,MPa$, until the desired dry density is reached. Temperature is maintained constant at $20℃$. The sample is laterally confined throughout the entire experiment; during the first phase it undergoes wetting under a constant axial loading of $0.1\,MPa$. One sample starts from an initial suction of $47\,MPa$ and is wetted to $1.4\,MPa$ of suction, another sample is soaked from $14\,MPa$ to full saturation. Subsequently, both samples are loaded at constant suction to a vertical load of $5MPa$.

Tang et al. (2008) uses an isotropic cell equipped to simultaneously control suction, temperature and pressure; the sample is laterally unconfined during the experiment. Qualitatively, the stress paths are similar to those previously described in Villar (2005). Nevertheless, the suction ranges involved are different: the initial value is $110\,MPa$, then one sample is soaked to $39\,MPa$ suction and another to $9\,MPa$ suction.

The equipment for the experiments is shown below.



(a) *(b)*

Figure 1: Experimental equipment: (a) the oedometer used in Villar (2005) and (b) the isotropic cell used in Tang et al. (2008).

Main learning points concerning bentonite homogenization / mechanical evolution and relevance for the project

The aforementioned tests are important for derivation of parameters (i.e. calibration) for the fully coupled hydro-mechanical (HM) constitutive models for unsaturated clays, such as the model introduced in the Beacon form ICL1 (implemented in the finite element software ICFEP, Potts & Zdravkovic, 1999, 2001). In particular, two frameworks are at disposal: the Barcelona Basic Model (BBM, Alonso et al., 1990), which has been expanded to account, amongst others, for a versatile yield surface, a nonlinear increase of apparent cohesion with suction and a nonlinear isotropic compression curve (Georgiadis et al., 2003, 2005; Tsiampousi, et al., 2013); a constitutive model for highly expansive clays which adopts, and further expands, the conceptual framework of the Barcelona Expansive Model (BExM, Gens et al., 1992; Alonso et al., 1999; Sanchez et al., 2005).

Both these models are numerically complex and thus require adequate experimental data for parameter derivation, as further discussed in the Beacon form ICL1 on the expansive model. Oedometric and isotropic studies are not sufficient to entirely carry out this process, however they are essential. In particular, a group of model parameters, $(\lambda(0);\ r;\ \beta;\ \kappa;\ \kappa_s)$, that is common to both numerical frameworks, can be derived from the tests:

- the post-yield gradient of the isotropic compression line obtained upon loading at constant suction of a fully saturated sample informs on the parameter $\lambda(0)$. Hence, this value can be deducted from Villar (2005);
- the post-yield gradients obtained upon loading at constant suction of several unsaturated samples provide experimental values, $\lambda(s_{eq})$, to approximate the assumed compressibility coefficient:

  $$\lambda(s_{eq}) = \lambda(0)[(1-r)e^{-\beta s_{eq}} + r]$$

  where $s_{eq} = s - s_{air}$ is the equivalent suction, s_{air} being the air-entry value of suction, and r and β are fitting parameters;
- the gradient of the loading-unloading path can be estimated from all 4 tests reported in the previous section: such information allows derivation of the elastic compressibility parameter, κ;
- focusing on the wetting phase rather than the loading phase, important information can be extracted about the compressibility of bentonite with respect to changes in suction. Plotting the stress paths in the equivalent suction – specific volume plane, (s_{eq}, v), and measuring its gradient, the parameter κ_s, elastic compressibility coefficient with respect to changes in suction, can be estimated. It is interesting to note that the values obtained vary with the boundary conditions imposed on the sample: in fact, a laterally confined specimen tends to swell less than under free swelling conditions. In this case, calibration requires a careful reflection on which situation best resembles the test for which the model is being calibrated for.

In order to complete the calibration process, further information is required from the triaxial behaviour and, in the case of the expansive framework, for the microstructural behaviour.

As an example of the results obtained from modelling these tests, the two constitutive frameworks are applied to reproduce one test from Villar (2005).

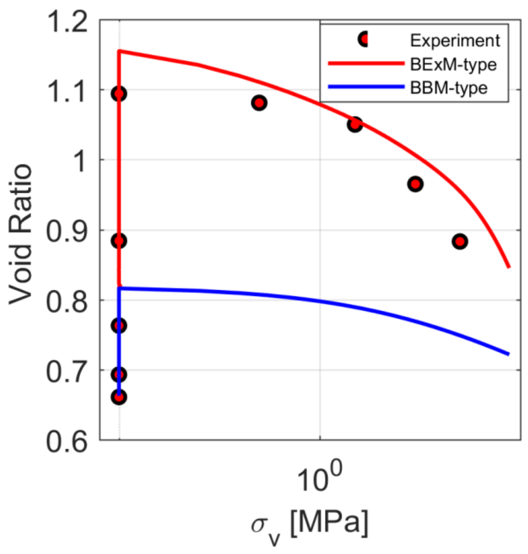


Figure 2: Simulation of a test from Villar (2005).

The prediction of the bentonite's volumetric response using the expansive model (BExM-type) agrees very closely with the experimental observation, compared to a significant under-prediction of swelling when using the BBM-type model.

How could this work inform a new experimental or modelling study in BEACON?

Overall, these oedometer and isotropic tests provide a good, yet partial, characterisation of bentonite because they consider wide ranges of suctions and different boundary conditions.

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Recommendations for BEACON project

By studying these tests and going through the calibration process previously described, the following observations arise:

- in most cases the axial loading at the end of the tests has stopped at relatively low stress levels, thus making it difficult to establish accurately the gradient of the post-yield compression curve; it would be beneficial for the derivation of this model parameter if compression paths could continue to higher loads (although it is recognised that this depends on the capacity of the equipment).
- the compaction process that all samples have undergone during their preparation is very important as it strongly influences the initial state of the material. Hence, providing a suitable description and monitoring of this phase is crucial to allow either a correct modelling of the initial condition or a correct modelling of the entire compaction process.

Project Acronym PhD research of G. Ghiadistri (Double structure framework for unsaturated, expansive clays)	**Location** Imperial College London	**Type** Laboratory test – triaxial (ICL3 form)
Lead organiser Imperial College London, reporting on triaxial experiments of: A. Dueck (ClayTech)	**Start date** 2015	**End date** 2017 2010
Main partners involved in the project Imperial College London, UK AMEC FW, UK RWM, UK	**Characteristics of swelling clay** Compacted MX-80 bentonite Dry density: $1.79 \frac{Mg}{cm^3}$ Initial water content: 44%	**Water Saturation** Artificial
Instrumentation Measurements of: • mean and deviatoric stress • strain • pore water pressure	**Main elements related to homogenization** Strength of material	**Interfaces with other material**
Modelling Yes: calibration of constitutive models Groups/Codes : Geotechnics section at Imperial College London/ICFEP	**Main processes studied** ☐T ☒H ☒M ☐Swelling pressure ☐Gas transfer ☐Other	**Reference concept if pertinent**

Main objectives of the experiment

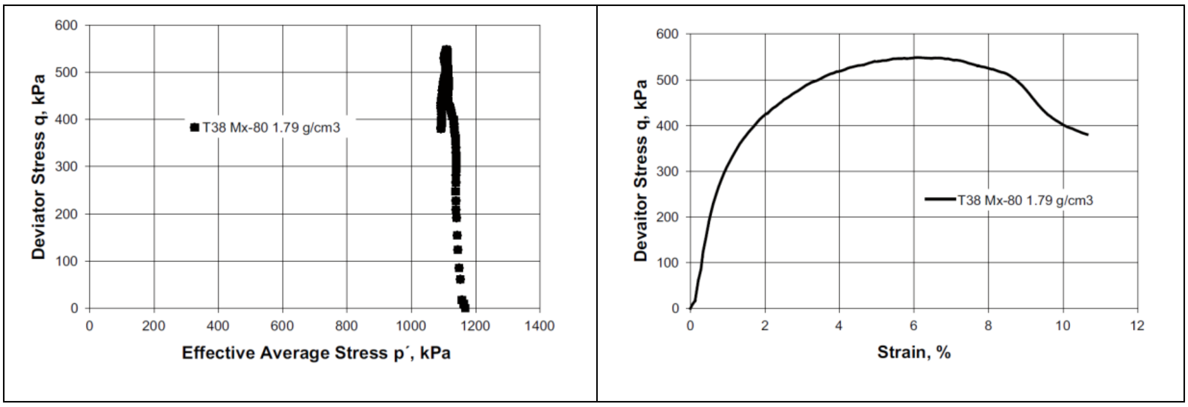
Dueck et al. (2010) report a number of experiments aimed at characterising MX-80 bentonite for the purpose of its employment as buffer material in nuclear waste disposal applications.

Among the results presents, it is of particular interest to examine two triaxial tests conducted on fully saturated bentonite samples. From the analysis and interpretation of these experiments it is possible to extract information on how to model the deviatoric aspect of clay behaviour (not only isotropic). This is essential for developing constitutive models of expansive clays that are generalised in the three-dimensional stress space and for their inclusion in general numerical software. These experiments were used in particular for the calibration of the constitutive models for unsaturated soils that have been implemented at Imperial College into the finite element software ICFEP (Potts & Zdravkovic, 1999, 2001), both a BBM-type model of Georgiadis et al., 2003, 2005, and a new BExM-type model for expansive soils reported in the Beacon form ICL1.

General description

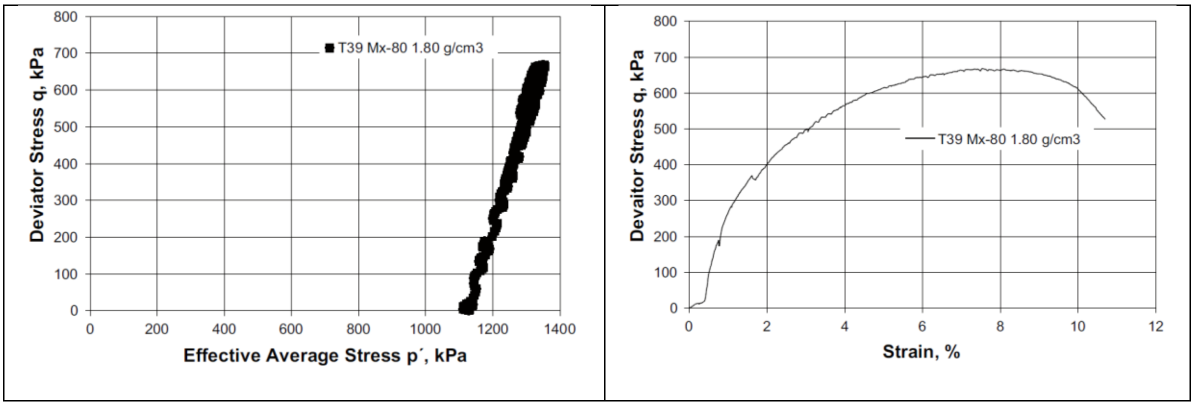
Prior to the start of the test, the material is placed inside an oedometer and is compacted using a maximum load of $1100\,kPa$. Simultaneously it is allowed to take up distilled water through the two porous discs at the top and the bottom of the sample: hence at first the height of the sample was reduced due to the load, but then it began to increase due to swelling upon hydration. After about two weeks the sample was saturated. Subsequently, several small samples of $35\,mm$ in diameter and $25\,mm$ high are carved out and the properties of these specimens are recorded: on average, the water content is 44%, the dry density is $1.79\ {}^{Mg}/_{cm^3}$, the degree of saturation is 98.5% and the void ratio is 1.22. Three samples are stacked on top of each other in order to obtain a larger sample (also 35mm in diameter and about 75mm in height, thus corresponding approximately to a standard triaxail size sample of 38x76mm) that is eventually mounted in a triaxial cell for consolidation. Therefore, it seems likely that there are interfaces within the specimen that may influence its behaviour.

The subsequent shearing phase, under triaxial compression is executed under both undrained and drained conditions. The results are reported in Figures 1 and 2, respectively, in terms of the effective stress path $q-p$ and deviatoric stress-axial strain curve $q-\varepsilon_a$, respectively for each test. Both samples are reported as normally consolidated.



(a) *(b)*

Figure 1: Results from the undrained triaxial test (Dueck et al., 2010).

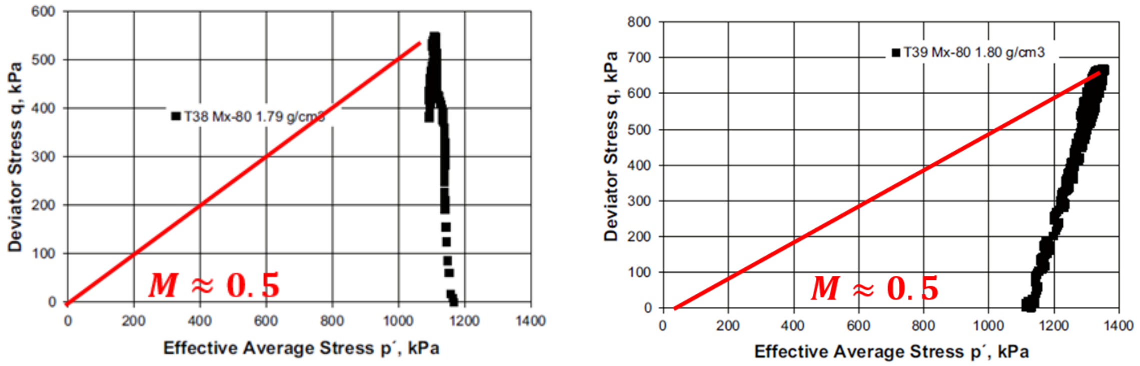


(a) *(b)*

Figure 2: Results from the drained triaxial test (Dueck et al., 2010).

Main learning points concerning bentonite homogenization / mechanical evolution and relevance for the project

The triaxial tests provide an estimate of the strength parameter, M, of the soil either in triaxail compression or extension. The value of M is obtained from the gradient of the critical state line (CSL).



(a) *(b)*

Figure 3: Interpretation of the results: the CSL slope is measured.

From the two tests in compression the parameter M is estimated at about 0.5, as shown in Figure 3, leading to the angle of shearing resistance of the material, in triaxial compression, of $\phi = 14^o$, using the following relationship:

$$\phi = sin^{-1}\left(\frac{3M}{6+M}\right) \approx 14°$$

This value is very low, which is typical for expansive clay materials.

Another useful piece of information that can be deducted from triaxial data is the shape of the yield surface in the generalised (p, J) plane. The modeling capabilities in ICFEP allow any possible shape to be assumed, according to the following relationship:

$$F = \frac{p + k \cdot s_{eq}}{p_0 + k \cdot s_{eq}} - \frac{\left(1 + \frac{\eta}{K_2(\alpha,\mu)}\right)^{K_2(\alpha,\mu)/\beta_f(\alpha,\mu)}}{\left(1 + \frac{\eta}{K_1(\alpha,\mu)}\right)^{K_1(\alpha,\mu)/\beta_f(\alpha,\mu)}} = 0$$

where α and μ are shape parameters. All other details can be found in Georgiadis et al. (2003, 2005). In most cases, however, given the scarcity of experimental evidence, the yield function arbitrarily assumes an elliptical shape according to the Modified Cam Clay model (i.e., $\alpha = 0.4$, $\mu = 0.9$). This modeling choice may not represent the actual behavior of the material hence additional information from testing may help improve the performance of the model.

How could this work inform a new experimental or modelling study in BEACON?

From the results showed in the previous section it is possible to observe that the material seems to soften after reaching a peak deviatoric stress. Such behaviour is typical of an over-consolidated sample rather than a normally consolidated one. Thus, there seems to be some difficulties interpreting the results.

References (ideally with web links)

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Recommendations for BEACON project

The tests discussed here have some issues when interpreting their behaviour as the initial states of the samples are somewhat ambiguous: the specimens are reported as normally-consolidated but their behaviour suggests overconsolidation. Therefore, new triaxial tests on saturated bentonite samples could be undertaken in order to avoid such uncertainties; preferably samples at different values of OCR should be investigated.

Triaxial data from unsaturated bentonite experiments would also be very interesting, though it is recognised that testing would become more difficult to carry out and to interpret.

Project Acronym PhD research of G. Ghiadistri (Double structure framework for unsaturated, expansive clays)	**Location** Imperial College London	**Type** Laboratory tests - fundamental swelling tests, basic series (ICL4 form)
Lead organiser Imperial College London, reporting on a series of swelling tests of: L. Börgesson (ClayTech)	**Start date** 2015	**End date** 2017 2011
Main partners involved in the project Imperial College London, UK AMEC FW, UK RWM, UK	**Characteristics of swelling clay** Compacted MX-80 bentonite Dry density: $1.66\frac{Mg}{cm^3}$ Initial water content: 12%	**Water Saturation** Artificial
Instrumentation Continuous measurements of axial and radial stress. Measurements at initial and final state: - dry density - degree of saturation	**Main elements related to homogenization** Initial suction, initial dry density and suction-controlled wetting	**Interfaces with other material**
Modelling Yes: boundary value problem, coupled HM analyses. Groups/Codes: Geotechnics section at Imperial College London/ICFEP	**Main processes studied** ☐T ☒H ☒M ☒Swelling pressure ☐Gas transfer ☐Other	**Reference concept if pertinent**

Main objectives of the experiment

To understand and predict the final condition of the buffer material upon hydration (Dueck et al., 2011, 2014).

Three swelling experiments on compacted MC-80 bentonite are selected from the above references, which can be simulated to examine the predictive capabilities of hydro-mechanical models for unsaturated swelling clays. The example here shows the simulation of these experiments employing the new hydro-mechanical model for unsaturated expansive clays implemented into the Imperial College Finite Element Program (ICFEP, Potts & Zdravkovic, 1999, 2001) and reported in the Beacon form ICL1.

General description

Three tests have been analysed: an axial swelling test, an outward radial swelling test and an inward radial swelling test. The former will be briefly described hereafter, whereas the remaining two will be discussed in the next section. For further information it is recommended to refer to Dueck et al.

(2011, 2014).

The axial swelling experiment consists of a constant volume saturation phase followed by free swelling in the axial direction until an axial strain of 25% is reached. The experimental set-up is a swelling pressure device shown in Figure 1.

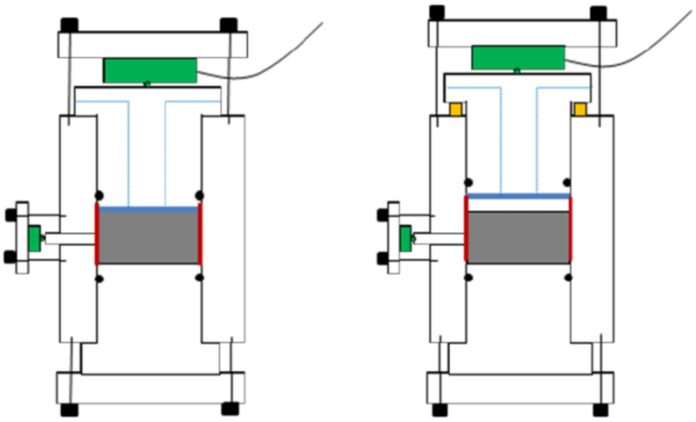


Figure 1: Experimental setup for the axial swelling test (Dueck et al., 2011, 2014).

The sample is confined laterally by means of a steel ring. A piston is placed above the specimen and, at different stages, it applies the force necessary to ensure isochoric conditions. No counteracting friction force is present on the lateral boundary as the friction is minimized by use of a lubricant. The wetting boundary corresponds to the top of the specimen.
Two load cells are placed in the vertical and radial direction, allowing total stresses to be measured.

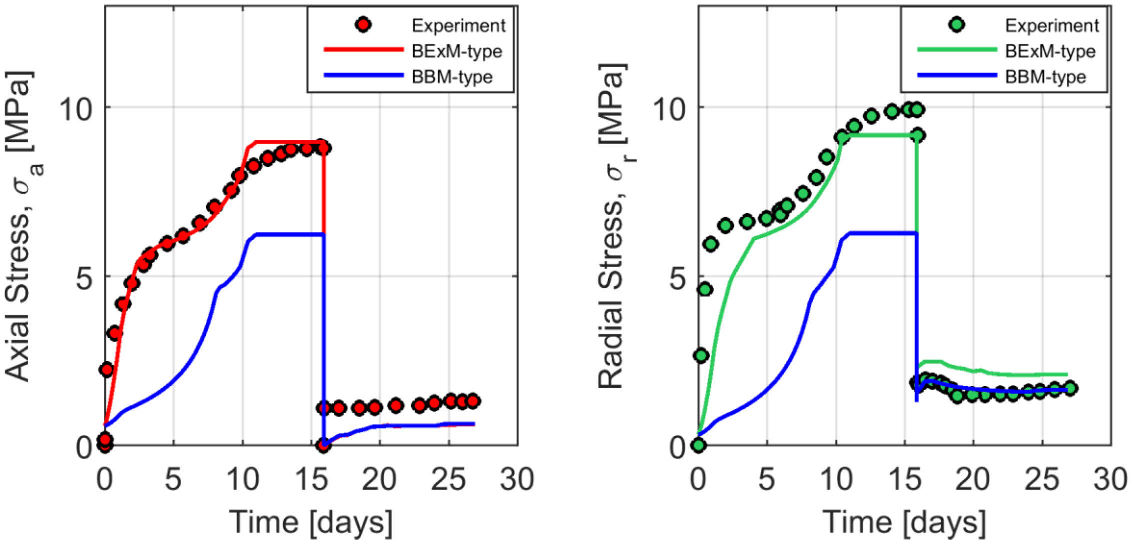
The experiment can be divided into the following stages:

1. Wetting at constant volume until saturation;
2. Piston is moved 5 mm upwards (i.e. 25% axial swelling deformation for initially 20 mm heigh sample). No contact with water is allowed at this stage;
3. Bentonite swells and fills the space left by the piston, while in contact with water;
4. Swelling pressures can be measured again once the sample-piston contact has been re-established.

From a numerical standpoint, the simulation of this test is axisymmetric and hydro-mechanically coupled. It is carried out using a finite element mesh consisting of quadrilateral, 8-noded finite elements, and is intentionally coarse as no mesh-dependency nor localisation phenomena are encountered (finer meshes have been employed to verify this).

The constitutive model used in the simulations is the new double structure framework for unsaturated, expansive clays implemented in ICFEP, which is described in the Beacon form ICL1. Nevertheless, it is also interesting to compare the performance of the new models with that of the expanded BBM-type model (Georgiadis et al., 2003, 2005), also implemented in ICFEP. The calibration of the models is carried out using information from oedometric/isotropic and triaxial studies, which are discussed in Beacon forms ICL2 and ICL3 respectively.

The simulation yields the results reproduced in Figure 2.



(a) *(b)*

Figure 2: simulation of the axial swelling test (Dueck et al., 2011, 2014). Both BBM and expansive frameworks are employed using the same set of material parameters.

The match between experimental data and numerical solution is very good in the case of the expansive model, which predicts a considerably higher swelling pressure than the BBM model. By comparison of the two magnitudes of the swelling stresses in the two figures, it can be argued that the microstructure captures a considerable amount of the swelling. It can also be noticed that, according to the laboratory data, the stress level reached upon full saturation is slightly higher in the case of radial stresses, whereas both models predict an isotropic behaviour.

Main learning points concerning bentonite homogenization / mechanical evolution and relevance for the project

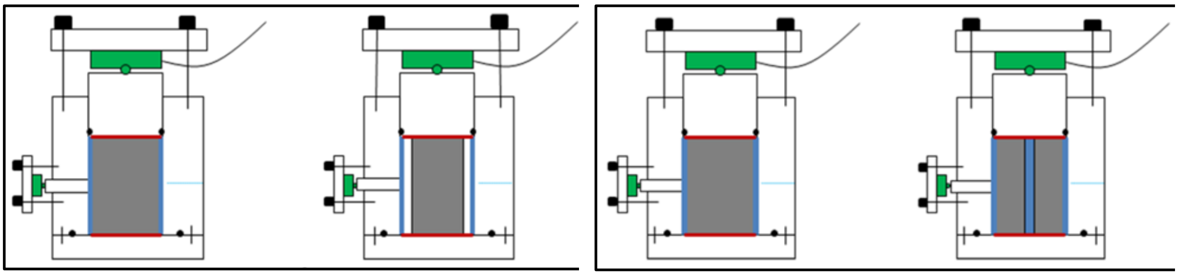
The above analyses are a good test for the new expansive model: they highlight how important the role of the microstructure can be, as the predictions of the swelling stress greatly improve when the double porosity structure is introduced.

From an experimental point of view, these tests are particularly useful as they allow the study of the hydration and swelling of bentonite in a relatively controlled laboratory environment. In fact, larger scale experiments, such as mock up tests of deep geological repositories, usually present a complex scenario where multiple phenomena overlap and influence each other. Hence, making it more difficult to isolate and analyse the HM evolution of bentonite.

How could this work inform a new experimental or modelling study in BEACON?

In order to gain further insight on bentonite behaviour, two additional experiments are analysed from the same series of basic swelling tests (Dueck et al., 2011, 2014). Conceptually these tests are similar to the axial test that is described above, nevertheless this time the swelling happens in the radial direction.

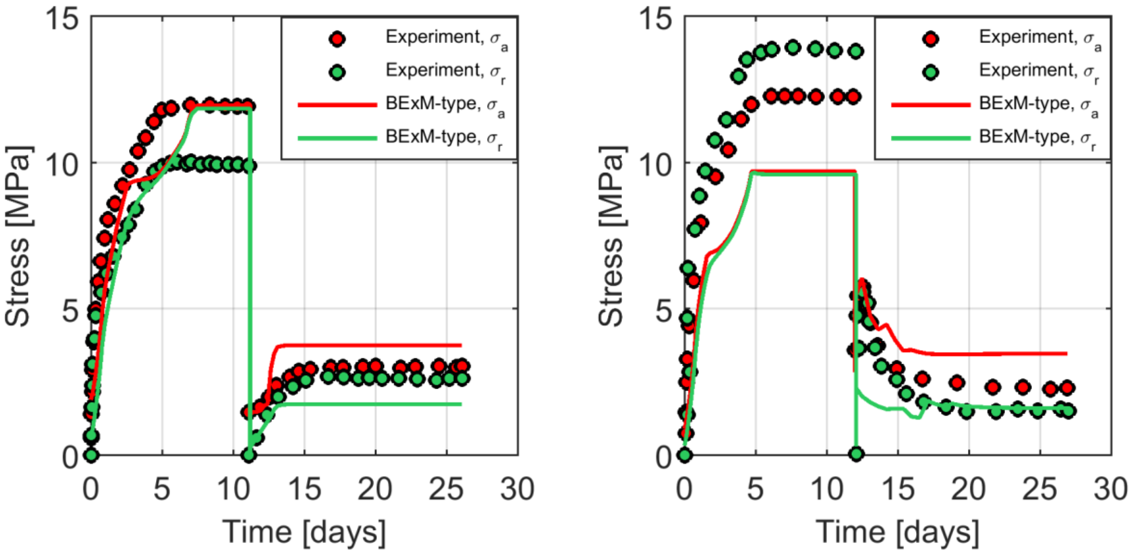
The tests involve seemingly identical samples of compacted bentonite, placed in an oedometer and wetted at constant volume from the samples' perimeter boundary, as shown by the initial set up in Figures 3(a) and 3(b). The blue lines indicate the wetting boundaries (i.e. the source of water). Upon reaching full saturation one specimen is trimmed around its perimeter, while an internal cylindrical cavity is created in the other. Both samples are then returned in the oedometer cell and the former is allowed to swell outwardly, Figure 3(a), and the latter inwardly, Figure 3(b), under axially confined conditions. Both the axial, σ_v, via the oedometer piston, and the radial, σ_r, via the transducer on the side of the sample, swelling pressures are measured throughout the tests.



(a) (b)

Figure 3: Test set ups for the (a) outward and (b) inward radial swelling pressure tests (Dueck et al., 2011, 2014).

The simulation using the new expansive framework yields the results reported in Figure 4(a) and 4(b).



(a) (b)

Figure 4: Radial swelling tests: on the left there is the outward radial case, on the right there is the inward case. All experimental data is from Dueck et al. (2011, 2014).

The newly developed expansive constitutive model is capable of reproducing reasonably well the pattern of evolution of swelling pressures with time, as shown in Figure 4 for the two tests. The model predicts isotropic swelling under isochoric conditions ($\sigma_v = \sigma_r$ for the first 12 days, until full saturation) in both tests, with different magnitudes of the mobilised maximum swelling pressures between the two tests. Although the samples are described as identical, they are reported to have slightly different initial stresses, which seems contradictory to their alleged compaction to the same initial suction and dry density. This difference in the initial stresses contributes to the slight difference in swelling pressures predicted in the analyses. However, inspection of experimental results, while showing similar axial swelling pressures in the two samples, highlights a marked difference in the radial swelling pressures, $10\,MPa$ in Figure 4(a) and $14\,MPa$ in Figure 4(b). The cause of this $4\,MPa$ difference is unclear and cannot be explained only by a slight difference in the initial stress states of the samples. This is more likely a consequence of different post-compaction states of the two samples in terms of their structure and dry density. As a general observation in this case, it is clear that the uncertainties related to experimental procedures in preparing the samples seem to affect the quality of the simulations far more markedly than the possible shortcomings of the model.

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Recommendations for BEACON project

The phase prior to the start of the actual test is of crucial importance: sample preparation and compaction influence greatly the behaviour of the material. A detailed reporting of such processes is necessary to allow modeling choices that suit the experiment best. Hence, it would be of great interest to have more details on how the samples are prepared for various experiments.

Furthermore, the free swell phase for all three tests lacks the information about the length of time that was necessary to obtain the desired expansion. The hydro-mechanical evolution of bentonite is a time-related process and therefore an accurate record of time durations of various test phases is essential for meaningful and realistic numerical analyses.

Project Acronym ILM (Internal Limit Model)	**Location** -	**Type** Model
Lead organiser Quintessa	**Start date**	**End date**
Main partners involved in the project RWM	**Characteristics of swelling clay**	**Water Saturation**
Instrumentation	**Main elements related to homogenization** Technological void between bentonite seal and host rock.	**Interfaces with other material**
Modelling Yes/no: Yes Groups/Codes : Quintessa, QPAC	**Main processes studied** ☒T ☒H ☒M ☐Swelling pressure ☐Gas transfer ☐Other	**Reference concept if pertinent**

Main objectives of the experiment

Testing new modelling strategy for coupled THM modelling. Model applied to SEALEX experiments and FEBEX-DP.

General description

A new model is presented, referred to as the Internal Limit Model, which makes use of key observations on limiting stresses supported in bentonite samples in experimental data. This model is based on the Modified Cam Clay model, and uses the observation that for a given dry density of bentonite, there is a limiting stress that the sample can support, be that stress due to swelling, compaction or suction, to explicitly couple the hydraulic and mechanical models.

Main learning points concerning bentonite homogenization / mechanical evolution and relevance for the project

The model has been applied successfully to the SEALEX and FEBEX experiments. It can reproduce the dry density distribution in the FEBEX experiments.

How could this work inform a new experimental or modelling study in BEACON?

Further modelling with the ILM model will build confidence in the approach and allow any improvements to be made

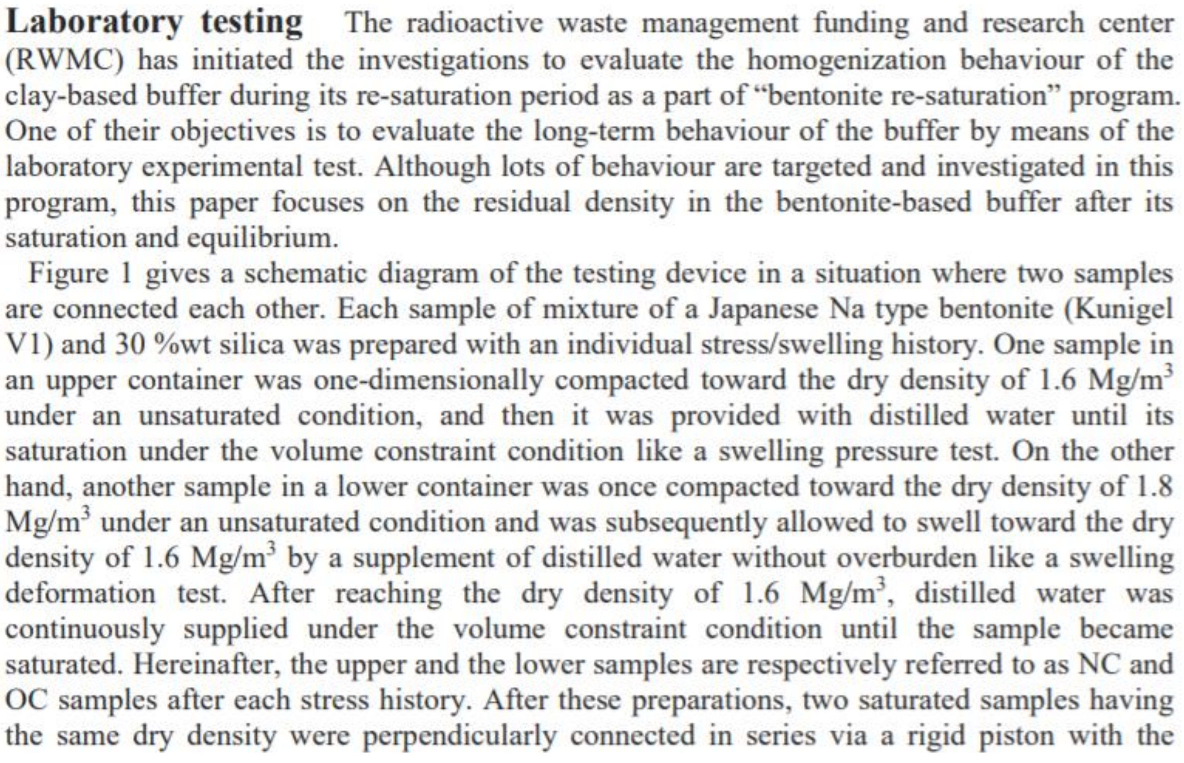
References (ideally with web links)

Thatcher KE, Bond AE, Robinson P, McDermott C, Fraser Harris AP and Norris S, 2016. A new hydro-mechanical model for bentonite resaturation applied to the SEALEX experiments. Environmental Earth Sciences, 75:1-17

Recommendations for BEACON project

Project Acronym Numerical Evaluation on the Bentonite Re-saturation Process	**Location**	**Type** Numerical simulation of lab test
Lead organiser RWMC	**Start date**	**End date**
Main partners involved in the project	**Characteristics of swelling clay** Japanese Na type bentonite (Kunigel V1), mixed with silica (30% wt)	**Water Saturation** Artificial
Instrumentation Water intake measured, dry density measured	**Main elements related to homogenization**	**Interfaces with other material**
Modelling Yes/no: Groups/Codes :	**Main processes studied** ☐T ☐H ☐M ☐Swelling pressure ☐Gas transfer ☐Other	**Reference concept if pertinent**

Main objectives of the experiment



Laboratory testing The radioactive waste management funding and research center (RWMC) has initiated the investigations to evaluate the homogenization behaviour of the clay-based buffer during its re-saturation period as a part of "bentonite re-saturation" program. One of their objectives is to evaluate the long-term behaviour of the buffer by means of the laboratory experimental test. Although lots of behaviour are targeted and investigated in this program, this paper focuses on the residual density in the bentonite-based buffer after its saturation and equilibrium.

Figure 1 gives a schematic diagram of the testing device in a situation where two samples are connected each other. Each sample of mixture of a Japanese Na type bentonite (Kunigel V1) and 30 %wt silica was prepared with an individual stress/swelling history. One sample in an upper container was one-dimensionally compacted toward the dry density of 1.6 Mg/m^3 under an unsaturated condition, and then it was provided with distilled water until its saturation under the volume constraint condition like a swelling pressure test. On the other hand, another sample in a lower container was once compacted toward the dry density of 1.8 Mg/m^3 under an unsaturated condition and was subsequently allowed to swell toward the dry density of 1.6 Mg/m^3 by a supplement of distilled water without overburden like a swelling deformation test. After reaching the dry density of 1.6 Mg/m^3, distilled water was continuously supplied under the volume constraint condition until the sample became saturated. Hereinafter, the upper and the lower samples are respectively referred to as NC and OC samples after each stress history. After these preparations, two saturated samples having the same dry density were perpendicularly connected in series via a rigid piston with the counter weight to offset its weight. As the connection results in the vertical stress continuity between two saturated samples, the main concern in subsequent response is the occurrence of additional deformation or the changes in dry density in the transition process toward equilibrium.

Fig. 2 shows the changes in the dry density of NC (upper) and OC (lower) samples including the swelling processes after compaction. In Process 1, the dry density of OC sample decreased with time due to swelling toward the targeted dry density of 1.6 Mg/m^3, while nothing happened in NC sample because the supplement of water had not yet started. Subsequently, both specimens were provided with distilled water while keeping the dry density of 1.6 Mg/m^3 constant in Process 2. By measuring the amount of water intake, it was confirmed that both specimens were fully saturated at the end of this process. Major finding in this test is the responses in dry density in Process 3; the difference in dry density between OC and NC samples began to generate immediately after the connection. This means that the stress equilibrium results in the gap of dry density between samples having the different stress/swelling histories and cannot sustain the dry density homogeneity.

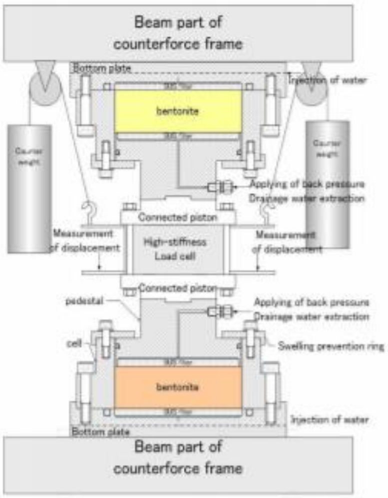


Figure 1 Schematic diagram of test apparatus

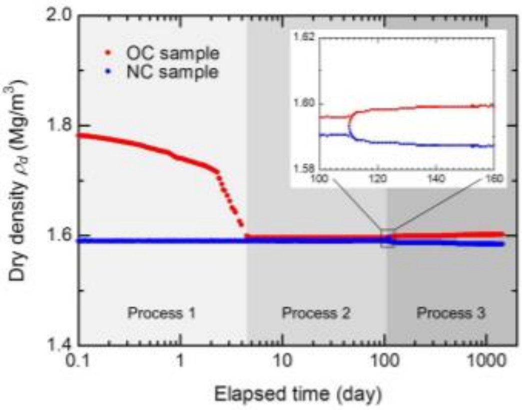


Fig. 2 Changes in dry density of NC and OC samples

General description

Numerical simulation The numerical simulation of the above-mentioned laboratory test was conducted by using the elasto-plastic constitutive model for bentonite buffer proposed by Takayama et al. (2017). The constitutive model used in this study is based on the Bishop's effective stress for unsaturated soils, while the effective degree-of-saturation is employed as a state parameter:

$$\boldsymbol{\sigma}' = \boldsymbol{\sigma} - u_a + S_e(u_a - u_w)\boldsymbol{1} = \boldsymbol{\sigma}^{net} + S_e s \boldsymbol{1} \qquad (1)$$

where $\boldsymbol{\sigma}$, $\boldsymbol{\sigma}^{net}$, u_a, u_w, S_e and s represent total stress tensor, net stress tensor, pore air pressure, pore water pressure, effective degree-of-saturation , and suction. $\boldsymbol{1}$ is the second order identity tensor. Although the model has a similar mathematical structure to the Cam-clay model, the hardening parameter is determined not only by the plastic volumetric strain but also by the effective degree-of-saturation after the hardening law by Ohno et al. (2006).

Yield function of the model is expressed as follows.

$$f\left(\boldsymbol{\sigma}', S_e, \varepsilon_v^p\right) = \frac{\lambda - \kappa(S_e)}{1 + e_0} \ln \frac{p'}{\zeta p_0'} + D \frac{q}{p'} - \varepsilon_v^p = 0 \tag{2}$$

where p', q, ε_v^p, λ and D represent effective mean stress, stress deviator, plastic volumetric strain, compression index, and dilatancy coefficient. Here, ζ represents the effect of degree-of-saturation as follows.

$$\zeta = \zeta(S_e) = \exp\left\{(1 - S_e)^n \ln a\right\} \tag{3}$$

where a and n represent material parameters which control the enlargement of yield surface due to changes in degree-of-saturation. Furthermore, the swelling index κ is formulated as a function of S_e so as to express the significant swelling and the changes in dilatancy characteristics as follows:

$$\kappa = \kappa(S_e) = \kappa_0 - (\kappa_0 - \kappa_{sat}) S_e^l \tag{4}$$

where κ_0 and κ_{sat} represent the swelling indices at driest and saturated conditions ($S_e = 0$ and $S_e = 1$), respectively. l is material parameter. The soil-water characteristic curve (SWCC) is also employed to describe the relationship between the suction and the degree-of-saturation. Swelling behaviour is dominant in this simulation. Thus, the swelling curve can be formulated as

$$S_r = S_{ra} + (1 - S_{ra}) / \left(1 + s^B \exp A\right) \tag{5}$$

where A and B are material parameters characterising the shape of SWCC. S_{ra} represents the lowest limit of degree-of-saturation.

In the simulation, the state changes of two samples are simultaneously calculated so as to set the constraint conditions to be consistent with the control conditions in laboratory test. In process 1, the suction of OC sample was increased until the dry density reach 1.6 Mg/m^3, while the vertical stress was kept to be constant ($\dot{s}^{OC} > 0$ and $\dot{\sigma}_v^{OC} = 0$). In process 2, the suction of OC and NC sample was increase up to their saturation, while the volumes of samples are constraint ($\dot{s}^{OC} > 0$ and $\dot{\varepsilon}_a^{OC} = 0$ for OC sample; $\dot{s}^{NC} > 0$ and $\dot{\varepsilon}_a^{NC} = 0$ for NC sample). In process 3, both saturated specimens are allowed to deform until a stable state while the stress equilibrium and constraint condition are satisfied ($\dot{\sigma}_v^{OC} = \dot{\sigma}_v^{NC}$ and $\dot{\varepsilon}_a^{NC} + \dot{\varepsilon}_a^{OC} = 0$). The lateral deformation of both specimens is not allowed in all processes ($\dot{\varepsilon}_r^{NC} = \dot{\varepsilon}_r^{OC} = 0$) to simulate the one-dimensional strain field. It is noted that both pore water

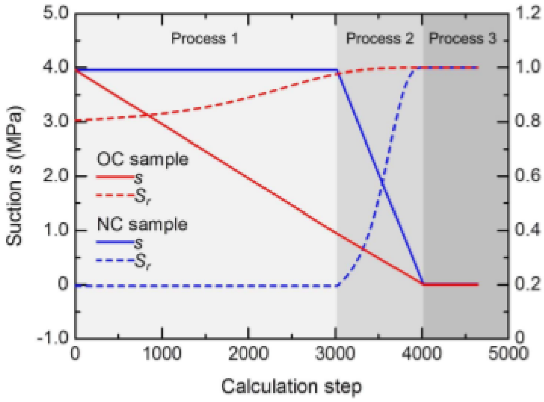


Figure 3: Changes in degree-of-saturation and suction

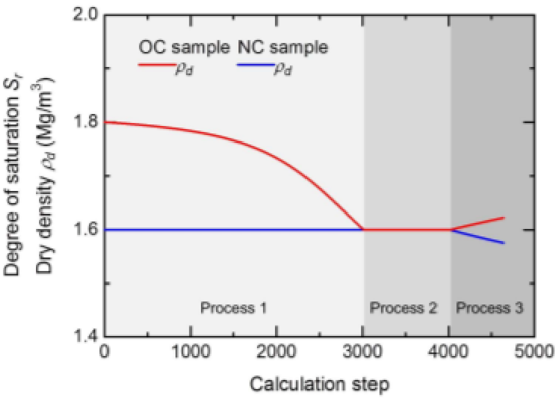


Figure 4: Changes in dry density

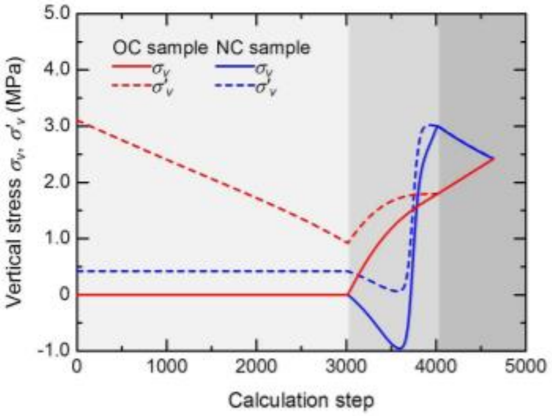


Figure 5: Changes in vertical stress

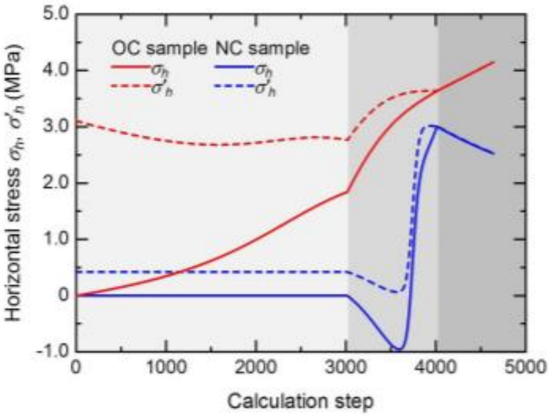


Figure 6: Changes in horizontal stress

and air are assumed to be incompressible and that dissolution of air into water is neglected in the simulation.

Results of the numerical simulation are shown in Figs. 3 to 6. The vales of degree-of-saturation of both samples increase until the end of Process 2 by each step-by-step control of suction history (Fig. 3). The prediction of changes in dry density, which is consistent with the result of laboratory test, indicates that the swelling of OC sample causes the contraction of NC sample by the same amount due to stress continuity in Process 3 (Fig. 4). Changes in vertical and horizontal stresses are respectively shown in Figs. 5 and 6. At the end of Process 3, the vertical stresses of OC and NC samples are met due to equilibrium while the horizontal stresses take different values depending on each history and constitutive response.

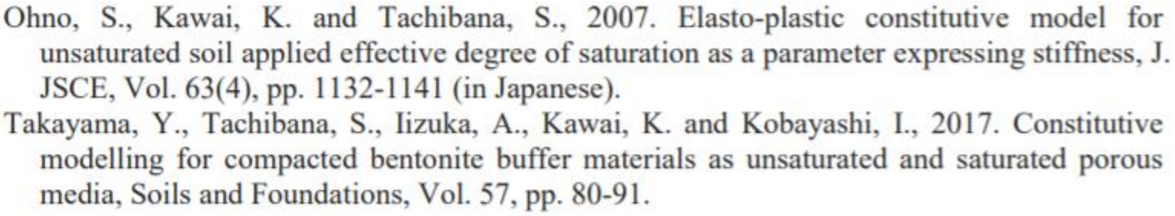
Main learning points concerning bentonite homogenization / mechanical evolution and relevance for the project

Conclusions Laboratory test results suggest that the residual heterogeneity of dry density after full saturation will remain or generate in the bentonite-based buffer even if the buffer is placed with a homogeneous density distribution. Results of numerical simulation support such tendencies and applicability of constitutive model applied in this study. Investigations on the homogenization behaviour of the bentonite-based buffer are ongoing and several laboratory tests under various conditions (i.e., initial dry density and saline water) have been conducted to evaluate the homogeneous behaviour more concretely.

How could this work inform a new experimental or modelling study in BEACON?

References (ideally with web links)

Recommendations for BEACON project



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Takayama, Y., Tachibana, S., Iizuka, A., Kawai, K. and Kobayashi, I., 2017. Constitutive modelling for compacted bentonite buffer materials as unsaturated and saturated porous media, Soils and Foundations, Vol. 57, pp. 80-91.

Project Acronym Homogenisation calculations for SR-Site	**Location** Clay Technology AB	**Type** Modelling study
Lead organiser Clay Technology/SKB	**Start date** 2008	**End date** 2010
Main partners involved in the project	**Characteristics of swelling clay** MX-80 Bentonite	**Water Saturation** Homogenisation cases with initially water unsaturated bentonite.
Instrumentation No	**Main elements related to homogenization** Hydro-mechanical material model used for buffer and backfill homogenisation.	**Interfaces with other material** No
Modelling Yes: HM material model for bentonite components by using the TEP (thermoelastoplastic) laws Codes : Code_Bright	**Main processes studied** ☐T ☒H ☒M ☒Swelling pressure ☐Gas transfer ☐Other	**Reference concept if pertinent** Analysed homogenisation cases in SKB reference concept KBS-3.

Main objectives of the modelling study

Development of HM material model for bentonite components by using the TEP laws implemented in Code_Bright.

General description

Engineered Barrier Systems are generally composed of different components with different initial dry density, for instance bentonite blocks, bentonite pellets-filled slots, or open slots. The homogenization process is a process through which these differences in dry density tend to decrease with time and is characterized by wide ranges of void ratios and water contents. Hydro-mechanical modelling of this process therefore requires a material model that can represent the behaviour of the bentonite for such wide ranges.

A material model for compacted bentonite components was developed for the thermoelastoplastic (TEP) constitutive laws, based on the Barcelona Basic Model (BBM) (Alonso et al. 1991) implemented in Code_Bright (CIMNE, 2002). This methodology consists of: i) the modification of TEP-law by implementation of a void ratio dependence into the definition of the swelling module; ii) a strategy for parameter value adoption and iii) a procedure for supporting the validity of the model results.

Constitutive laws

The BBM model is an elasto-plastic model which can be viewed as a generalization of the Modified Cam Clay model to water-unsaturated conditions, and uses the net mean stress (p´) and suction (s) as independent state variables for representing isotropic stress states. The strain in composed three parts: elastic (ε^e), plastic (ε^p) and hydraulic (ε^h). The elastic stress-strain relation is basically governed by the κ_i modulus (see Figure 1) and the Poisson´s ratio (ν). Plastic deformations are activated once the yield surface is reached (Figure 1). This surface is composed of two functions in the s-p´ plane: the tensile strength (p_s) and the preconsolidation stress (p_0), which both are expressed as functions of suction, and the latter is also a function of the preconsolidation stress for saturated conditions (p_0^*). These lines are joined with an elliptic function in the q-p´ plane, described with p_s, p_0 and the critical state line parameter (M). The hardening law describes a relation between increments in the plastic volumetric strain and in increments in p_0^* which is governed by the κ_i and λ_0 modulii. Finally, the hydraulic suction-strain relation is governed by the κ_s modulus.

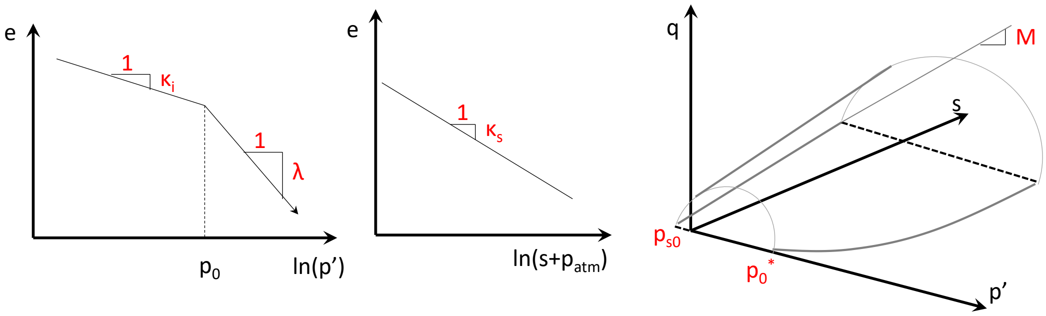

Figure 1. *Elements of the BBM used in Code_Bright.*

In the original formulation of BBM, the κ_i and κ_s parameters were regarded as constants. In the TEP constitutive laws of Code_Bright, however, they have been elaborated as functions. The κ_i is defined as a function of suction, while κ_s is defined as a function of p´, suction and the void ratio. The latter dependence is based on a defined swelling pressure relation, $p_{swell}(e)$, and this means that the swelling stops precisely when the mean stress reaches the swelling pressure for the current void ratio (Figure 2).

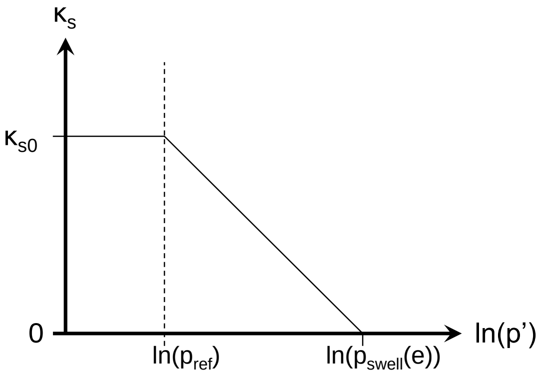

Figure 2. *Void ratio dependence and pressure dependence of kappa_s.*

Strategy for parameter value adoption

It is obviously of interest to have a methodology that can be used for a specific bentonite material (e.g. MX-80) for different system components (blocks and pellets) with different initial dry density and water content. A methodology was developed with this aim for the SR Site Data report (Åkesson et al. 2010a). Some parameters can essentially be set to the same value regardless of the initial conditions, whereas other parameters (plastic) are strongly related to the void ration. The aim was to develop a general and clear-cut method to quantify the parameter values for all relevant void ratios and a scheme for this is illustrated in Figure 3.

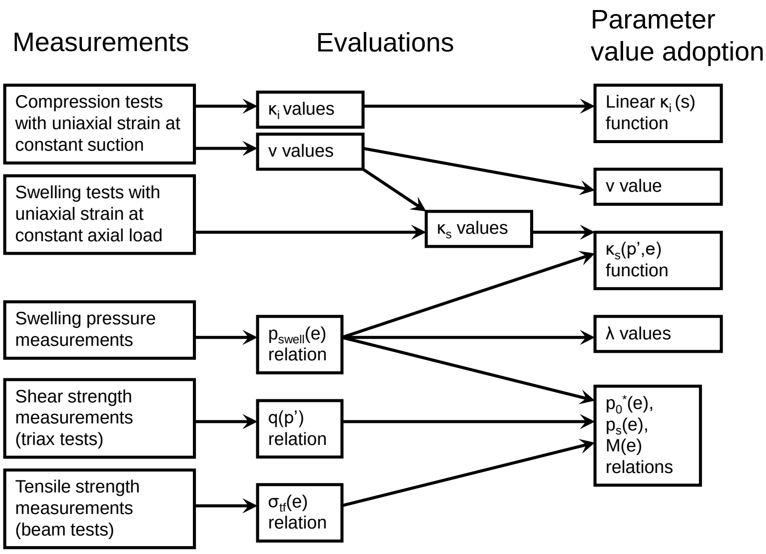

Figure 3. *Strategy for adoption of mechanical parameter values.*

For the elastic parameters essentially the same values are used for all considered void ratios. Exceptions are however made for parameters describing the suction dependence of κ_i and κ_s.

The plastic parameters, both the stress-strain modulus (λ) and the parameters describing the yield surface (M, p_s and p_0^*), are highly related to the void ratio. The λ value corresponds to the slope of the $p_{swell}(e)$ relation in the e-ln(p´) plane. The yield surface parameters and their void ratio dependences can be derived from empirical relations for swelling pressure $p_{swell}(e)$, the deviator stress at failure $q_f(p´)$, and the tensile strength $\sigma_{tf}(e)$, and from the assumption that the p´ value at the failure point equals the swelling pressure for the void ratio in question (Figure 4). The suction dependences of λ and p_s as provided by the TEP laws are generally omitted.

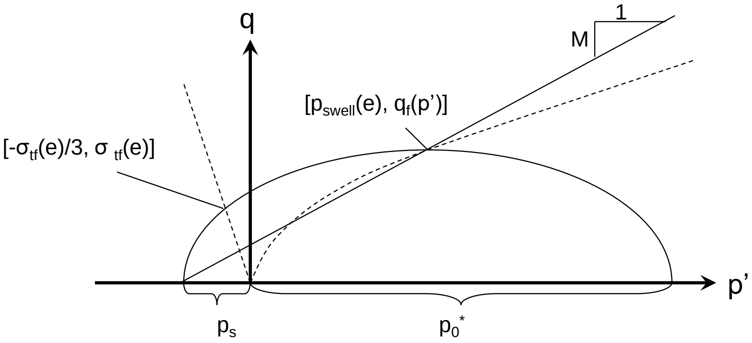

Figure 4. *Strategy for adoption of parameter values for the yield surface.*

The TEP laws imply that the yield surface can expand due to strain hardening (increased p_0^*) during consolidation. However there is no corresponding mechanism for yield surface contraction during isotropic swelling. This limitation has motivated the parameter value adoption for components that will undergo swelling (i.e. high density blocks) for a *homogenized target void ratio*, which corresponds to a complete homogenisation of the installed bentonite filling (e.g. for both blocks and pellets). For a pellets filling that will undergo compression, however, the parameters are adopted for the *initial void ratio*. The λ value for pellets are set for the slope between the initial and the target void ratios.

Finally, the validity of this approach can be supported by comparing the final (mean) stresses in the model with an empirical swelling pressure curve. All points in the model in the final saturated state should be somewhere in-between the swelling pressure curve and the same curve multiplied with a factor of two. Similarly, the deviator stresses in the model can be compared with, and should not exceed, the empirical relation between the deviator stress at failure and the mean effective stress.

Applications

The approach was first used for analyses of the homogenisation processes in initially water unsaturated KBS-3 buffer and backfill (Åkesson et al. 2010b). For example, stress paths from backfill homogenization calculations with a 1D axisymmetric block/pellets geometry, showed that the swelling of the inner parts of the blocks was limited by the void ratio dependence of the swelling module, whereas the stress path for pellets and the outer parts of the blocks were governed by the yield surface and the plastic compression module, which together gave rise to a remaining heterogeneity (Figure 5).

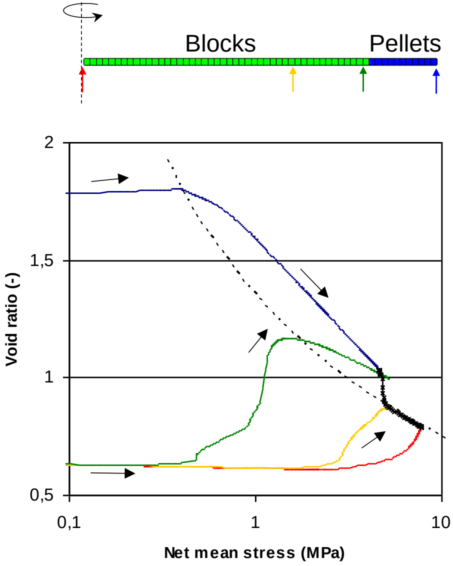

Figure 5. *Stress paths for 1D backfill homogenization calculation. Lines denote nodes in pellet (blue) in outer part of blocks (green) and inner part (yellow and red). Crosses denote final state.*

The material model has subsequently been used to analyse (and predict) the mechanical evolution of different field experiments: TBT (Åkesson et al. 2012); CRT (Åkesson et al. 2010b, Börgesson et al. 2016); Domplu (Börgesson et al. 2015; Grahm and Malm 2015); and Febex in situ test (in progress). It has also been used for HM analyses of the KBS-3H concept (in progress).

Main learning points concerning bentonite homogenization / mechanical evolution and relevance for the project

The presented material model is quite capable for prediction of the mechanical evolution of bentonite. Nevertheless, it has some important limitations; for instance, there are generally no defined void ratio dependences for the parameters; there is no mechanism for the yield surface to contract during isotropic swelling; and suction (>0) cannot be represented for water saturated conditions. This has motivated the development of a new hydromechanical material model, the Hysteresis Based Material model (HBM) (Åkesson 2017).

How could this work inform a new experimental or modelling study in BEACON?

The TEP law material model could potentially be used for *scoping calculations for new experimental studies* in BEACON, and also as *a modelling tool for new modelling studies* in BEACON, especially for cases for which it is not possible to new HBM model (Åkesson, 2017).

In spite of the limitations of the TEP law material model mentioned above, there may be some potential for further development, for instance regarding the water retention curve. In may also be valuable to have a better description of the foreseen limitations of the model applicability.

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Recommendations for BEACON project

Project Acronym SR-Site : Mechanical Evolution	**Location** N/A	**Type** Modelling study
Lead organiser SKB	**Start date**	**End date**
Main partners involved in the project	**Characteristics of swelling clay**	**Water Saturation** Artificial/natural
Instrumentation	**Main elements related to homogenization**	**Interfaces with other material**
Modelling Yes/no: Yes Groups/Codes : Abaqus, Code_Bright	**Main processes studied** ☐T ☐H ☐M ☒Swelling pressure ☐Gas transfer ☐Other	**Reference concept if pertinent**

Main objectives of the experiment

In the SR-Site safety assessment (SKB 2011) the mechanical processes in the bentonite buffer was evaluated in the description of the reference evolution. The reference evolution consisted of: the excavation and operation phases, the initial period of temperate climate after closure, the remaining part of the reference glacial cycle and subsequent glacial cycles.

General description

The main mechanical process during the excavation and operation phases is resealing of a mass loss from piping and erosion during the phase with high hydraulic gradients. In order to investigate how well the buffer material seals the openings resulting from the mass loss a number of finite element calculations with the code Abaqus was performed. The calculations showed that the lowest final swelling pressure after a mass loss of up to 240 kg is around 1.2 MPa for the given geometry (Figure 1).

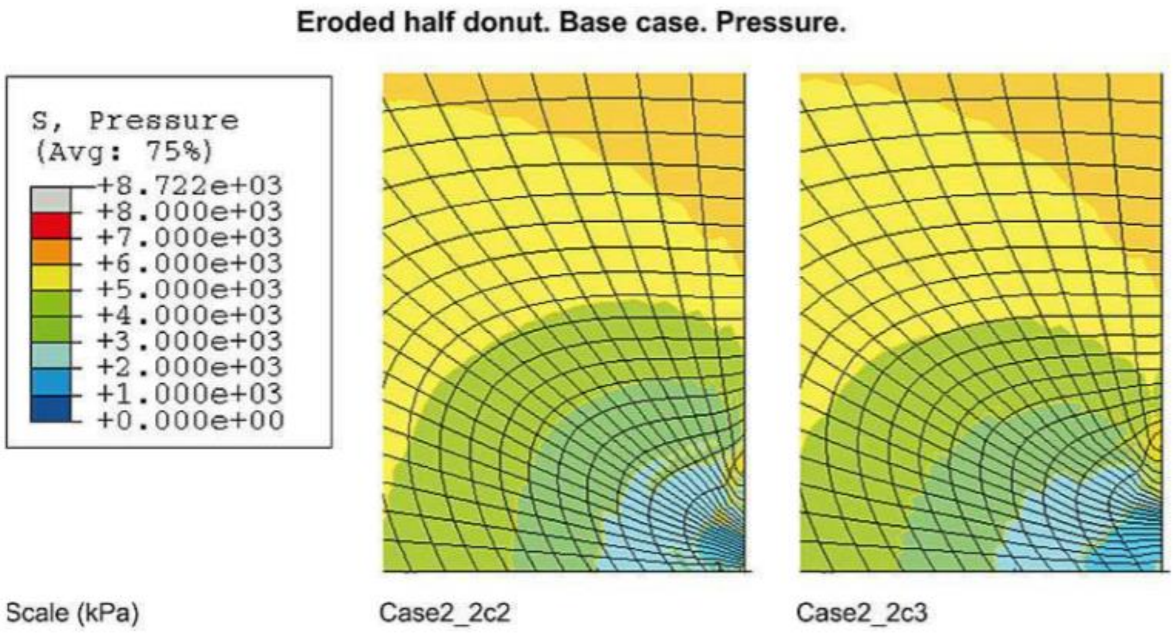

Figure 1 Final average stress of the base case with deviating water supply. Water supply from the hole and the backfill (left) and from only the backfill (right) /Åkesson et al 2010/

In the initial period of temperate climate it was needed to verify that the intended conditions after swelling will be reached, it was necessary to assess more carefully the swelling process with focus on:

- Buffer homogenisation.
- Buffer upward expansion. (Figure 2)
- Movement of the canister in the deposition hole.
- Homogenisation after loss of bentonite mass

Different analyses of the natural homogenisation process in the buffer were carried out using analytical solutions as well as the finite element codes Code_Bright and Abaqus. The results show that under expected conditions the buffer density and swelling pressure will homogenise to a situation where the relevant safety functions will be upheld.

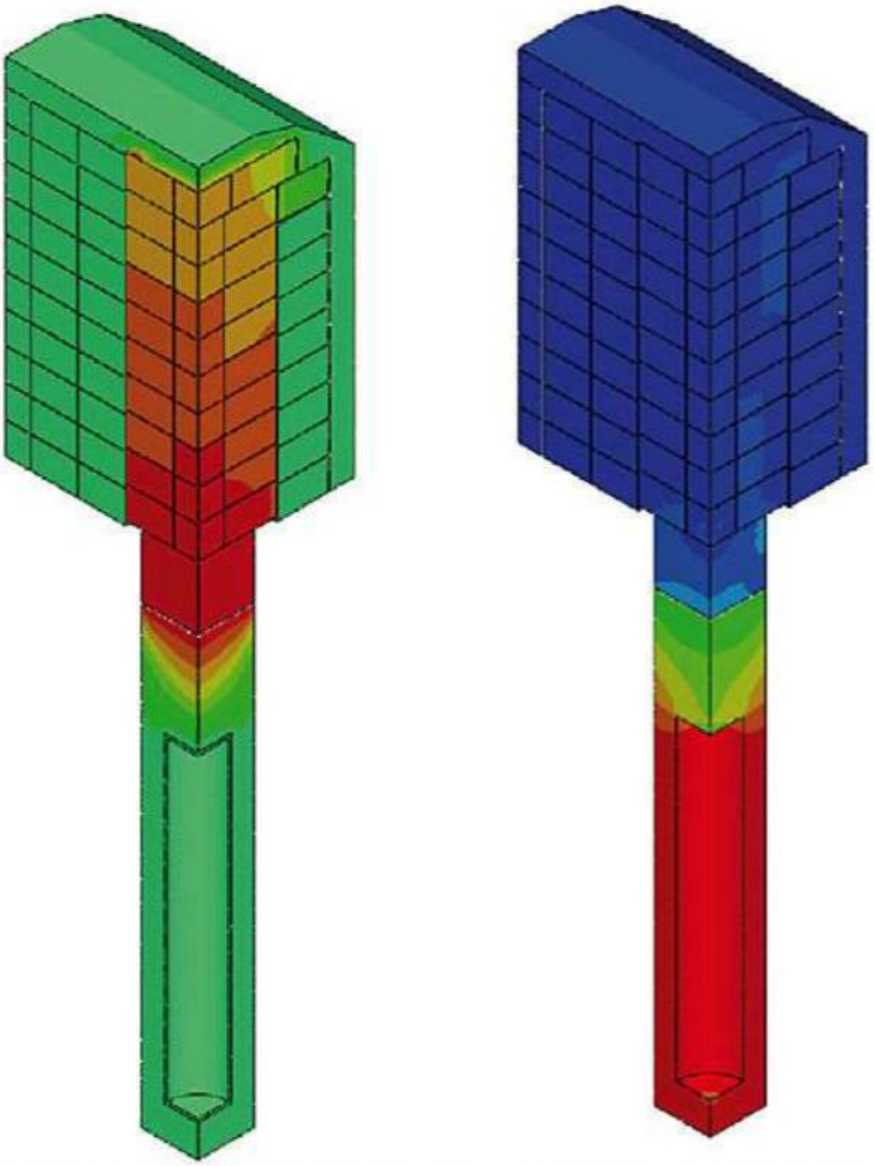

Figure 2 Vertical displacements (U, m) and average stress (S, kPa) in the buffer and backfill after completed swelling for a case with a swelling buffer and a dry tunnel backfill. U2 is the direction (vertical) of the displacement U /Börgesson and Hernelind 2009/.

The remaining part of the reference glacial cycle

Dilute melt waters may occur within the repository volume for some period of time during the advance and retreat of an ice sheet. This may lead to erosion and mass loss from the bentonite buffer. In order to investigate how well the buffer material seals the openings resulting from the erosion a number of finite element calculations with the code Abaqus was performed. The analyses show that in the case where large amounts of bentonite are lost from a deposition hole or missing from the start the remaining bentonite swells and fills the empty space but the density and resulting swelling pressure will be rather low due to the friction in the buffer and the friction against the rock surface. For a 50 cm vertical opening in a deposition hole, the resulting swelling pressure will be in average 0.5–1 MPa in almost the entire former hole (Figure 3).

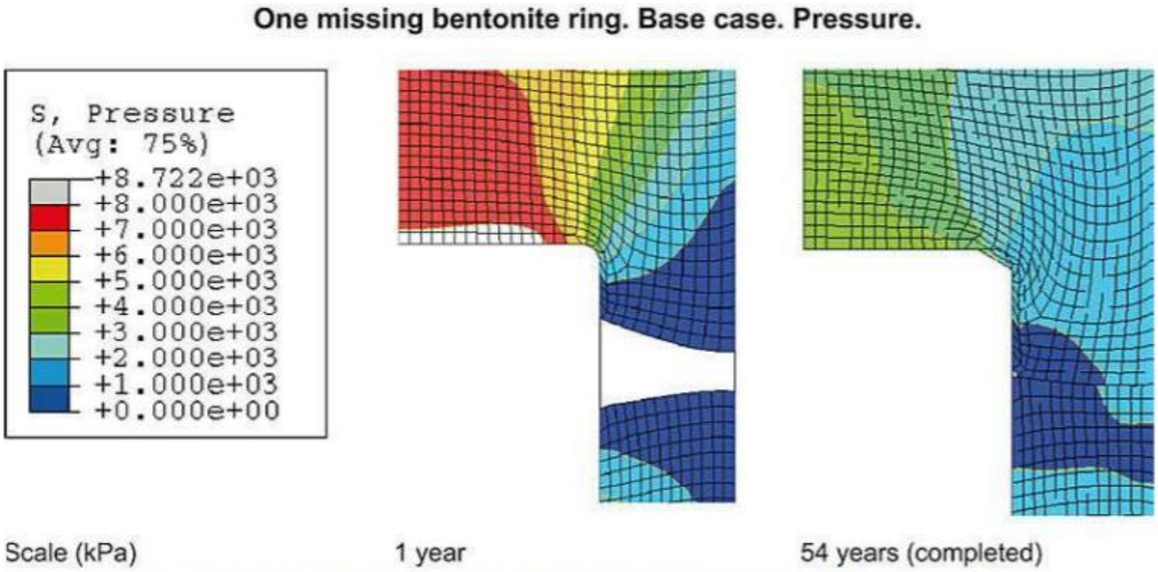

Figure 3 Average stress plotted at different times for the base case of one missing ring. /Åkesson et al 2010/

Main learning points concerning bentonite homogenization / mechanical evolution and relevance for the project

How could this work inform a new experimental or modelling study in BEACON?

References (ideally with web links)

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Recommendations for BEACON project