D8.12 BEACON
Bentonite Mechanical Evolution

Proceedings Beacon Initial Workshop, 19-20 June 2017

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Minutes Beacon WP2 Initial Workshop

Date and place: 19-20 June 2017 in Kaunas, Lithuania
Participant list: See attachment 1

Purpose, objectives and aim of the initial workshop
The purpose of the Workshop was to kick start Beacon work package 2 – Collection and compilation of existing data and available models. The objective was to present and discuss the current state-of-art regarding the mechanical evolution of bentonite barriers, the information available from national and international projects at the beginning of the Beacon project which are relevant for the exploration of the role of heterogeneities in bentonite components on long term performance assessment.

Another aim of the Beacon Initial Workshop was to establish a network of specialists in support of the project, and further to initiate a process leading to successful dissemination of the results.

The outcome of the workshop will serve as a foundation for the state-of-art report that will be produced as a part of the Beacon projects WP2.

The WP2 Initial Workshop was also preceded by a very short Kick off for the whole Beacon project Monday morning, for the Beacon consortium and involved in the project.

Participants
The workshop targeted a wider scientific community consisting of as well persons involved with studies of mechanical properties of bentonite barriers as for example involved in final repository EURATOM programs, those not yet or directly involved but would like to get informed about how to join the activities or would like to have a first-hand overview of the latest information followed by detailed proceedings.

The Beacon WP2 Initial Workshop gathered 69 participants from 39 organisations and 13 countries; Belgium, Czech Republic, Finland, France, Germany, Hungary, Japan, Lithuania, Netherlands, Spain, Sweden, Switzerland, United Kingdom.

All Beacon consortium partners were represented, but one was represented by another one of the partners, and the Project Officer from the European Commission was present. 4 out of 5 of the members of the EARB (the Beacon Expert Advisory and Review Board were able to attend.

The agenda
The agenda of the WP2 Initial workshop can be found as Attachment 2.
The Workshop started with an introduction of our host organisation Lithuanian Energy Institute and a presentation of the EC and the coming program by the Beacon project´s Project officer, Athanasios Petridis.

After that the work packages of the Beacon project were presented by their respective work package leaders, and two invited speakers gave a good picture of the background to the project. The afternoon on Monday gave 6 oral presentations focused mainly on experiments followed by an hour with poster introductions. In the evening the participants all gathered for the poster session together with which some finger foods and beverages were served.

The Tuesday from early morning until late lunch 10 plenary presentations were made, focussing both on experiments and modelling.
After lunch the upcoming Beacon Training Course was presented, followed by an interesting summary discussion.

Requested abstracts/papers
Papers for oral and/or poster presentations to the workshop were requested from anyone working in the field of mechanical properties of bentonite, both from inside and outside the radioactive waste management community.
The papers were requested to focus on available information, since the objective was the state of art and the requested presentations were therefore not to cover the planned work in Beacon. Review papers of the findings from earlier work were strongly encouraged.

37 abstracts were received. 18 were invited to make a full oral presentation, 19 to participate with a poster presentation. Poster presenters were also invited to make a 3 minute oral poster introduction before the poster session that was held between 17 and 20 the first day of the workshop. Some additional posters were also

The presentations from the workshop can be found as Beacon Deliverable D2.1 and on the project website www.beacon-h2020.eu

Final discussion
The first topic of the discussion after the plenary and poster sessions was the observed difference in mechanical evolution in the FEBEX compared to the Prototype Repository. It is not obvious why these differences have developed and the understanding of this will be a challenge for the BEACON project. There are however a large data set available from these tests as well as from the EB and the CRT and it should be possible to evaluate the difference in behaviour.

There are a number of factors that could responsible for the difference in behaviour: temperature gradient, scale, original dry density, hydration history, material properties, etc. Since the observed phenomena are difficult to describe conceptually, it is clear that quantitative modelling will be a challenge and that very good models will be required. This is also the key motivation for the BEACON project. The coupling between the work packages was also discussed. The aim of the project is to understand better. The final output will be used be safety assessment and engineering. There will be residual heterogeneity in the systems and it has to be verified that the final state is sufficient for the intended performance.

The WP 2 State-of-Art report will be ready in M6. However, the other work packages still need to start the work. There is a need for a strong interaction. The development in WP3 needs to be driven by the needs from WP5. This should however not be a major concern since the same groups are represented in both WPs. WP4 need to support WP3 and WP5 and requirements for the experiments must come from the modellers. There should be sufficient flexibility in WP4 to accommodate for requests. There is an urgent need for an initial test for the modellers. WP5 will distribute a "virtual" test well before the end of the year. Additional test cases according to the strategy in Description of Work will be defined at the first WP3-WP5 meeting.

Upcoming meetings: WP2 October, WP3-5 January, WP4 after WP3-5

Attachments:
Attachment 1 Participant list
Attachment 2 Agenda Initial Workshop
Attachment 3 Short Abstracts

BEACON
Bentonite Mechanical Evolution

List of participants, Workshop 19-20 June 2017

Mechanical properties of bentonite barriers

First name	Last name	Org	Signature
Aleš	Balvín	Technical University of Liberec	
Jean-Dominique	Barnichon	IRSN	
Fabien	Bernachy-Barbe	CEA	
Frédéric	Bernier	FANC	
Martin	Birgersson	Clay Technology AB	
Robert	Charlier	University of Liege	
Guangjing	Chen	EURIDICE	
Frédéric	Collin	University of Liege	
Olivier	Cuisinier	Université de Lorraine	
Benjamin	Dardé	ANDRA	
Remi	de la Vaissiere	ANDRA	
Ann	Dueck	Clay Technology AB	
Joerg	Feierabend	TU Clausthal	
Masaaki	Fukaya	Obayashi Corporation	深谷正明
Antonio	Gens	Universitat Politecnica de Catalunya - UPC	
Jon	Harrington	British Geological Survey	
Lucie	Hausmannová	SÚRAO	

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Bentonite Mechanical Evolution

List of participants, Workshop 19-20 June 2017

Mechanical properties of bentonite barriers

First name	Last name	Org	Signature
Erika	Holt	VTT Technical Research Centre of Finland	
Rubén	Iglesias Martínez	CIEMAT	
Tomoko	Ishii	Radioactive Waste Manegement Funding and Research Center	
Lars-Erik	Johannesson	SKB	
Kóbor	József	University of Pécs - Green Circle of Pécs	
Darius	Justinavicius	Lithuanian Energy Institute, LEI	
Ola	Karnland	Clay Technology AB	
Markku	Kataja	University of Jyväskylä (JYU)	
Ichizo	Kobayashi	Kajima Corporation	
Petri	Koho	Posiva Oy	
Jaroslav	Kruis	Czech Technical University in Prague	
Rainer	Laaksonen	STUK - Radiation and Nuclear Safety Authority	
Lasse	Lavikainen	Posiva Oy	
Olivier	Leupin	Nagra	
David	Luterkort	SKB	
Aldo	Madaschi	Ecole Politechnique Fédérale de Lausanne	
Paul	Marschall	Nagra	

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BEACON
Bentonite Mechanical Evolution

List of participants, Workshop 19-20 June 2017

Mechanical properties of bentonite barriers

First name	Last name	Org	Signature
David	Mašín	Charles University	
Jan	Najser	Charles University	
Asta	Narkūnienė	Lithuanian Energy Institute, LEI	
Soshi	Nishimoto	Central Research Institute of Electric Power Industry	西本壮志
Mika	Niskanen	Posiva Oy	
Simon	Norris	Radioactive Waste Management	
Nikol	Novotná	SÚRAO	
Athanasios	Petridis	EC - DG RTD	
Wilfried	Pfingsten	Paul Scherrer Institut	
Povilas	Poskas	Lithuanian Energy Institute, LEI	
David	Potts	Imperial College London	
Veli-Matti	Pulkkanen	VTT Technical Research Centre of Finland	
Roland	Pusch	Miljöorganisationernas kärnavfallsgranskning (MKG)	
Timo	Riikilä	University of Jyväskylä (JYU)	
Franz	Rinderknecht	KIT-INE	
Michael	Rutenberg	TU Clausthal	
Klaus-Jürgen	Röhlig	TU Clausthal	

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Mechanical properties of bentonite barriers

First name	Last name	Org	Signature
Thorsten	Schäfer	KIT-INE	
Annika	Schäfers	Federal Institute for Geosciences and Natural Resources (BGR)	
Patrik	Sellin	SKB	
Tomoyuki	Shimura	Obayashi Corporation	
Ito	Shinji	Kobe University	
Sigita	Subačiūtė	Lithuanian Energy Institute, LEI	
Johan	Swahn	Miljöorganisationernas kärnavfallsgranskning (MKG)	
Shinya	Tachibana	Kobe University	
Jean	Talandier	ANDRA	
Kate	Thatcher	Quintessa Ltd	
Yasutaka	Watanabe	Central Research Institute of Electric Power Industry	
Jacques	Wendling	ANDRA	
Mary	Westermark	SKB	
Patrik	Vidstrand	SKB	
Klaus	Wieczorek	GRS	
María Victoria	Villar	CIEMAT	
Shuichi	Yamamoto	Obayashi Corporation	

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Mechanical properties of bentonite barriers

First name	Last name	Org	Signature
Borys	Zlobenko	SIIEG NAS of Ukraine	
Mattias	Åkesson	Clay Technology AB	Mattias Åkesson
Tessel	Snijders Blok	Shell	TSB

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AGENDA Workshop 19-20 June 2017

Mechanical properties of bentonite barriers

Monday 19 June 2017

8:15-10:00	Coffee and registration	
09:00-09:40	Beacon Kick off: Beacon partners, EARB and WP6-involved only	
10:00-10:25	**Workshop starts**	
10:00-10:05	Welcome to the workshop and practicalities	Mary Westermark
10:05-10:10	Welcome to LEI	Mr. Sigitas Rimkevicius
10:10-10:25	EC information	Athanasios Petridis
10:25-11:45	**Introduction to the Beacon project:** background, objectives planned activities	
10:25-10:35	WP2 – Collection and compilation of existing data and available models	Simon Norris
10:35-10:45	WP1 – Definition of assessment case/Application to the assessment cases	Olivier Leupin
10:45-10:55	WP3 – Model development	Antonio Gens
10:55-11:05	WP4 – Laboratory testing	Klaus Wieczorek
11:05-11:25	Coffee	
11:25-11:35	WP5 – Testing, verification and validation of models	Jean Talandier
11:35-11:45	WP6 – Civil society interaction	Johan Swahn
11:45-12:45	**Invited talks**	
11:45-12:15	Invited speaker/Background Beacon	Antonio Gens, UPC
12:15-12:45	Invited speaker - Considerations on the significance of the pre-hydration state on the long-term safety functions of bentonite from the implementer's perspective	Paul Marschall, Nagra
12:45-14:00	Lunch	
14:00-16:20	**Plenary presentations** (each 15 min + questions)	
14:00-14:20	EB - Engineered Barrier Emplacement Experiment	Antonio Gens, UPC for ENRESA
14:20-14:40	Homogenisation of bentonite- Laboratory test results	Ann Dueck, Clay Technology
14:40-15:00	Research activities at RWMC on the bentonite re-saturation process – (3) A box-type cell experiment to evaluate buffer material homogenization during the process of saturation	Ichizo Kobayashi, Kajima RWMC

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AGENDA Workshop 19-20 June 2017

Mechanical properties of bentonite barriers

15:00:15:20	Coffee	
15:20-15:40	Some insights on the swelling pressure development of compacted bentonite upon wetting and its long term evolution	Olivier Cuisinier, Un. de Lorraine
15:40-16:00	Homogenisation of laboratory scale plugs: development of porewater pressure and stress	Jon Harrington, BGS
16:00-16:20	Swelling pressure acting to the constraining material with slight deformability	Yasutaka Watanabe, Criepi
16:20-17:30	**Poster introductions** (3 slides each: title and two describing, white background)	
17:30-20:00	**Extensive poster session** (finger food/buffet served)	

POSTERS

HYDRAULIC EVOLUTION OF THE LONG-TERM IN-SITU TEST AT THE GRIMSEL TEST SITE AND SUPPORTING EXPERIMENTS	Rinderknecht (KIT INE)
THE APPROACHES FOR SIMULATION OF PROCESSES IN THE ENGINEERED BARRIERS OF THE RADIOACTIVE WASTE REPOSITORY	Balvin et al (Technical University of Liberec)
SWELLING PROPERTIES OF MX-80 BENTONITE MATERIALS	Bernachy-Barbe et al (CEA)
DENSITY REDISTRIBUTION IN COMPACTED BENTONITE EXPOSED TO EXTERNAL WATER PRESSURE DIFFERENCE	Birgersson (Clay Technology)
LARGE SCALE GAS INJECTION TEST (LASGIT): HYDRATION AND HYDRAULIC TESTING	Harrington (BGS/SKB)
THE CZECH CONSORTIUM'S PLAN FOR THE BEACON PROJECT	Hausmannova (SÚRAO)
RESEARCH ACTIVITIES AT RWMC ON THE BENTONITE RE-SATURATION PROCESS (1) OVERVIEW	Ishii (RWMC)
RESEACH ACTIVITIES AT RWMC ON THE BENTONITE RE-SATURATION PROCESS (2) LABORATORY AND NUMERICAL EVALUATION	Ito, Tachibana (Kobe University/ RWMC)
PROTOTYPE REPOSITORY – MASS REDISTRIBUTION IN THE BUFFER AND THE TUNNEL BACKFILL	Johannesson et al (SKB)
SWELLING PRESSURE AND HYDRAULIC CONDUCTIVITY - INFLUENCE OF SALINE SOLUTIONS	Karnland (Clay Technology)
BLOCK-PELLET HOMOGENIZATION IN KBS-3V BUFFER – LABORATORY SCALE TEST	Lavikainen et al (Posiva)
BUFFER AND BACKFILL INTERACTION	Luterkort et al (SKB)
ROCK STRESS- AND TIME-DEPENDENCY IN OVERPACK DISPLACEMENT AND BENTONITE PRESSURE BY CENTRIFUGE PHYSICAL MODELLING TEST IN PREDICTING FUTURE OF NEAR-FIELD	Nishimoto (Criepi)

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AGENDA Workshop 19-20 June 2017

Mechanical properties of bentonite barriers

LEI - STATUS OF WASTE MANAGEMENT IN LITHUANIA, ONGOING WORK AND WORK PLANNED IN BEACON	Poskas, Justinavicius (LEI)
HETEROGENEOUS DRY DENSITY OF GRANULATED BENTONITE MIXTURES EMPLACED BY SCREW FEEDERS: A DIRECT MEASUREMENT USING A DIELECTRIC METHOD	Sakaki/LEUPIN (Nagra)
HANDLING OF THE MECHANICAL EVOLUTION OF THE BENTONITE BUFFER IN THE SR-SITE SAFETY ASSESSMENT	Sellin (SKB)
MOCK-UP-CZ	
MOCK-UP-JOSEF	
LABORATORY DATA FROM PERMEAMETERS (WATER IN-FLOW AND SWELLING PRESSURE EVOLUTION ON BENTONITE SAMPLES – USEFUL FOR MODEL VALIDATION AS THEY CAPTURE SATURATION & PRESSURE EVOLUTION ON CONFINED, INITIALLY DRY SAMPLE)	Svoboda et al (CTU, Surao)
HETEROGENEITIES AND HYDRO-MECHANICAL BEHAVIOR OF BENTONITE-BASED STRUCTURE: LESSONS LEARNT FROM LARGE SCALE EXPERIMENTS	Talandier (Andra)
THM MODELLING OF BENTONITE: AN APPROACH TESTED ON MX-80 AND FEBEX BENTONITE	Thatcher (Quintessa)
HYDROMECHANICAL MODELLING OF BENTONITE HOMOGENISATION	Åkesson (Clay Technology)
IN-SITU PRACLAY SEAL TEST IN URF HADES, BELGIUM	Chen (Mol team)
CODE COMPARISON OF COUPLED THM PROCESSES IN ENGINEERED BARRIERS PERFORMED WITHIN THE TASK FORCE ON ENGINEERED BARRIER SYSTEMS	Schäfers et al (BGR)

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BEACON
Bentonite Mechanical Evolution

AGENDA Workshop 19-20 June 2017

Mechanical properties of bentonite barriers

Tuesday 20 June 2017

09:00-12:40	**Plenary presentations** (each 15 min + questions)	
09:00-09:20	Effects of heterogeneities on the hydromechanical behaviour of bentonite-based engineered barriers: results and current works at Laboratoire Navier	Benjamin Darde, Andra
09:20-09:40	X-ray imaging measurement of water transport and swelling deformation in bentonite	Markku Kataja, JYU
09:40-10:00	EPFL - lab programme on bentonite	Aldo Madaschi, EPFL
10:00-10:20	Febex and Febex-DP projects at the Grimsel test site	Maria Victoria Villar, CIEMAT
10:20-10:40	Upscaling homogenization experiments of block-pellet systems for KBS-3V Finland application	Erika Holt, VTT
10:40-11:00	Coffee	
11:00-11:20	Canister Retrieval Test, a large scale experiment made at Äpö Hard Rock Laboratory with well-defined hydraulic and mechanical boundaries	Lars-Erik Johannesson, SKB
11:20-11:40	Re-saturation and gas release of bentonites	Klaus Wieczorek, GRS
11:40-12:00	Czech B75 bentonite: its application in physical experiments of bentonite barrier, mechanical properties and constitutive and numerical modelling	David Mašín, Univerzita Karlova
12:00-12:20	Water retention behaviour of compacted bentonites: experimental observations and constitutive model	Robert Charlier, ULg
12:20-12:40	Numerical modelling of bentonite mechanical evolution at Imperial College	David Potts, ICL
12:40 – 13:40	Lunch	
13:40-13:55	About the Beacon training course	Antonio Gens, UPC
13:55-15:15	Summary discussion	Simon Norris, Beacon WP2
15:15	**End of workshop**	
	Coffee and snack available	

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Short Abstracts
Beacon Workshop 19-20 June 2017

Mechanical properties of bentonite barriers

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HYDROMECHANICAL MODELLING OF BENTONITE HOMOGENISATION

Mattias Åkesson (ma@claytech.se), **Ola Kristensson**, **Daniel Malmberg**
Clay Technology AB, IDEON Science Park, SE-223 70 LUND, SWEDEN

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. The processes can occur under either saturated or unsaturated conditions. In both cases, the homogenization is driven by the hydration and the swelling of the bentonite. The process is characterized by wide ranges of void ratios and water contents, and to perform hydromechancial (HM) modelling of this therefore requires a material model that can represent the behaviour of the bentonite for such wide ranges.

Analyses of the homogenisation processes in initially water unsaturated KBS-3 buffer and backfill, have been performed using the thermoelastoplastic (TEP) constitutive laws (based on BBM) implemented in Code_Bright (Åkesson et al. 2010a). In addition, analyses of well-defined homogenisation tests with water saturated bentonite specimens motivated the development of a new HM material model based on a swelling pressure/suction relation with hysteresis (Åkesson 2017). This model is based on a description for which the clay potential (defined as stress + suction) for a specific void ratio is assigned in an allowable interval bounded by two lines, for swelling and consolidation respectively, and that the actual state between these lines is governed by the strain history. Of vital importance for both approaches was the incorporation of the fundamental properties into the material models, e.g. the swelling pressure and shear strength, which both display a strong void ratio dependence. For the TEP laws, these properties were used to adopt plastic parameters for specific void ratios (Åkesson et al. 2010b). For the new HM model, in contrast, no parameter value adoption was needed for specific void ratios.

Both models resulted in relevant build-up of stresses (without exceeding the shear strength), final states consistent with the defined swelling pressure curve, and with remaining heterogeneities due to hysteresis effects. The models are different, however, in terms of stress variables: suction and net stresses are independent variables in the TEP laws, whereas the clay potential is the sole variable in the new model.

Despite the similarities between the models, there are some important limitations with the TEP model: 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) can not be represented for water saturated conditions. In contrast, the new model can apparently mimic the main features of different water saturated tests with a quite limited set of parameters. In order to address more complex geometries, this material model is currently being implemented in the general finite element code COMSOL Multiphysics.

References

Åkesson M, Kristensson O, Börgesson L, Dueck A, Hernelind J, 2010a. THM modelling of buffer, backfill and other system components. Critical processes and scenarios. SKB-10-11. Svensk Kärnbränslehantering AB.

Åkesson M, Börgesson L, Kristensson O, 2010b. SR-Site data report. THM modelling of buffer, backfill and other system components. SKB TR-10-44, Svensk Kärnbränslehantering AB.

Åkesson M, 2017. EBS-TF Homogenization – Task 1. Report in progress.

THE APPROACHES FOR SIMULATION OF PROCESSES IN THE ENGINEERED BARRIERS OF THE RADIOACTIVE WASTE REPOSITORY

Ilona Hancilova, Ales Balvin (ales.balvin@tul.cz), Milan Hokr

Technical University of Liberec, Studentska 1402/2, 461 17 Liberec 1, Czech Republic

Presented work summarizes our considered approaches for modelling of coupled processes in the engineered barriers of the radioactive waste repository. We show different model concepts and representative examples of solved problems which are mainly concentrate on hydraulic and coupled hydro-mechanic and thermo-hydraulic processes. Example problems are focused on the hydraulic interactions of bentonite barrier with inhomogeneous water inflows from the rock, bentonite swelling or temperature influenced process of bentonite saturation.

Beacon Initial Workshop

SWELLING PROPERTIES OF MX-80 BENTONITE MATERIALS FOR ANDRA'S REPOSITORY ENGINEERED BARRIERS

Fabien Bernachy-Barbe (fabien.bernachy-barbe@cea.fr), Claude Gatabin, Christophe Imbert, William Guillot, Den-Service d'Etude du Comportement des Radionucléides (SECR), CEA, Université Paris-Saclay, F-91191, Gif-sur-Yvette, France, Jean Talandier, Andra, 1-7 Rue Jean Monnet, F-92298 Chatenay Malabry, France

The Andra underground radioactive waste repository concept makes use of a bentonite material for the plugs and seals. One of the forms studied is a mixture of pellets and crushed pellets of Wyoming MX-80 bentonite. This granular form allows for a relatively simpler setting compared to the compacted brick form and its feasibility has been shown recently by the FSS (full scale seal) demonstrator. Its performance, in terms of hydraulic conductivity and swelling pressure reached is largely dependent on the resulting density. The material hydromechanical properties must therefore be thoroughly characterized in representative conditions.

The resaturation of the bentonite core will be achieved by water coming from the host rock (clay formation) and through concrete components. In this context, resaturation experiments using bentonite have been conducted in constant volume cells with samples of various sizes and instrumentation, using different water chemical compositions and initial dry densities. The swelling pressure kinetics and final value have been determined for a water obtained from a borehole at the Andra's Meuse/Haute-Marne underground laboratory, for a synthetic site water, and waters representative of the pore solution of a CEM I concrete (pH 13.5) as well as the pore solution of a low pH concrete (pH 10.6).

The hydro-mechanical response of the bentonite was found to be quantitatively similar using the standard synthetic site water and the site water, which validated the use of synthetic water for laboratory tests. The swelling pressures reached by samples hydrated using ordinary concrete water were found to be significantly lower than using synthetic site water, at the time of the dismantling of these tests. The swelling pressure obtained with low pH concrete water was close to the one measured with synthetic site water, justifying the use of such specific concrete in the vicinity of bentonite based components. Moreover, the long-term stability of the swelling pressure in the case of hydration by high pH water can be questioned considering the pressure evolutions at the time scales accessible in laboratory testing (slow decrease in some cases). This effect was shown to be lower when the thickness of the sample was increased, pointing towards concentration gradients of the responsible chemical species, localised at the interface where samples are hydrated. The saturated water permeability of a sample hydrated with high pH concrete water also consistently shown a tenfold increase.

The degree of re-homogenisation of these initially heterogeneous (at a centimetre scale) assembly. The heterogeneity of the stress state inside the samples was investigated using constant volume cells equipped with local radial measurements of the total pressure. Local swelling pressure evolutions are shown to be very different and do not converge at saturation to the average sample swelling pressure, pointing towards residual heterogeneities. Those heterogeneities could potentially be associated to some structural effects due to the size of the cell and the contact surface between bentonite and metal.

DENSITY REDISTRIBUTION IN COMPACTED BENTONITE EXPOSED TO EXTERNAL WATER PRESSURE DIFFERENCE

Martin Birgersson (mb@claytech.se), Ola Karnland, Clay Technology AB, Lund, Sweden

This work has provided experimental data on density redistribution in bentonite samples exposed to large water pressure differences. A supporting theoretical framework has been developed, based on the osmotic nature of the material.

As far as we are aware, these results are unique. The applied maximum pressure are several times larger than the initial swelling pressure of the bentonite samples, which allows for exploring non-linear flow and pressure response, thus giving a possibility for deeper understanding of the hydro-mechanical behaviour of bentonite.

A main result is shown in figure 1 which shows the steady-state density profiles of two MX-80 bentonite samples exposed to water pressure differences of approximately 5 MPa. The samples were cylindrical with diameter 3.5 cm height 2 cm, and their nominal average dry densities were 1166 kg/m^3. According to the developed theory, the steady-state porosity distribution in this geometry is

$$n(x) = n_0 - \frac{x}{L} \cdot \frac{2}{B} \operatorname{asinh}\left(\frac{P_w}{2P_s^0}\right)$$

Where it is assumed that the sample is confined within $-L/2 \leq x \leq L/2$, P_w is the applied water pressure difference, n_0 is average porosity, B is a parameter reflecting the derivative of the retention curve with respect to porosity, and P_s^0 is the swelling pressure (i.e. the bentonite pressure without elevated external pressure). The prediction from this theoretical description is also plotted in figure 1.

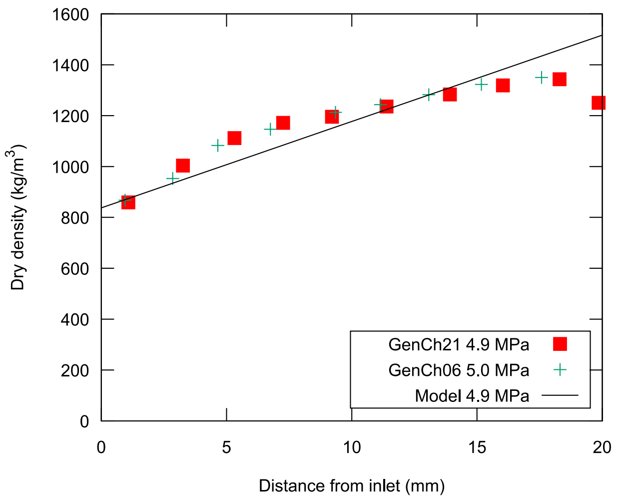

Fig. 1 Steady-state density distributions in two MX-80 bentonite samples exposed to external water pressure differences of 4.9 MPa and 5.0 MPa, respectively. The line shows the corresponding prediction from the developed theory.

The results of this study implies that density response in bentonite is primarily governed by montmorillonite interlayer properties. It follows that hydro-mechanical effects are of osmotic nature and should not be described using e.g. conventional two-phase flow models. The developed theoretical framework is suitable for being extended and applied for a general description of flow- pressure- and density response in compacted bentonite.

Beacon Initial Workshop

ABSTRACT FORMATs

WATER RETENTION BEHAVIOUR OF COMPACTED BENTONITES: EXPERIMENTAL OBSERVATIONS AND CONSTITUTIVE MODEL

Anne-Catherine Dieudonne[1,2,], Georgia Radioti[1], Claude Gatabin[3], Jean Talandier[4], Frédéric Collin[1] and Robert Charlier[1]*
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The water retention capacity of compacted bentonites is one of the fundamental properties required for predicting the behaviour of unsaturated engineered barriers. In the context of deep geological repositories for nuclear waste, bentonite-based materials are generally manufactured and emplaced at their hygroscopic water content. Under repository conditions, the engineered barrier experiences hydration from the surrounding geological formation. Because of the existence of unavoidable technological gaps, the periphery of the engineered barrier swells under free conditions first. During this stage, technological gaps are progressively filled by bentonite and the effective density of the buffer decreases. When contact between the geological formation and the engineered barrier is reached, the global volume constraints imposed to the bentonite buffer are close to constant volume conditions and a swelling pressure develops on the gallery wall. The objective of the engineered barrier is to form a tight contact with the surrounding formation and to create a zone of low permeability that is able to limit water flow around the excavated galleries, thereby delaying the release of radionuclides to the biosphere.

Because of the evolution of the volume constraints during the hydration process of the bentonite buffer, a good characterization of the material under both free and restricted swelling is required. To date, few experimental studies have investigated both volumetric and water retention behaviours of compacted bentonite with the aim of obtaining suction – degree of saturation relationships [1-4].

In this paper, the water retention properties of a compacted bentonite/sand mixture are first investigated under both constant volume and free swelling conditions. Then, based on observations of the material double structure and the water retention mechanisms in compacted bentonites, a new retention model is proposed. The model considers adsorbed water in the microstructure and capillary water in the aggregate-porosity. The model is validated against the experimental data. It is used for better understanding competing effects between volume change and water uptake observed during hydration under free swelling conditions. Finally the effect of bentonite heterogeneity is discussed, based on numerical simulation of some very simple cases.

IN-SITU PRACLAY SEAL TEST IN URF HADES , BELGIUM

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To study the response of Boom Clay to a thermal transient due to the disposal of heat-emitting radioactive waste, the PRACLAY Heater test is being operated in the PRACLAY gallery (PG) in the HADES underground research facility in Mol, Belgium (Fig. 1). By installing a hydraulic seal at the intersection between the heated and the nonheated part of PG, and backfilling the heated PG with water-saturated highly permeable sand, the PRACLAY Heater Test imposes nearly-undrained boundary conditions which are more penalizing than those prevailing in a real repository in terms of Thermo-Hydro-Mechanical (THM) evolution of the host rock. The THM behaviour of the bentonite ring in the seal is studied in the Seal test.

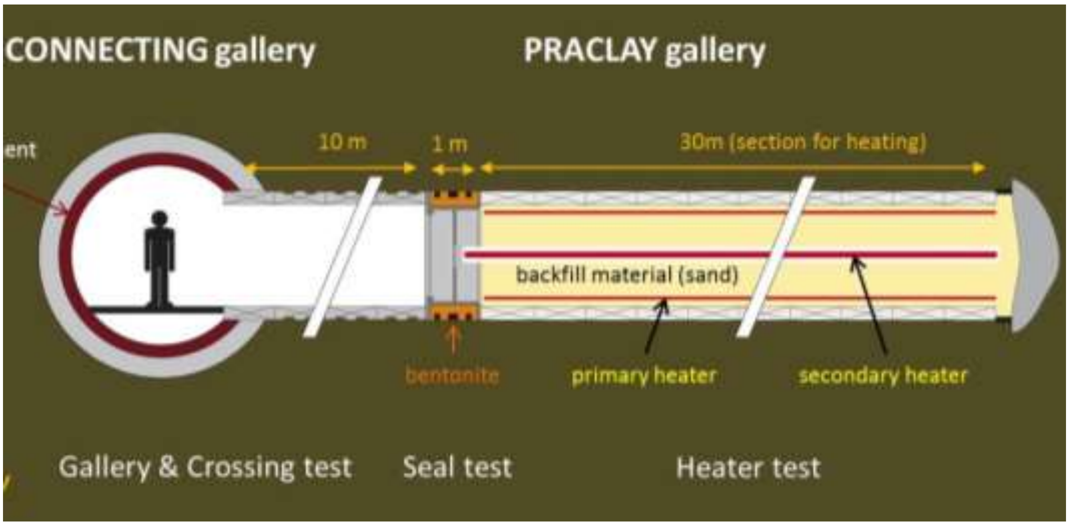


Fig. 1: Schematic view of PRACLAY gallery, Heater test and Seal test

The seal is located at 10 m from the access gallery (Connecting gallery) to limit the mutual interaction between the Heater test and the access gallery. The seal does not only have to close the heated part of the PG, but it also has to hydraulically cut off the potentially preferential hydraulic pathway to the main gallery through the excavation damaged zone (EDZ) around the gallery. MX 80 bentonite was chosen as the main seal material due to its high swelling capacity and low intrinsic permeability when compacted to an appropriate dry density.

Fig. 2 shows a schematic view of the layout of the seal. Highly compacted bentonite blocks fill the major space encompassed by the Boom Clay, the steel structure (steel cylinder and two flanges) and the four steel ribs which were installed for safety issue. There are two initial technological voids (each about 1 cm wide) in the seal, which inevitably result from the installation of the different bentonite blocks and instrumentation in the bentonite.

To monitor the THM behaviour of the seal, a large number of sensors measure the pore water pressures, displacements, total stresses, temperatures etc. in and around the bentonite. Most sensors were installed at three sections (see Fig. 3).

Coupled THM modelling was performed for the design and prediction of the PRACLAY seal test, and the finite element code "CODE_BRIGHT" developed by Technical University of Catalonia (UPC) was used for the numerical modelling.

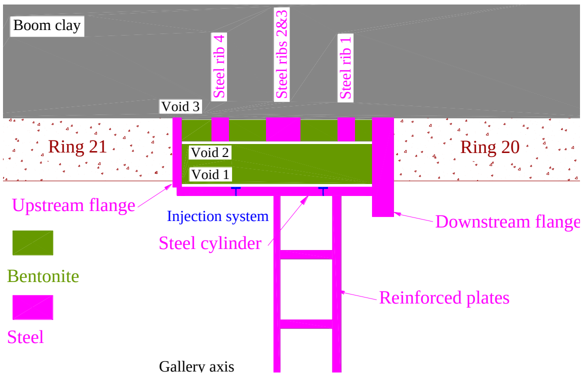


Fig. 2: Schematic view of Praclay seal

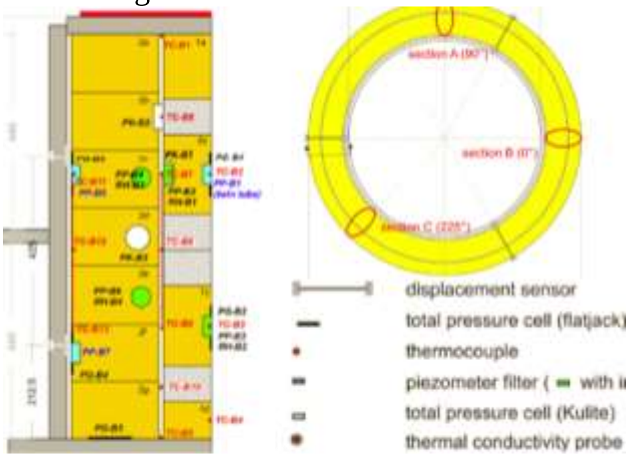


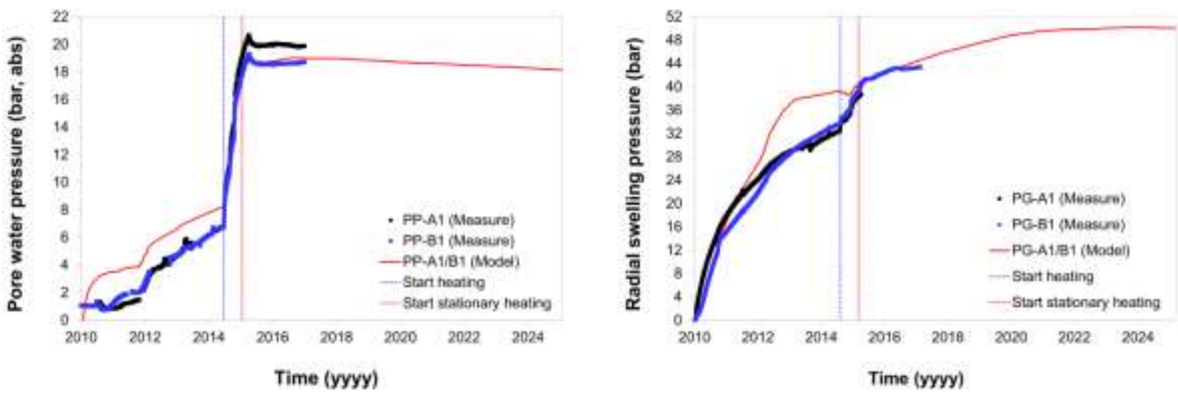
Fig. 3: Instrumented sections and section B detail

The modeling simulates the actual and planned evolution of PRACLAY Heater and Seal tests since the PG excavation until the end of heating, including gallery construction, drainage, unlocking of steel ribs, seal installation, injection of water into seal, backfilling and pressurization of the PG. The main THM parameters of the materials (Boom Clay, backfill sand, lining, steel, bentonite, etc.) are determined based on extensive literature review, laboratory tests and back analysis of in-situ measurements before heating.

Fig. 4 and Fig. 5 give the measured pore water pressures by sensors PP-A1 and PP-B1 (Fig. 2) and radial swelling pressures by sensors PG-A1 and PG-B1 (Fig. 2) at the interface between bentonite and Boom Clay respectively, and the corresponding modeled results are presented for comparison and prediction; generally, a good agreement between measurement and modeling has been observed.

Only limited and more important results are presented here. Continuous effort is underway to further improve the interpretation of the measurements discussed here, as well as many other observations, which currently show varying degrees of agreement with the model predictions.

Till now, the seal fullfils its role to ensure the hydraulic bounbdary condition of the Heater test.



(a) Pore water pressure at interface (b) Radial swelling pressure at interface

Fig. 4: Comparison between measurement and modelling

Some insights on the swelling pressure development of compacted bentonite upon wetting and its long term evolution

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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) Swelling pressure development and inter-aggregate porosity evolution upon hydration of a compacted swelling clay; (iii) Impact of high-pH fluid circulation on long term hydro-mechanical behavior of a compacted clay.

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 the 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 the full saturation state, 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 (salt solutions) technique, to investigate the respective impact of the matric and osmotic components of suction on the development of the swelling pressure upon wetting.

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, was designed both to monitor swelling pressure over time and to visualize inter-aggregate porosity changes through X-ray micro-computed tomography (µCT), on a unique specimen (Massat et al. 2016). The results, which combined both swelling pressure measurements and quantification of microstructure evolution upon hydration for two different solutes, give sound understanding on the development of osmotic and/or crystalline swelling and their relative impact both on the microstructure and on the magnitude of the macroscopic swelling pressure of compacted montmorillonites.

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. (2013, 2014) assessed the impact of high-pH water circulation on compacted clay samples. After the circulation of high-pH water, 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 and the precipitation of neoformed illite, which is a non-swelling mineral.

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Effects of heterogeneities on the hydromechanical behaviour of bentonite-based engineered barriers: results and current works at Laboratoire Navier.

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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 or constant volume cells have notably been developed to study the behaviour of these materials upon suction variations.

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. Therefore, technological voids reduce the swelling pressure of the engineered barrier at equilibrium.

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 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.

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, DEM-simulations are currently being performed (PhD Thesis of Darde). Swelling pressure tests on mixtures with varying powder contents will be carried out to determine relevant material's characteristics for simulations, and assess the influence of local heterogeneities on the hydromechanical behaviour.

This contribution will be essentially focused on main results obtained in previous experimental programs performed at Laboratoire Navier highlighting the role of heterogeneities in the hydromechanical behaviour of bentonite. Current numerical and experimental works concerning the homogenisation of pellets mixtures during hydration will also be presented.

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HOMOGENISATION OF BENTONITE - LABORATORY TEST RESULTS

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Swelling of the buffer blocks and buffer homogenisation are important functions to meet the requirements on the buffer in a deposition hole after full water saturation. It is important to understand the homogenisation process and be able to predict the final density distribution of the buffer after swelling and homogenisation, which occurs both during the initial water saturation stage and after possible loss of bentonite caused by for example erosion. To increase the knowledge of the homogenisation processes an SKB project was initiated and has been running during several years.

The laboratory tests made in the project 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 in long tubes. 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. In the test series with loss of bentonite two medium scale tests have been completed, and in the series with long tubes one out of ten tests has been completed and dismantled. Two different bentonites have been used for the tests.

In Figure 1 the test results are exemplified by the stress evolution at different positions (left), and the initial and final dry density distributions (right) from one of the fundamental swelling tests involving axial swelling.

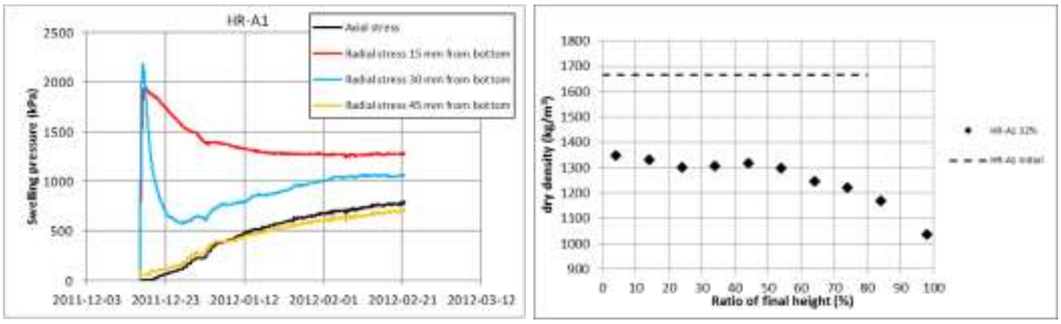

Figure 1. *Example of test results from one of the axial swelling tests with the stress evolution measured at different positions (left), and the initial and final dry density distributions (right).*

The results of this project are increased knowledge about how homogenisation evolves and ends, how different factors influence the homogenisation and how much remaining inhomogeneities may prevail in the bentonite. In addition, some test results have already been used for improvement and verification of material models and for evaluation of model parameters. The test results have been presented in three SKB Technical Reports (TR-12-02, TR-14-25, TR-16-04) and an additional report in preparation (Status report 4).

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Homogenisation of laboratory scale plugs: development of porewater pressure and stress

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[1] British Geological Survey (BGS)
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Questions regarding homogenisation 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. However, the role of porewater pressure, its spatial development and impact on swelling potential, self-sealing and permeability have yet to be adequately explained. This introduces uncertainty in the description of the long-term behaviour of the bentonite including a full understanding of the development and persistence of heterogeneities (e.g. locked in stresses, density variations, persistent interfaces etc.) within the clay. In addition, the accurate description of key parameters (swelling pressure, permeability, strength, friction coefficients etc.) will be affected by temporal constraints encountered by the development and distribution of pore water pressure within the buffer. Indeed, such slow time-dependent phenomena associated with wetting and potentially the localised nature of these processes may account for a significant component of the heterogeneity observed in many small- and full-scale experiments.

Data from previous experiments will be presented. These show that the non-uniform development of porewater pressure and its coupling to total stress, both within the bentonite and across interfaces around its circumference, results in persistent heterogeneities within the bentonite. As hydration progresses, differential stress (difference between maximum and minimum stress) reduces, however, density, porewater pressure and permeability variations persist. Such observations are seen in both laboratory- and field-scale experiments (discussed elsewhere), such that the scale and longevity of these features and the final degree of homogenisation that can be expected for compact bentonite remains unclear. Additional data from dual density bentonite experiments also exhibits complex behaviour, with the distribution of stress and development of gas pathways (during multiphase flow experiments), influenced by the low density zone. An overview of these experiments will be presented to illustrate the importance of these issues and to highlight awareness of temporal considerations in the description of bentonite properties.

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.

Large scale gas injection test (Lasgit): hydration and hydraulic testing

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[1] British Geological Survey (BGS)
[2] Svensk Kärnbränslehantering AB (SKB)

In the Swedish KBS-3V disposal concept, copper/steel canisters containing spent nuclear fuel will be placed in large diameter disposal 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 any construction gaps. Once hydrated, the bentonite will act as a low permeability diffusional barrier, severely limiting the migration of any radionuclides released from a canister after closure of the repository. Understanding the rate of hydration, the development of swelling pressure and the impact of water inflow on the maturation of the buffer is therefore of fundamental importance in the description of these complex repository systems.

This paper describes the initial results from the hydration and hydraulic test phases of the Lasgit (large scale gas injection test) experiment, performed at the Äspö Hard Rock Laboratory, Sweden. Lasgit is a heavily-instrumented fully field-scale experiment based on the Swedish KBS-3V repository concept, primarily designed to examine the processes controlling gas and water flow in compact buffer bentonite. However, the first two years of testing focused on the natural and artificial hydration of the bentonite. Here, saturation and equilibration of the buffer were monitored by measuring pore pressure, total pressure and suction at multiple locations along the buffer/rock interface and at key locations within individual clay blocks. A complex picture of stress and porewater pressure development emerged with localised hydration of the clay occurring around conductive fractures and artificial hydration sources. The development of porewater pressure within the blocks of bentonite occurred very slowly, lagging well behind the development of stress within the deposition hole. This phase of testing provides a valuable, isothermal dataset against which the uptake of water and development of stress within the clay can be benchmarked.

THE CZECH CONSORTIUM'S PLAN FOR THE BEACON PROJECT

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The Czech Republic is currently in the planning phase with respect both to DGR engineered barriers and the future DGR itself. According to the 2011 Reference Project, the buffer will be based on bentonite blocks and the backfill on a mixture of bentonite and crushed rock. However, other options (e.g. the use of pellets or a combination of blocks and pellets) have not been excluded. All the options deal with a certain level of the heterogeneity of the bentonite barriers which affect long-term safety requirements.
The needs of safety assessment regarding the evaluation of non-homogenous bentonite buffer/backfill properties (mainly swelling pressure, degree of saturation, dry density and hydraulic conductivity) have to be addressed. In particular, in how bentonite barrier heterogeneities affect long-term safety.
Several laboratory-based (e.g. Mock-Up CZ; Pacovský et al. 2007) and in-situ experiments (e.g. Mock-Up Josef; Šťástka J. 2014 and the EPSP plug; Hanusová et al. 2016) involving Czech bentonites have been conducted over recent years. The BEACON project will use principally data collected from the Mock-Up Josef experiment which was designed at approximately half the scale of the KBS - 3V storage container system. The experiment, built in the form of a supercontainer and weighing 2.5 tonnes, was transported from the Josef Facility surface complex and lowered into a specially-prepared underground storage well in 2012. The experiment is still underway at the Josef Underground Laboratory. The Mock-Up Josef experiment is made up of bentonite segments, the gaps between which were filled with bentonite powder. The bentonite consisted of Czech B75 material extracted from the Černý vrch (Black Hill) deposit and supplied by the KERAMOST company.
According to the latest analysis of the Mock-Up Josef, it is clear that the bentonite layer is not being saturated in a uniform manner, e.g. pressure sensors positioned in identical locations but at different depths have recorded different pressure values. It is important to note in this respect that the differences in pressure values may have been partly influenced by inhomogeneities resulting from the structure of the experiment itself, e.g. the joints (between the bentonite blocks and between the blocks and the various sensors) and their gradual diminution due to the swelling of the bentonite (Šťástka 2014).
The CTU and CU, in cooperation with SÚRAO, intend to construct a mathematical model of the Mock-Up Josef experiment, the principal outcomes of which will consist of the determination of the hydro-mechanical homogeneity/heterogeneity of Czech bentonites. Moreover, development of requirements for homogeneity of bentonite barrier for long-term safety will be performed.

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BEACON INITIAL WORKSHOP (19-20 June 2017)

Title: Upscaling homogenization experiments of block-pellet systems for KBS-3V Finland application

Authors: Erika Holt, Harri Kivikoski, Ville Rinta-Hiiro, Heidar Gharbieh – VTT Technical Research Centre of Finland.
Lasse Lavikainen, Ville Heino, Pasi Rantamäki – Posiva Oy

Keywords: KBS-3V, buffer, backfill, pellets, blocks, demonstration, up-scaling, experiments, density, monitoring

Abstract:

The Buffer-Backfill Interaction (BBI) test was an example of a large-scale investigation to demonstrate repository safety, commissioned in 2014 between Posiva Oy and VTT[1]. 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 actual repository at about 1/6 scale. The focus of the BBI tests was on understanding the effects of flowing water on the bentonite clay products regarding swelling, formation of water channels and erosion. Also, homogenization of different material types of bentonite blocks and the surrounding bentonite pellets was investigated to improve the hydrogeochemical modelling.

During the 2-month BBI test duration per scenario, a system containing buffer and backfill, both blocks and pellets, was exposed to water inflow of 0.1 litres/minute, using simulated Olkiluoto deep groundwater with a salinity of 1 %. The outflowing water was analysed for bentonite content, indicating erosion. Swelling of the bentonite at various locations was also monitored during the tests. After the tests during dismantling, bentonite samples were taken for water content and density analyses. Also, vertical displacement of the buffer due to swelling was investigated, showing that the heave of the buffer led to almost fully saturated tunnel pellets with high densities above the buffer. Also, possible homogenisation between the blocks and pellets occurred in the buffer and also in the tunnel above the buffer.

Another example of VTT-Posiva commissioning of large-scale homogenization studies is the 40% Scale Buffer Test[2] conducted in ONKALO during 2011-present. Two buffer demonstrations were done with geotechnical design proportions identical to the Posiva 2012 reference design, containing isostatically-pressed MX-80 buffer blocks and a 35 mm outer gap filled with pellets. The holes are 3 metres deep, 4 metres apart and included a dummy canister with heating for a surface temperature of +90°C. One of the two holes was artificially wetted, while the other was subjected only to water inflow from fissures in the surrounding rock. Monitoring was done with over 100 sensors to assess swelling pressures, moisture and temperature distribution. After two years, one of the holes was dismantled and over 1000 samples were taken to assess homogeneity of the system. The second hole continues to be monitored in-situ to-date.

Results from these two experiments are used to update Posiva's buffer and backfill designs, material specifications, material manufacturing and safety case analysis. Such information supports Posiva's next phase of repository operational licensing and safety analyses. The results can also be utilised by other parties interested in understanding bentonite clay material performance and homogenisation processes.

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RESEARCH ACTIVITIES AT RWMC ON THE BENTONITE RE-SATURATION PROCESS (1) OVERVIEW

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Radioactive Waste Management Funding and Research Center (RWMC) conducts research activities on engineered barrier system (EBS) of radioactive waste disposal aiming to ensuring and/or increasing its integrity. For that research, it's needed to consider the series of processes such as production, construction and after closure, then the design of EBS and its evolution from initial condition shall be evaluated and/or discussed taking into consideration of the disturbances in short-term and evolution in long-term. Especially study on the buffer material is one of important theme among them. Therefore, we are focusing its mechanical behavior during the re-saturation period.

We are focusing following five phenomena as the important behaviors of the buffer material during the re-saturation period. (Fig.1).

- Seepage rate,
- Residual density distribution,
- Migration of pore air,
- Chemical influence,
- Piping and erosion.

Our approach consists of three components such as 1) understanding through experiments, 2) modeling and 3) evaluation and/or analyzing these phenomena through 1) and 2). The purpose of these studies are

- to specify initial condition at the installation of EBS, and
- to update the design and installation method.

The long term laboratory tests aiming to the verifications of numerical analyses model have been carried out for over 5 years, and effective results (data which can be reflected in the analyses) have been obtained（It will be reported in another presentation）. Regarding the “piping and erosion”, the tests have been carried out both in laboratory and underground research laboratory (URL). The tests at the laboratory have been run under different conditions and scales, and the tests at the URL with the actual boundary conditions have been run with 60cmφ test pits since 2014. (It will be presented at Clay 2017). In addition, regarding the “residual density distribution” and “seepage rate”, it has been discussed and/or tried to reproduce behaviors observed at laboratory test by using numerical analysis model. (It will be presented at Clay 2017 and this workshop).

This research is a part of “Development of Advanced Technology for Engineering

Components of HLW Disposal "under a grant from the Japanese Ministry of Economy, Trade and Industry (METI).

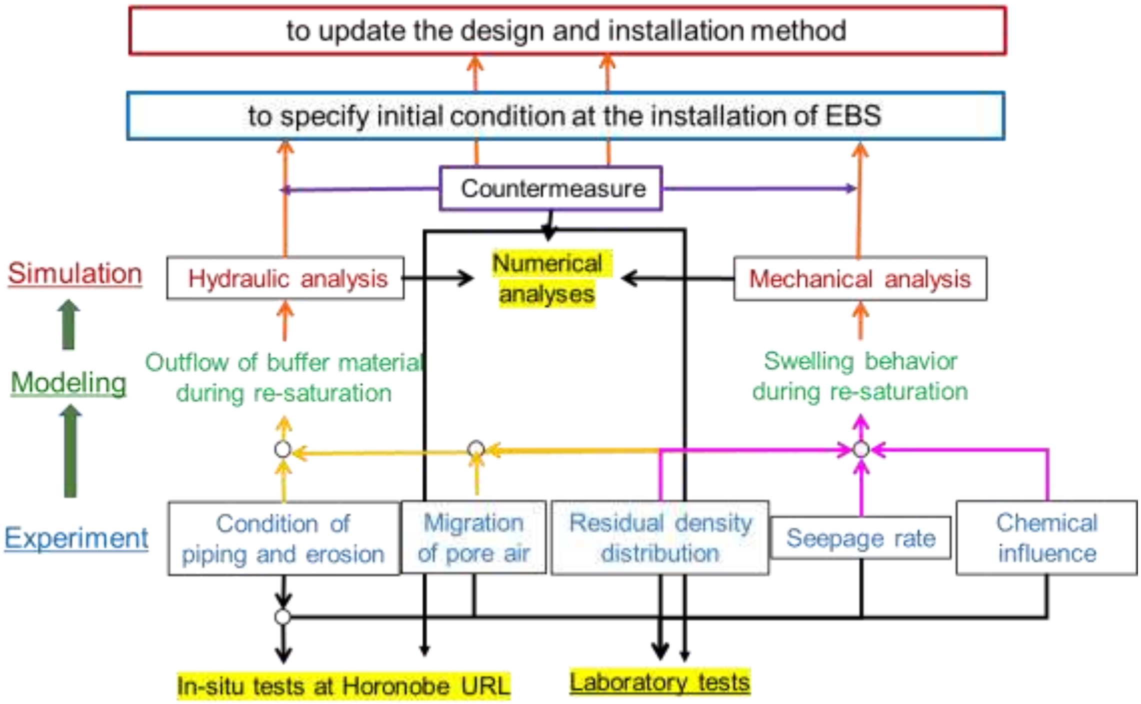

Fig.1 Purpose and study policy

Canister Retrieval Test, a large scale experiment made at Äpö Hard Rock Laboratory with well-defined hydraulic and mechanical boundaries.

Lars-Erik Johannesson, SKB

A full size canister with a bentonite buffer was installed in the deposition hole in the autumn of 1999 at the Äspö Hard Rock Laboratory. The bentonite buffer consisted of highly compacted blocks and with an outer slot between the blocks and the wall of the deposition hole (~ 5 cm width) filled with bentonite pellets. The bentonite surrounding the canister was saturated through filters installed on the wall of the deposition hole. This test, Canister Retrieval Test (CRT), was primarily designed to test technique to retrieve canisters from a water saturated buffer. One such technique has been 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 before the retrieval test was started so that water and density samples could be recovered. This abstract describes the work with the sampling in the upper part of the buffer and the determination of the water content and the density of the taken samples.

Most of the samples were taken from the upper portion of the buffer by core drilling from the upper surface of each installed bentonite block. The cores had a diameter of about 50 mm and a maximum length equal to the original height of the bentonite blocks (about 500 mm). The drilling occurred from the tunnel floor using a rig designed for taking geotechnical soil samples.

The water content of the buffer was determined by drying a sample at a temperature of 105°C for 24 h and the bulk density was determined by weighing a sample both in the air and immerged in paraffin oil with known density.

The water content, degree of saturation and dry density of the buffer were then analysed. The data show that the buffer was far from saturated above the canister lid, while the buffer at the canister level was fully saturated. The data is also showing that the initial large variation in dry density for different part of the buffer has reduced during the saturation although there are still noticeable differences in the density at the dismantling.

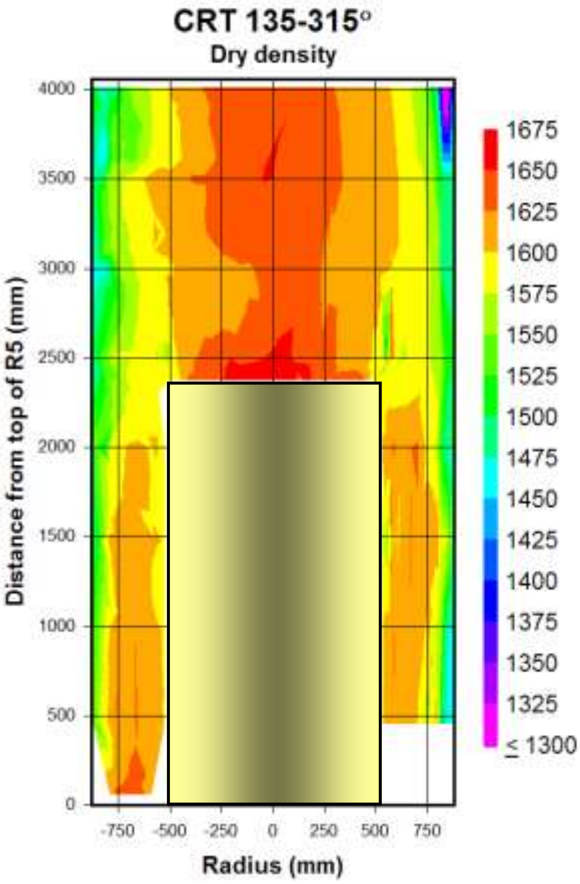

Figure 1. *The contour plot of the dry density in direction 135-315° for the buffer.*

Swelling pressure and hydraulic conductivity - Influence of saline solutions

Ola Karnland, Clay Technology, Lund, Sweden, ok@claytech.se, Nick Jefferies, Amec Foster Wheeler, Harwell Oxford, Simon Norris, RWM, Didcot, Oxon, United Kingdom

Background

In order to study the impact of various saline solutions on swelling pressure and hydraulic conductivity of a defined commercial bentonite, a series of tests was run on MX-80 bentonite at different densities and exposed to a range of water compositions. In total, six different MX-80 samples were tested, ranging in density from 820 kg/m^3 to 1530 kg/m^3.The work was performed within in RWM bore-hole sealing project, phase two.

Test procedure

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. 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.

Results and conclusions

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.

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.

X-RAY IMAGING MEASUREMENT OF WATER TRANSPORT AND SWELLING DEFORMATION IN BENTONITE

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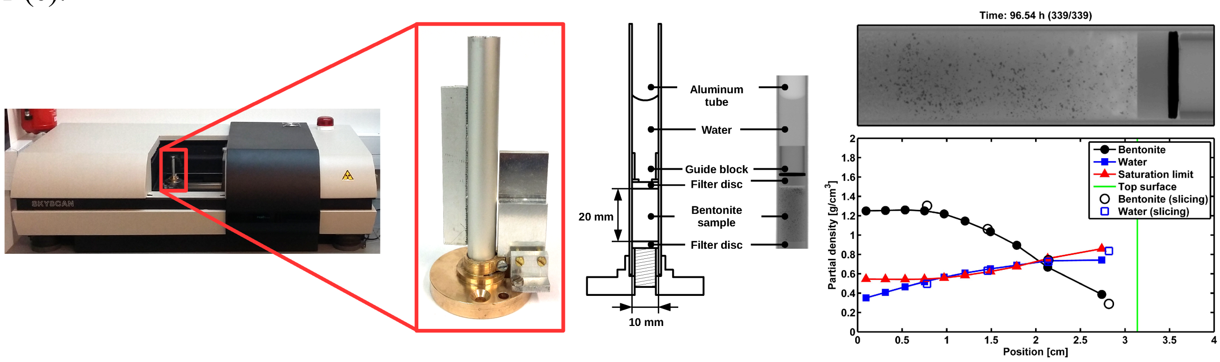
Department of Physics, University of Jyväskylä

The purpose of this work 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 in planned nuclear waste repository concepts. To this end, a non-destructive method based on X-ray imaging was developed and used to study one-dimensional deformation and water transport in bentonite samples during wetting experiments. Here, the samples were placed in an aluminum tube and wetted from the top end through a sintered block (Fig. 1). The sample was either constrained in a constant volume throughout the experiment, or allowed to swell freely upwards in the tube. A microtomographic device was used to take sequential X-ray images of the samples during the wetting/swelling process. In order to correct various imaging artifacts, a separate aluminum reference target was imaged alongside with the sample. The corrected X-ray images were 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 was measured by tracking the motion of added tracer particles between consecutive X-ray images. The measured displacement field and the initial density of the sample were used to calculate the local partial density of the (dry) bentonite material. Finally, the local water content was found based on total density and dry density. An example of results from free swelling experiments is shown in Fig. 1 (c).



(a) (b) (c)

Figure 1. (a) The X-ray tomographic device and the aluminum tube sample holder with aluminum reference target (inset). (b) Schematic illustration of the sample holder set-up and an X-ray image of the initial state of the sample. (c) An X-ray image of a freely swollen MX80 bentonite sample (top) and the measured axial mass distribution of dry bentonite and water in the tube (bottom).

The results obtained by the method are in close agreement with the gravimetric validation data measured by slicing the sample after the experiment, and appear useful for the planned purpose related to model development. Similar techniques, but extended to two and three-dimensional geometries [1] will be used in the Beacon project for studying homogenization of compacted bentonite and bentonite pellet materials.

[1] Harjupatana T, Alaraudanjoki J, Kataja M. X-ray tomographic method for measuring three-dimensional deformation and water content distribution in swelling clays. Appl.Clay.Sci. 2015;114:386-94.

RESEARCH ACTIVITIES AT RWMC ON THE BENTONITE RE-SATURATION PROCESS
(3) A BOX-TYPE CELL EXPERIMENT TO EVALUATE BUFFER MATERIAL HOMOGENIZATION DURING THE PROCESS OF SATURATION

Ichizo Kobayashi (koba13@kajima.com), Kajima Corporation; Tomoko Ishii, Hidekazu Asano, Radioactive Waste Management Funding and Research Center; Patrik Sellin, David Luterkort, Peter Eriksson, SKB

1. Introduction

When HLW disposal facility is closed, the mechanical, hydraulic and chemical equilibrium states of buffer materials change as groundwater levels recover and permeation progresses. As this permeation triggers such changes, determining the long-term performance of disposal facilities requires evaluation of how groundwater penetrates buffer materials and how the materials are homogenized by related swelling. In this research, homogenization of buffer materials during the process of saturation was experimentally evaluated using a box-type cell.

2. Experimental conditions

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. The 14 load cells 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 measure resistivity. The arrangement of the electrodes was determined in consideration of the block arrangement.

3. Results

Temporal changes in saturation distribution are shown in Figure 2, with the degree of saturation calculated from resistivity. The seepage of NaCl solution was faster than that of distilled water. Resistivity data indicated that groundwater permeated the gaps between the blocks after filling the inter-pellet voids. Temporal changes in swelling pressure are shown in Figure 3. It should be noted that both initial values were different because they were generated by the setting of the cell lid. In both cases, the distribution of swelling pressure became smooth with increasing 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 4. The homogenization of dry density with distilled water progressed in comparison with that observed with NaCl solution.

4. Conclusions

The outcomes of the study help to explain temporal changes in seepage and the saturation process in consideration of buffer material placement and clarify how the effects of dry density distribution in buffer materials relating to construction influence long-term performance. The results can be considered an appropriate benchmark for testing in HMC multi-physics analysis.

This research is a part of “Development of Advanced Technology for Engineering Components of HLW Disposal "under a grant from the Japanese Ministry of Economy, Trade and Industry (METI).

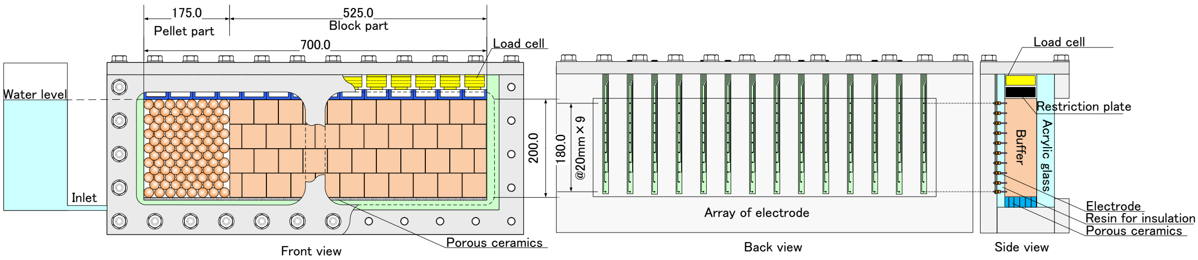
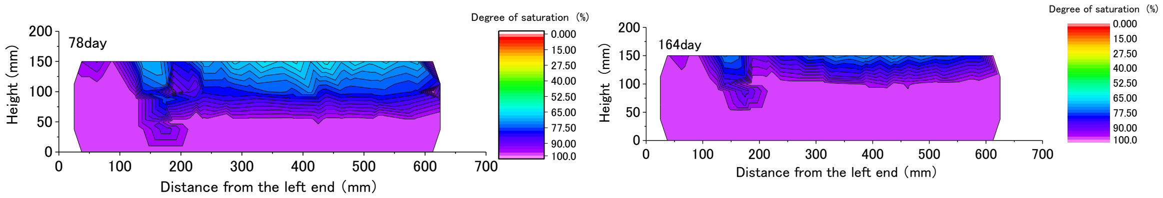
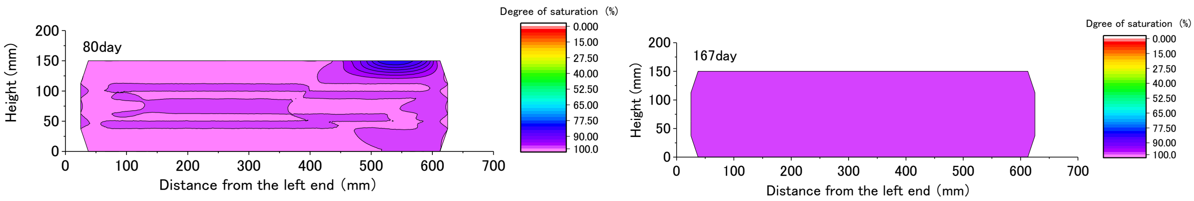


Figure 1 Overview of test apparatus

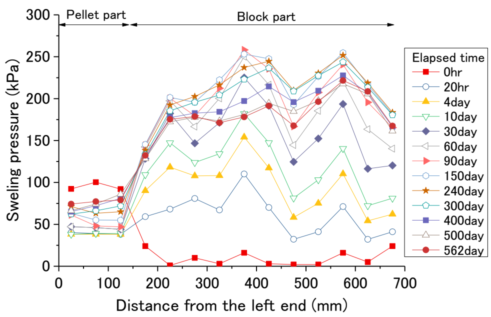


(a) Distilled water

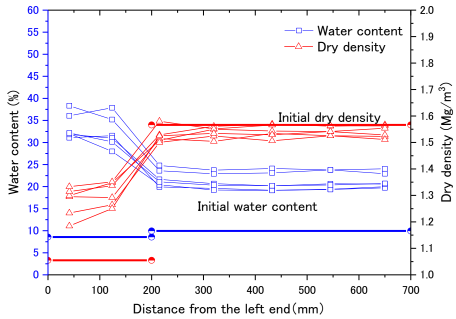


(b) NaCl solution

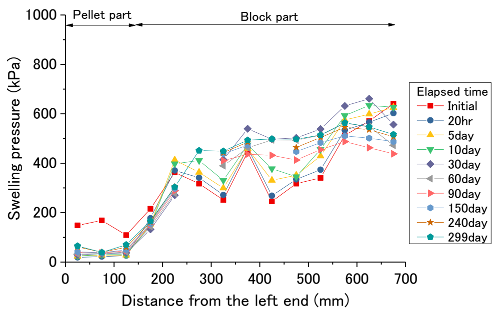
Figure 2 Distribution of degree of saturation



(a) Distilled water

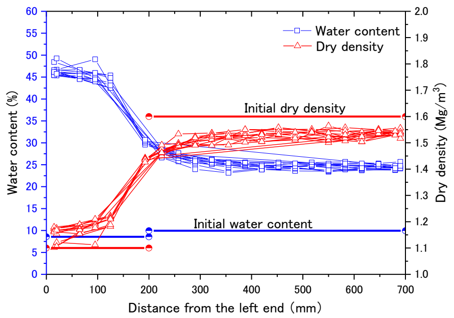


(a) Distilled water



(b) NaCl solution

Figure 3 Distribution of swelling pressure



(b) NaCl solution

Figure 4 Distribution of water content and dry density

BLOCK-PELLET HOMOGENIZATION IN KBS-3V BUFFER – LABORATORY SCALE TEST

Lasse Lavikainen (lasse.lavikainen@posiva.fi), Posiva Oy
Jari Martikainen, Teemu Laurila, Saanio&Riekkola Oy

Homogenization in KBS-3V repository between bentonite buffer blocks and pellets is assessed by laboratory tests. The components match Posiva's buffer design with MX-80 blocks and pellets (Juvankoski 2012). Approximately full saturation of the block-pellet system (100 mm height) is obtained in ~5 months. The test setup is illustrated in Figure 1.

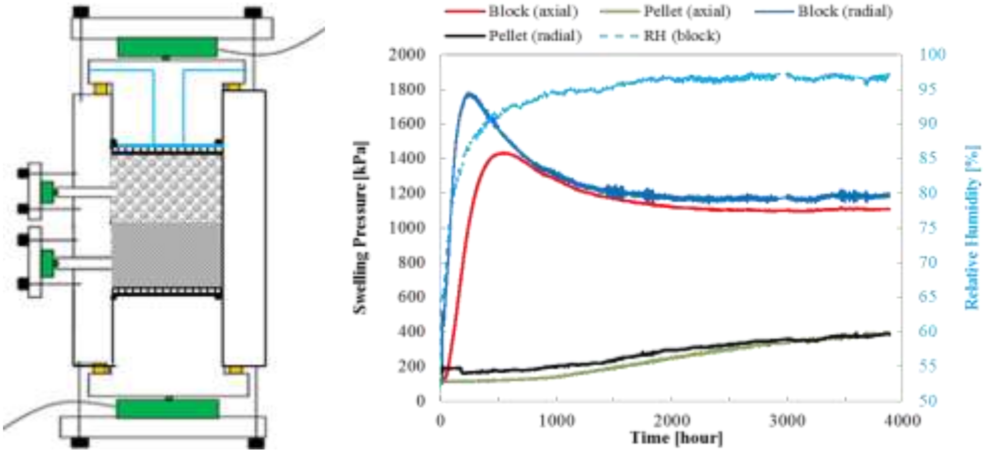


Figure 1. Schematic of the homogenization test (left). Swelling pressure during the test (right).

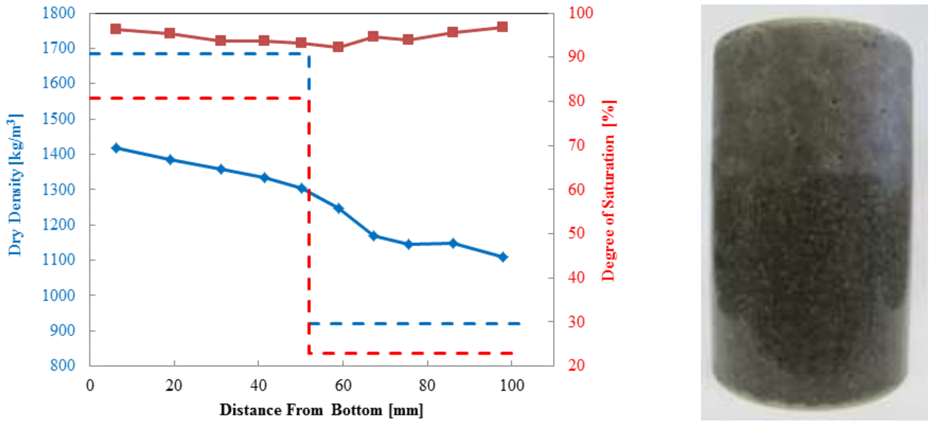


Figure 2. Density profile at the beginning and end of test (left). Photograph of the bentonite after test termination (right).

A notable swelling pressure difference was observed between the block and pellet end, but axial and radial pressures are strikingly similar at each end (Figure 1). Density profile at termination shows ~12% difference persisting between the lowest density and the average density (Figure 2). A clear density gradient remains in the block, whereas the pellet region is more evenly compressed. The axial pressure difference indicates that contact friction with the cell wall is an artefact affecting the observed inhomogeneity. This effect should be accounted for in the analysis of lab scale tests to cost-effectively assess homogenization.

References: Juvankoski M. 2012, Buffer Design 2012, Posiva Report 2012-14

BUFFER AND BACKFILL INTERACTION

David Luterkort (david.luterkort@skb.se) SKB; Lennart Börgesson, Clay Technology AB

One important role of the backfill in the KBS3-V concept is to restrict upwards swelling of the buffer in deposition holes. In most scenarios the high swelling pressure of the buffer results in an upwards expansion and subsequent compression of the backfill. If the buffer swelling is large the density loss of the buffer may be extensive and important properties may be impaired. In order to design buffer and backfill, so that the overarching requirements on the buffer are met, the buffer backfill interaction needs to be understood. In earlier work where the interaction was simulated with numerical models /Börgesson and Hernelind 2009/ it was found that the unlikely case with a fully water saturated buffer and a dry backfill is the most critical one.

To check and develop the numerical models for a dry backfill a full scale test was performed /Sandén et al 2016/. 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 and the force and displacement were measured. The test was modelled by two teams and results were compared to the test results /Leoni et al 2016/. Based on the increased knowledge from the test a sensitivity analyses with changes of buffer and backfill parameters was also performed / Börgesson and Hernelind 2016/.

Comparison between modelled and measured results of the swelling test showed a very good agreement for both models up to 8 cm displacement, after which cracking of the blocks took place / Leoni et al 2016/. Figure 1 shows the results.

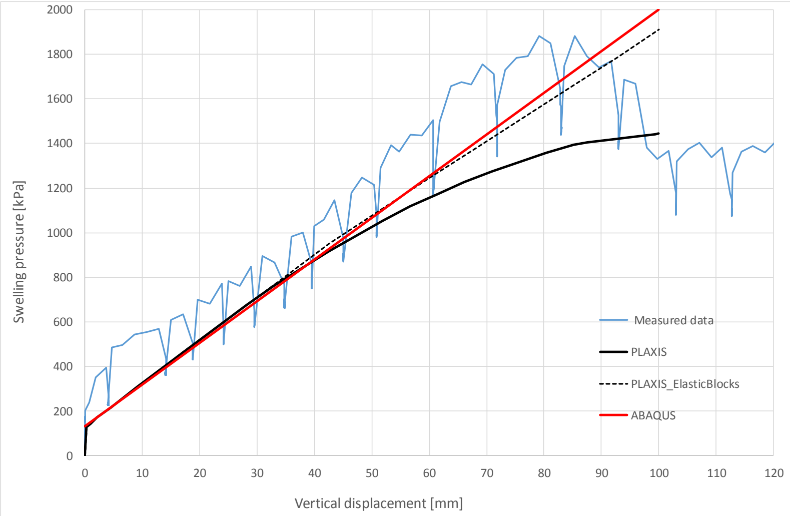


Figure 1. *Comparison of measured and modelled relation between vertical displacement of the plate and applied normal stress on the plate. The black solid and dashed lines are the PLAXIS results and the red line corresponds to the Abaqus results.*

The sensitivity analyses showed that the stiffness and thickness of the pellet filling in the floor and roof were the factors most sensitive to changes.

The backfill model has been used to predict the buffer/backfill interaction at dry backfill for different cases /Börgesson and Hernelind 2016/. In those predictions also the deposition hole with a water saturated buffer was included. The buffer was modelled with similar models and techniques that were used for SR-Site /SKB 2011/ and which have been further developed and tested.

Figure 2 shows examples of results for one case with an initial average swelling pressure of the buffer of 7 MPa and a pellet filling thickness in the floor of 10 cm. This corresponds to the current reference design

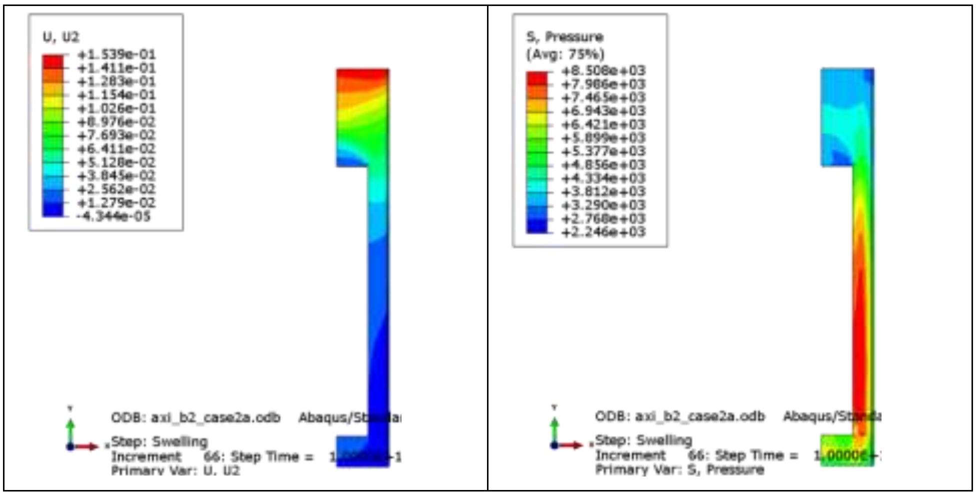


Figure 21. *Axial displacements (m) (left) and average stress (kPa) of case 2a (σ=7 MPa, t_p=10 cm).*

This type of modelling is the key tool for designing and verifying buffer and backfill with respect to buffer upward swelling.

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Formaterat: Engelska (Storbritannien)

Czech B75 bentonite: its application in physical experiments of bentonite barrier, mechanical properties and constitutive and numerical modelling

David Mašín, Jaroslav Kruis, Jiří Svoboda

Preliminary abstract:

The objective of the workshop is to present and discuss the current state-of-art regarding the mechanical evolution of bentonite barriers. In our presentation, we will focus on bentonite research performed by the Czech team to date, which will be used as a background for the research within BEACON project. The presentation will cover the following topics:
- Physical modelling of bentonite barriers (Mock-up tests and small-scale physical experiments)
- Laboratory testing of bentonite behaviour
- Constitutive modelling of bentonite using double-structure thermo-hydro-mechanical hypoplastic models.
- Finite element modelling of coupled THM processes within bentonite barrier using SIFEL finite element package.

In the following, we describe in more detail hypoplastic constitutive model and finite element package:

The thermo-hydro-mechanical model for expansive soils including double structure is based on the previously developed double structure hypoplastic model, in which the hydro-mechanical coupling is considered at each of the two structural levels. The model also includes separate effective stress definitions and water retention curves for the two levels of structure and they are linked through the double-structure coupling function. In the model, thermal effects are considered both on the mechanical behaviour of macrostructure and microstructure. This is combined with a temperature-dependent water retention curve for the macrostructure and an enhanced double-structure coupling law. Good predictions of the model are demonstrated by comparing the simulations with experimental data on MX80 bentonites taken from the literature and by simulations of the B75 bentonite adopted in Czech Mock-up experiments.

SIFEL is an open source computer code which has been developing since 2001 at the Department of Mechanics of the Faculty of Civil Engineering of the Czech Technical University in Prague. It is composed from several parts which can be used independently or they can be linked together in order to gain higher functionality. All parts are released under GNU General Public License (GPL). There are three modules that can be exploited in the field of expansive soil modelling. Simulations of the mechanical behaviour can be conducted by the module MEFEL which represents Finite Element Method (FEM) program for 1D, 2D or 3D simulations. It contains many constitutive models based on creep theory, visco-plasticity, damage and hypoplasticity. For the simulation of bentonites, the most promising implemented model seems to be the hypoplasticity model for unsaturated soils with the influence of temperature. Several integration schemes based on Runge-Kutta-Fehlberg method have been implemented and some benchmark examples have been tested successfully. Description of transport processes represents another important part of the expansive soil simulations. This problem can be solved by TRFEL module which is devoted to the FEM for transport problems in 1D, 2D and 3D. In this module, several constitutive models were implemented for the simulation of transport processes in concrete and soils. The simplified Lewis-Schreffler's model was implemented and tested for the water flow simulation in a bentonite specimen. It is known from experiments that transport and mechanical processes are coupled. For this kind of problems, METR module was implemented. It interconnects TRFEL and MEFEL modules and it provides all constitutive models and finite elements implemented in these modules can be exploited in coupled problems.

Considerations on the significance of the pre-hydration state on the long-term safety functions of bentonite

Paul Marschall, Nagra

Empirical evidence from dismantling of large-scale demonstration experiments on seal performance, dedicated laboratory investigations and microstructural investigations on hydrated bentonite material reveal consistently over a wide range of scales, that bentonite preserves structural characteristics of the pre-hydration state when saturated. Thus, when the FEBEX experiment was dismantled after two decades of hydration (FEBEX-DP), the construction joints between the bentonite blocks could be clearly identified by visual inspection. The bentonite blocks could be separated easily from each other along the contact zones, indicating marginal cohesion. Furthermore decent indications for chemical alternations were seen along some of the block boundaries. Noteworthy, visual inspection did not reveal any open gaps between the bentonite blocks, confirming that all technical voids had been closed by swelling in response to the long-term hydration process.

In the framework of SKB’s Task Force on Engineered Barriers a series of well-established laboratory experiments were conducted for a variety of geometrical settings (radial / linear swelling, closure of gaps / holes), aimed at assessing the homogeneity of the swelling process of bentonite during hydration in terms of density distributions and local swelling pressures. The experiments confirmed the general capacity of highly compacted bentonite to homogenize in response to the hydration process. Moderate deviations from predicted swelling behavior were observed, which were explained by the limited capabilities of the existing modelling frameworks. The role of the as-compacted state of the bentonite before hydration had not been subjected to detailed analyses and may have contributed to the uncertainties in model predictions.

Microstructural investigations of bentonite samples before and after hydration have been conducted with various techniques such as FIB-nano-tomography, X-ray tomography and mercury porosimetry (EBS-Task Force / “Gas transport in Bentonite”). The different techniques show in a consistent manner, that the hydration process does not remove the entire macro-porosity of the bentonite, even though a significant re-arrangement of the pore structure takes place. The re-arrangement of the pore structure in response to hydration comprises a marked increase of the fraction of micro- and meso-pores at the cost of the macro-pores and depends on the grain-size distribution of the as-compacted state.

The observed deviations of hydrated bentonite from ideal homogenization have implications concerning the long-term safety functions of the engineered barrier system. While the bulk swelling pressure and the hydraulic barrier function of the bentonite is not significantly affected at the scale of the tunnel / repository seals, impacts may be expected in the bentonite buffer of the canister near-field. Thus, hydro-chemical interactions such as iron-bentonite interactions, microbial activities, gas- and radionuclide transport in the buffer may be controlled by the small-scale variability of the bentonite density. From a long-term performance perspective, it is mandatory to gain in-depth understanding of the phenomena and processes, which are associated with the deviations of hydrated bentonite from ideal homogenization. Insight must be gained in the origin of spatial variability of bentonite density of the engineered barriers and engineering measures are required to mitigate negative impacts on the long-term safety functions.

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.

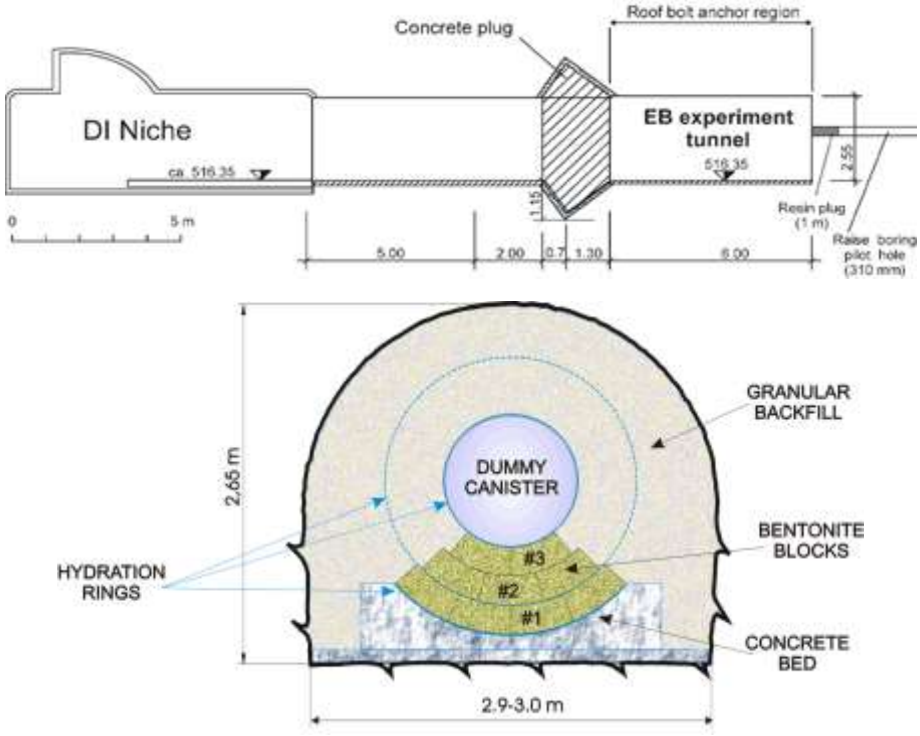

Figure 1: EB niche at Mont Terri URL, longitudinal and cross sections

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 x 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

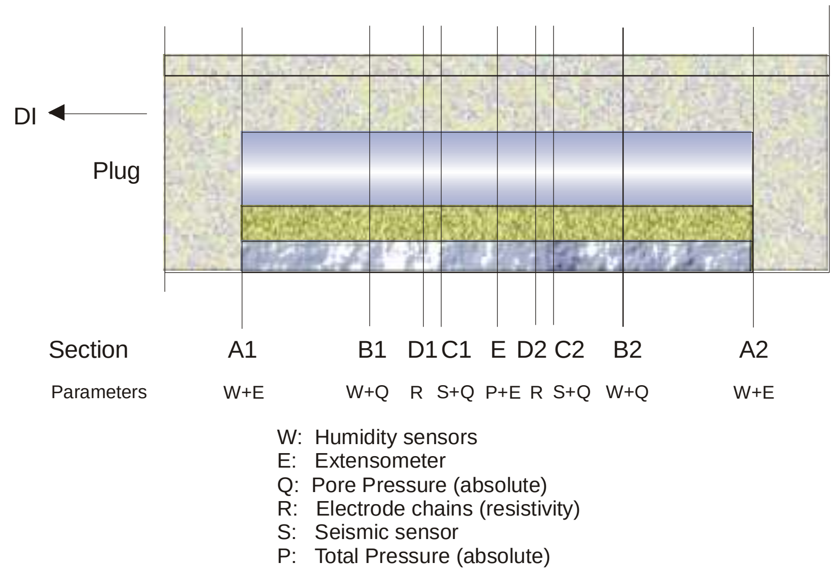

Figure 3: Position of instrumented sections in EB Niche

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.

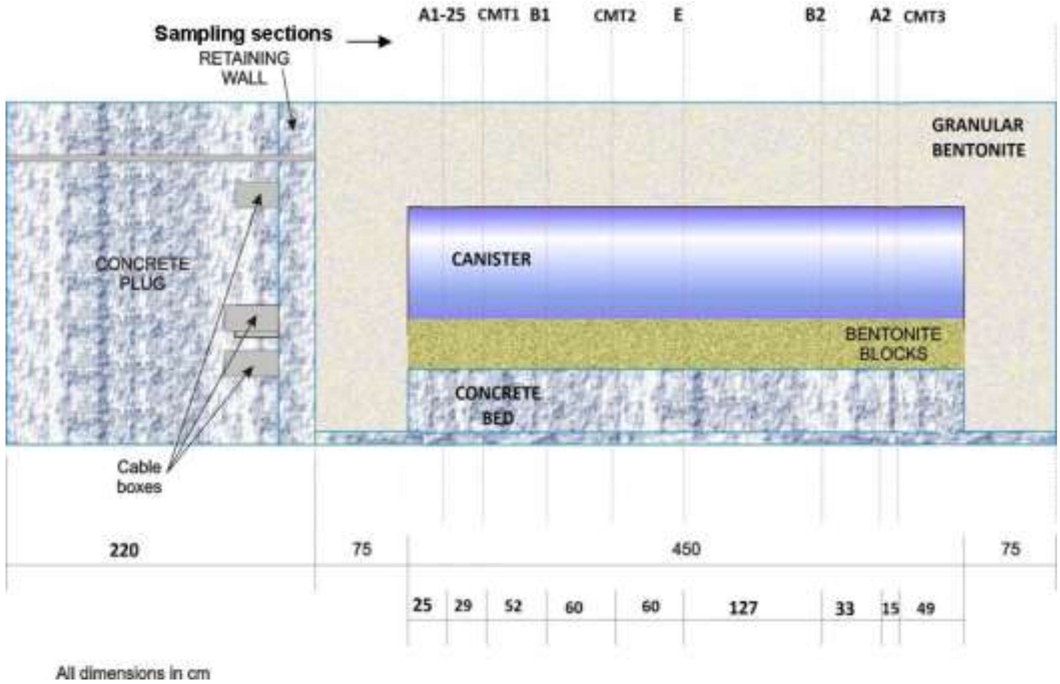

Figure 4: Position of the bentonite sampling sections

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.

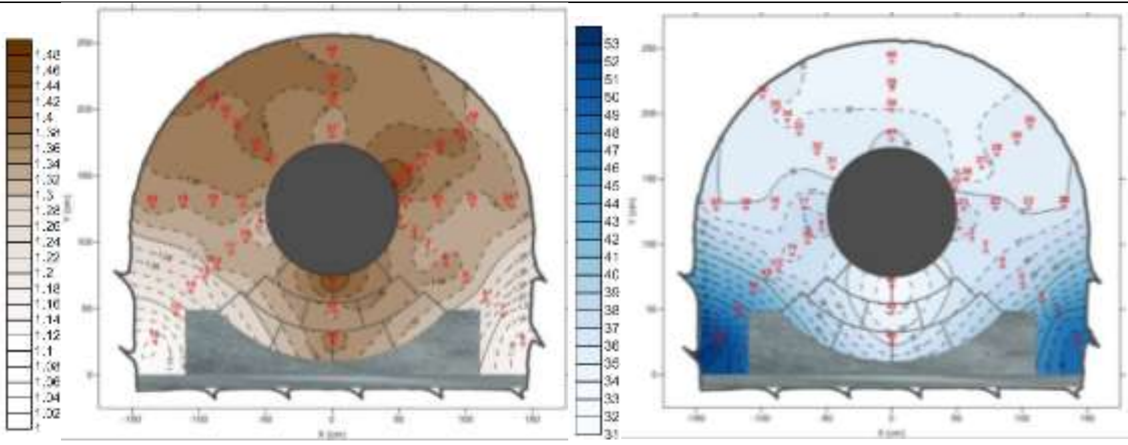

Figure 5: Isolines of the dry density (g/cm³), left, and water content (%), right, in Section E

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.

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RE-SATURATION AND GAS RELEASE OF BENTONITES

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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/cm³, 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.

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 [3]. Ongoing water uptake experiments at GRS concern restricted water inflow and the final shape of the water content distribution under strong non-isothermal conditions.

In another series of in-situ and laboratory experiments, a production of gases by air-dry and hydrated FEBEX bentonite was studied for different amounts of time between one day and ten years at the Grimsel underground laboratory and at the GRS laboratory from 1996 to 2007 [2]. Following the observations of about 40- and 200-fold increases within one year of, respectively, methane and carbon dioxide concentrations inside the bentonite buffer heated to 100°C in the in-situ study, laboratory experiments at 20°C, 50°C and 95°C were started. They 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 production decreased considerably. Since such a gas release from bentonite may be of relevance for performance of a repository for high-level radioactive waste, a series of laboratory investigations on the gas release from different bentonites is currently underway at the GRS laboratory, which provides data on fluid pressure and should contribute to elucidation of the open questions identified in the previous study.

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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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Short abstract

The long-term behavior in the near-field of deep geological disposal is governed by coupled thermal-hydraulic-mechanical (THM) processes, such as heat generation from the overpack, resaturation, and deformation of the bedrock. THM transition will continue for hundreds of years in the initial stage of disposal (construction, operation, and closure stage). These processes influence the displacement of the overpack, the swelling behavior of the bentonite 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 stiffness of 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, the researches by the full-scale tests and the numerical analyses have been carried out. However, the former are difficult due to location, time, and economic restraints, and the latter are necessary to verify the applicability of the numerical model.

A geotechnical centrifuge is an important tool available to geoscientists and engineers, because it enables rapid study and analysis of design problems using actual geotechnical materials. Physical modelling using such a centrifuge can be used to replicate an event, similar to what can be done with a prototype, and in fact is a reduced-scale version of a prototype. Based on centrifugal scaling laws for THM behavior, any two investigations of the same conditions using a centrifugal model test and a prototype are similar and related. However, the centrifugal model test has the advantage that it can greatly shorten the long time needed to see behavior resulting from the typically slow flow of groundwater that satisfies Darcy’s law. If the time acceleration test using the reduced-scale 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.

Our aim 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.

Beacon Initial Workshop

Numerical modelling of bentonite mechanical evolution at Imperial College

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The Geotechnics research group at Imperial College develops the finite element software ICFEP (Potts & Zdravkovic, 1999, 2001) as a computational platform for their research and industrial applications in general geotechnical engineering. Relevant to the Beacon project are the facilities for modelling the behaviour of unsaturated soils, including fully thermo-hydro-mechanical (THM) coupled formulation, boundary conditions and constitutive models. In addition to the numerical capabilities, the group's experimental capabilities include a high suction-controlled oedometer (Mantikos et al., 2016), which is currently used to study homogenisation of MX80 bentonite, and a temperature-controlled oedometer, currently used to study the effect of temperatures up to 85^{o}C on the mechanical behaviour of MX80 bentonite. A temperature- and suction-controlled triaxial cell and a hydraulic permeability/thermal conductivity cell are currently under development. The focus of this abstract is on numerical modelling.

The adopted constitutive framework is that of 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., 2013a). This model is considered generally suitable for simulating moderately expansive soils. The authors have recently developed a constitutive model for highly expansive clays (the ongoing research of Ghiadistri), arising from the need to understand the behaviour of bentonite buffers used to protect containers in the disposal of radioactive waste. The new 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). In particular, it introduces two distinct levels of structure characteristic of compacted clays: the micro-structural level at which swelling of active minerals occurs, and the macro-structural level responsible for major structural rearrangements.

The macro-structure uses two independent stress variables: equivalent net stress ($\sigma_{eq} = \sigma - u_{air} + s_{air}$), computed as the excess of the total stress, σ, over the air pressure, u_{air}, plus the air entry value of suction, s_{air}; and equivalent suction ($s_{eq} = s$-s_{air}), computed as the difference between current suction, s, and the air entry value of suction, s_{air}. The microstructure is assumed to be elastic, volumetric and fully saturated, therefore its framework is formulated in terms of mean effective stress $p' = p + s_{eq}$, where p is the mean total stress. Unlike the BBM framework, in the expansive model the behaviour below the yield surface is not elastic, and the elastic micro-strains that derive from changes in the effective stress produce plasticity through the use of interaction functions between the two levels of structure. Consequently, the two overlapping structures are independent but coupled through the hardening law. An additional hardening parameter, the void factor, is introduced in order to express the evolution of the micro-structure, being the fraction of the micro void ratio to the total void ratio. Hence, its magnitude indicates whether the fabric resembles primarily the macro-structure or whether the micro-structure is dominant. The application of

the new model to simulations of bentonite swelling tests has shown very good agreement with experimental data, as well as exposed some deficiencies in the experimental set ups.
To simulate laboratory experiments such as water infiltration in constant volume column tests and large-scale mock-up laboratory tests, as well as in-situ tests under repository conditions, requires the use of fully coupled hydro-mechanical (HM) or thermo-hydro-mechanical (THM) governing equations. ICFEP's HM coupled formulation for unsaturated soils (Smith, 2003; Tsiampousi et al., 2017) is consistent with the available constitutive and the soil-water retention (SWR) models. The latter model (Tsiampousi et al., 2013b) accounts for hydraulic hysteresis and is formulated in the three-dimensional space $S_r - s_{eq} - v$, where S_r is the degree of saturation and v is the specific volume. Furthermore, the inclusion of realistic permeability models is central to the simulation of coupled HM phenomena. In ICFEP, permeability may vary as a function of void ratio (or mean effective stress), suction or degree of saturation, and temperature, while desiccation under tensile principal stresses can also be modelled.

ICFEP's library of mechanical and hydraulic boundary conditions includes excavation, construction, compaction, prescribed displacements and pore water pressures, tied degrees of freedom, infiltration, precipitation, which are necessary in the numerical analysis of laboratory and in-situ tests. Available thermal boundary conditions include prescribed temperatures, heat flux, and convective heat loss. All formulations are established in the generalised stress space and are appropriate for any type of analysis (2D plane strain and axisymmetric, 3D).

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THE LONG-TERM IN-SITU TEST (LIT) AT THE GRIMSEL TEST SITE AND SUPPORTING LABORATORY STUDIES

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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.

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).

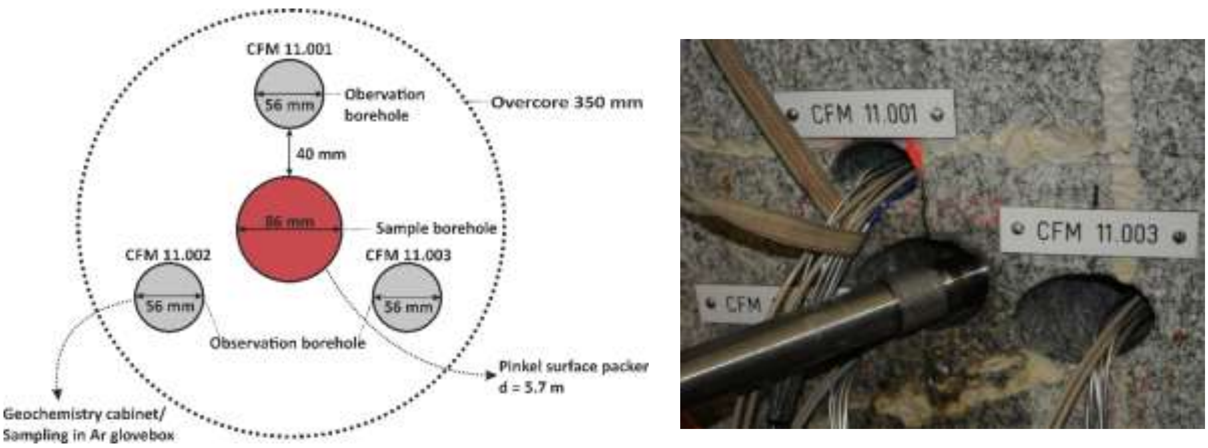

Figure 1: LIT arrangement of the observation boreholes (filled grey circles) and the central borehole (marked in red color. A schematic overview (left) and a picture of the site (right) is shown. The bentonite source is located in the central borehole and the surrounding boreholes (CFM 11.00X) are for 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.

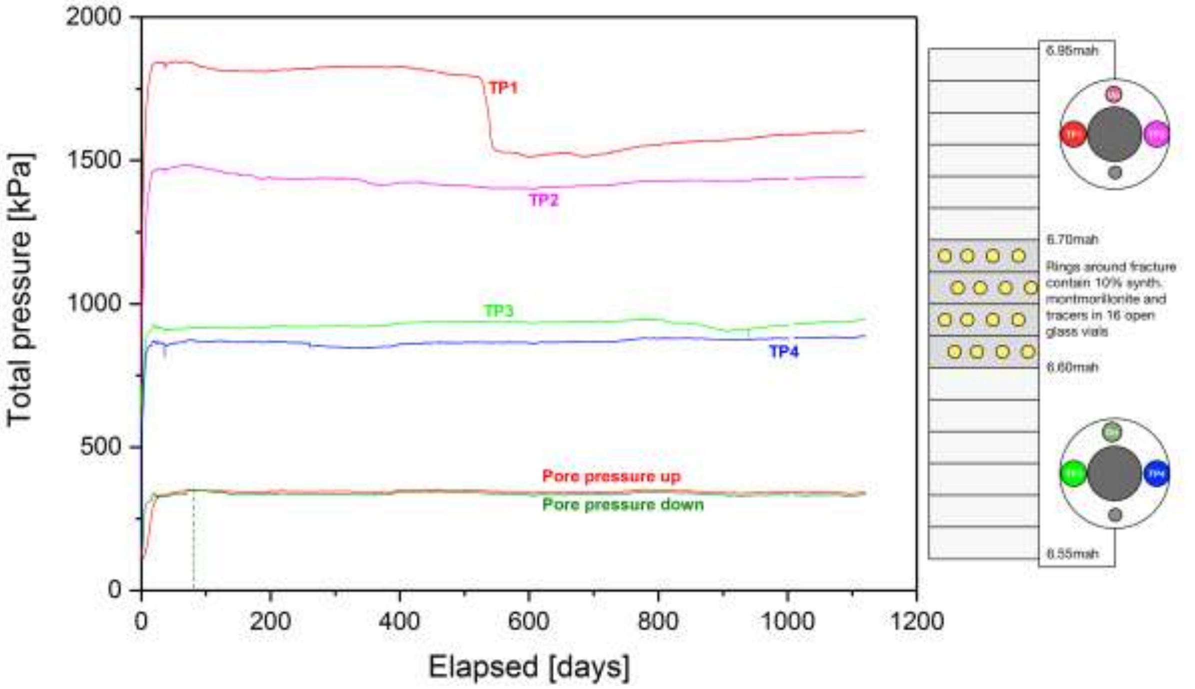

Figure 2: Total pressure and pore pressure evolution within the LIT bentonite source.

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.

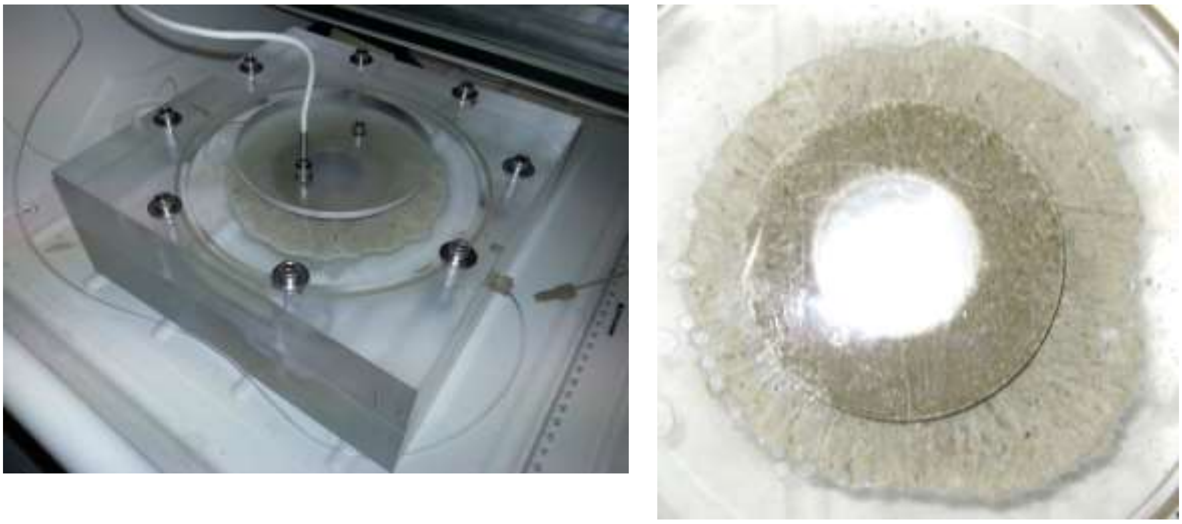

Figure 3: Pictures taken from the Febex bentonite erosion experiment. The experimental layout with the pressure sensor on top of the sample (left) and the swelling of the sample after ~20 days (right).

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.

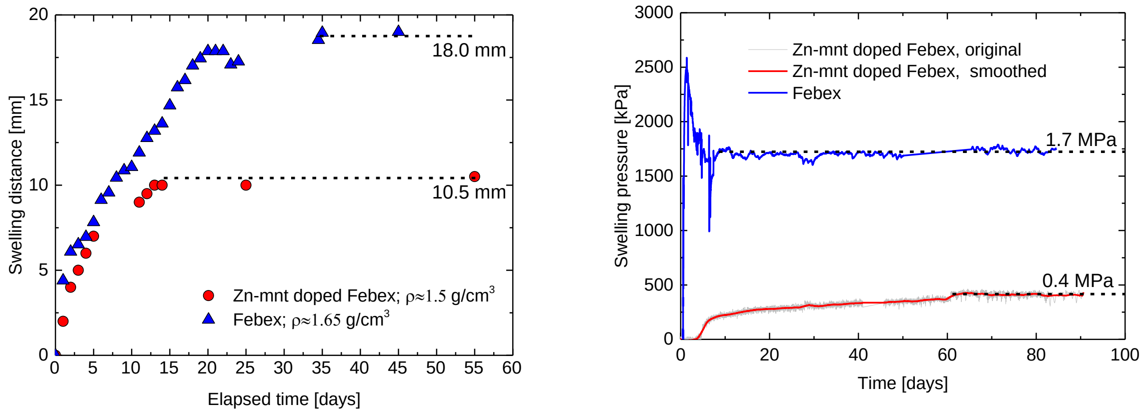

Figure 4: Swelling distance (left) and pressure evolution (right) in the artificial horizontal fracture experiments.

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.

Acknowledgement

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Heterogeneous dry density of granulated bentonite mixtures emplaced by screw feeders: A direct measurement using a dielectric method

Toshihiro Sakaki, Nagra

In the Full-Scale Emplacement (FE) Experiment at the Mont Terri Rock Laboratory, Nagra has constructed a 5-arm screw feeder system to emplace granulated bentonite mixture (GBM) around three heaters that are placed horizontally on bentonite block pedestals. The target dry density of the bulk GBM as emplaced is 1.45 Mg/m^3 or higher.

Prior to the backfilling of the FE tunnel, the prototype backfilling machine was tested in a series of pretests for the achievable density of the emplaced GBM. In one of the pretests, a 1:1 scale mock-up tunnel with a dummy waste canister and pedestal was constructed and filled with the GBM. The mockup tunnel was equipped with a dielectric tool for a direct measurement of the dry density of the GBM. With a capability to measure dry density along a 1m-long profile, the measurement was performed along 11 radial profiles around the dummy heater between the screw feeders as well as in the immediate vicinity of the screw feeders. The average GBM dry density was also calculated by monitoring the amount of GBM emplaced and the volume filled (i.e., conventional mass balance method).

The measured dry density profiles as shown in **Figure 1** indicate, in general, that; 1) dry density was higher near the screw feeders (as high as 1.7 Mg/m^3), 2) dry density was lower along the tunnel wall (as low as ~1.3 Mg/m^3), and the average dry density estimated based on the profiles (1.53 Mg/m^3) agreed closely with that estimated by mass balance (1.51 Mg/m^3). Although not shown, the section without the heater also showed a similar variation in the dry density.

The measurement indeed showed a quite complex heterogeneous dry density field. This variation in dry density could result in highly heterogeneous thermal conductivity and permeability field. It would also be essential to understand how this initial heterogeneity at the time of the emplacement evolves/homogenizes over time as hydration proceeds.

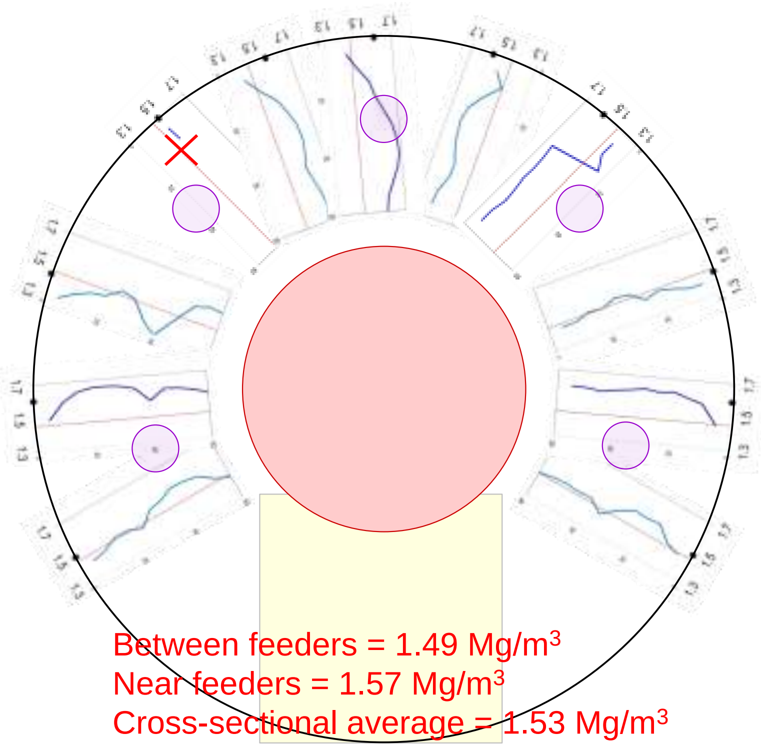

Figure 1. Measured dry density profiles in radial direction. “X” indicates that the instrumentation was damaged doe to thrust.

Beacon Initial Workshop

CODE COMPARISON OF COUPLED THM PROCESSES IN ENGINEERED BARRIERS PERFORMED WITHIN THE TASK FORCE ON ENGINEERED BARRIER SYSTEMS

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Previous studies on the THM modelling of engineered barrier systems (EBS) showed strong sensitivities of the output quantities to changes in the input parameters. 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.

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. 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. 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 simulations of the near field. The code comparison was divided into different stages with increasing complexity, from TH- to THM-calculations using a simplified swelling law for the bentonite. 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.

From the code comparison, it can be concluded that very good agreement between the results of the different codes was achieved for the TH-coupled processes. 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 and definition of the mechanical material behaviour of the bentonite.

The cross code comparison 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.

Handling of the mechanical evolution of the bentonite buffer in the SR-Site safety assessment

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In the SR-Site safety assessment 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.

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.

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.
- 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.

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.

Mock-Up-CZ (CTU&SURAO)

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. 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. 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%).
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. 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.

Jiri Svoboda

Mock-Up-Josef (CTU&SURAO)

Mock-up Josef consists of an in-situ physical model, the first of its kind in the Czech Republic, which simulates the vertical emplacement of a container with spent nuclear fuel. The experiment involves research into the effects of heat and groundwater on the bentonite sealing barrier (the so-called buffer) which will surround containers with spent nuclear fuel in the future Czech deep geological repository.
Experiment is located in the Josef Underground laboratory. The experiment was launched in December 2012 and is running since then. Pressure, temperature and relative moisture, both within the bentonite barrier and the surrounding rock massif, are monitored on a continuous basis. These parameters are measured within the bentonite barrier every ten minutes in five horizontal profiles and one vertical profile. Metal samples intended for corrosion monitoring were placed within the barrier to be investigated following the conclusion and subsequent dismantling of the experiment. In regular intervals the sampling of the bentonite blocks forming the buffer is carried out by drilling. The samples are then tested for dry volume density, moisture content by weight, saturation degree, hydraulic conductivity and swelling pressure. The values obtained were subsequently compared with values obtained following previous sampling. In cooperation with SÚRAO experts, mineralogical changes within the bentonite are also being monitored on a continuous basis.

Jiri Svoboda
CTU and Surao

RESEACH ACTIVITIES AT RWMC ON THE BENTONITE RE-SATURATION PROCESS (2) LABORATORY AND NUMERICAL EVALUATION

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It is generally assumed that homogenization will occur and that mechanical-hydro properties of the buffer will be equivalent to those of mean installed dry density in long term assessments of bentonite barriers. However, some residual heterogeneity even after full saturation will affect the performance of bentonite barrier since the hydraulic conductivity of the zone with lower dry density must be dominant over the sealing ability of barrier system. It is therefore of importance to evaluate whether the dry density heterogeneity of bentonite buffer at emplacement will remain or disappear after its deposition/saturation.

This paper deals with the laboratory and numerical verification of the sustainability of dry density homogeneity of bentonite-based buffer material after saturation and equilibrium. In laboratory testing, two mixture samples of a Japanese Na type bentonite (Kunigel V1) and 30 %wt silica sand, which were saturated with distilled water and had the same dry density of 1.6 Mg/m^3, were prepared with an individual stress/swelling history. One sample was one-dimensionally compacted toward the dry density of 1.6 Mg/m^3 under an unsaturated condition in an oedometer container, and then it was provided with water until its saturation under the volume constraint condition like a swelling pressure test. On the other hand, another sample was saturated by water after reaching the dry density of 1.6 Mg/m^3 in a similar manner to the former one, while it 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. Hereinafter, the former and the latter are respectively referred to as NC and OC samples. After these preparations, two saturated samples in each oedometer container 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 having the same dry density, the main concern in this testing is the occurrence of additional deformation or the changes in dry density in the transition process toward equilibrium. In addition, this paper demonstrates the numerical simulation of the above-mentioned laboratory test by using the elasto-plastic constitutive model for bentonite buffer proposed by Takayama et al. (2017) to validate the reproducibility of the behaviour. 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. Although it 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). The soil-water retention curve model is also employed to describe the relationship between the suction and the 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.

Fig. 1 shows the test apparatus used in the laboratory test in a situation where the two samples are connected each other. Herein, NC sample was placed in the upper oedometer container, while OC sample in the lower one. Fig. 2 shows the changes in the dry density of NC and OC 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. Subsequently, both specimens were provided with the distilled water while keeping dry density of 1.6 Mg/m^3 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. 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.

This research in a part of “Development of Advanced Technology for Engineering Components of HLW Disposal” under a grant from the Japanese Ministry of Economy, Trade and Industry (METI).

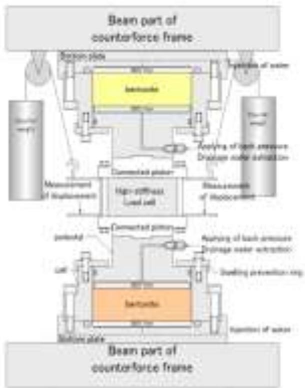

Fig. 1 Overview of test apparatus

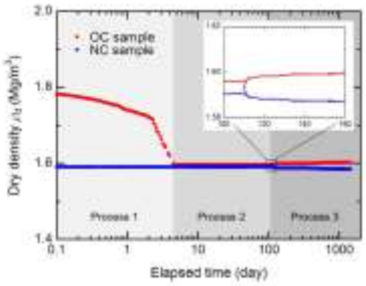

Fig. 2 Changes in dry density (experiment)

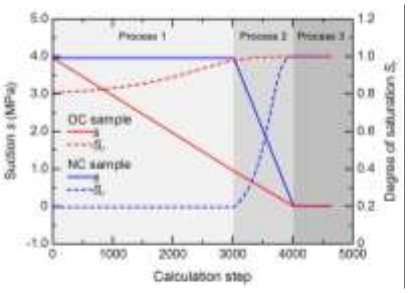

Fig. 3 Degree-of-saturation (calculation)

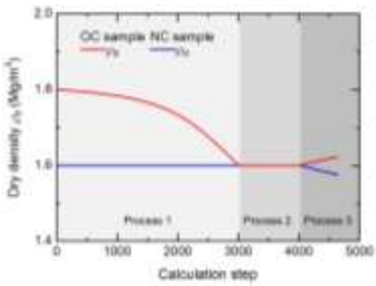

Fig. 4 Dry density (calculation)

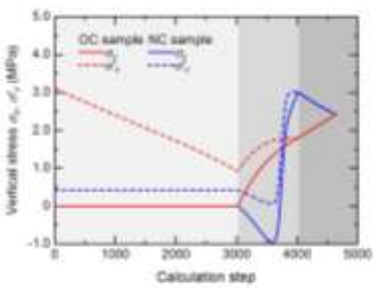

Fig. 5 Vertical stress (calculation)

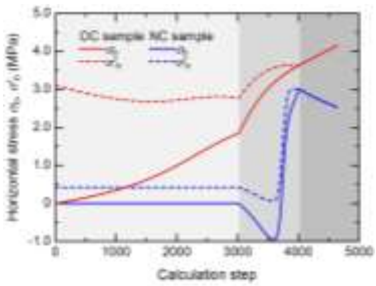

Fig. 6 Horizontal stress (calculation)

HETEROGENEITIES AND HYDRO-MECHANICAL BEHAVIOR OF BENTONITE-BASED STRUCTURE: LESSONS LEARNT FROM LARGE SCALE EXPERIMENTS

AUTHORS and AFFILIATIONS

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In Andra geological disposal facility (GDF), bentonite based materials are mainly used to seal drift and shaft. To demonstrate its capacity to build seals and to show that expected properties can be reached, Andra has developed some field scales experiments especially in its underground research laboratory in Meuse/Haute–Marne. Among those experiments or demonstration tests, several illustrate the needs to explore the effect of heterogeneities in the bentonite based materials on long term performance.

NSC (French acronym for Noyau de SCellement) was designed to study the efficiency of a seal in regards of its hydraulic performances at full saturation. Its half size compared to a real seal (4.5 meters diameter), gives a lot of precious information about its hydro-mechanical behavior especially at the interface with the excavation damaged zone. Most of the plug has been built with pre-compacted bricks made with a bentonite/sand mixture (40/60%). The gaps and technological voids have been filled with pellets/powder pure bentonite (WH2). This installation induces initial heterogeneities and the monitoring in terms of average permeability or swelling pressure provides important information on the path followed to reach the final state at full saturation. Relative humidity and total pressure measurements at several locations inside the plug clearly indicate that water hydration in that kind of structure is not homogeneous despite the regularity of the geometry.

In PGZ2 set of experiments, several bentonite plugs have been installed in 10 cm diameter boreholes. Two type of material have been used, compacted blocks (bentonite/sand mixture 70/30%) and pellets/powder of pure bentonite (WH2). If in most cases, total pressure measurements show a good homogenization of the material, it is not the case for pellets/powder mixture. Differences still remain between the two faces of the bentonite plug after several years. Nevertheless, hydraulic tests made at different stages indicate that the performance expected for this seal has been reached (low water permeability).

FSS (Full scale seal experiment) was designed to make technological demonstration of a seal at full scale. One of the objectives was to demonstrate the industrial capacity to satisfactorily emplace large volumes of swelling clay (pellets/powder mixture of bentonite WH2) at a satisfactory specific density value. About 750 m3 of pellets/powder of bentonite has been installed. Analysis of initial density of the mixture indicated some local heterogeneities especially differences have been observed between the top and the bottom of the structure. The mean value of density estimates on both mass of bentonite and initial volume is in accordance with what was expected but the role of local heterogeneity on global performance of the system have to be investigated. Another topic emerged when the demonstrator have been realized is the capacity to estimate the distribution of installed bentonite density in a large scale structure.

In this contribution, Andra will present first an analysis of some large scale experiments and the consequences of detected heterogeneities on hydro-mechanical behavior of bentonite structure. Secondly, some non-intrusive instrumentation tracks to identify the density variations within the bentonite plug will be presented.

THM modelling of bentonite: an approach tested on MX-80 and FEBEX bentonite

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Bentonite barriers perform safety critical functions in many radioactive waste disposal concepts, but it is challenging to accurately predict bentonite mechanical behaviour in repository settings. Coupled models of the thermo-hydro-mechanical (THM) response of bentonite are used to demonstrate understanding of bentonite behaviour in experiments and to predict the response of bentonite in a repository environment. Following trials of a range of numerical approaches, 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. The model is applied to experimental data from the SEALEX experiments, involving a 70/30 by mass mixture of MX80 bentonite and sand and to experiments on FEBEX bentonite, including the FEBEX in-situ experiment.
The approach has been shown to be able to represent key features of experimental data. The work also highlights that some of the elastic behaviour of bentonite does not necessarily conform to standard equations for solid mechanics of elastic materials.

SWELLING PRESSURE ACTING TO THE CONSTRAINING MATERIAL WITH SLIGHT DEFORMABILITY

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Introduction

Bentonite-based material will be used in radioactive waste disposal facilities to prevent nuclide migration. 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. Stress distribution in the bentonite at the completion of saturation is resulted from swelling of the bentonite.

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 have 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 in a laboratory.

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 inserted into the specimen in order to measure the height of the specimen directory 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 $Mg/m^3$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 2.0 MPa. The smallest elastic modulus corresponding to a soft rock, 750 MPa, caused 40—50 μm of the displacement and 1.5 MPa of the swelling pressure. It can be found that larger deformation of the constraining material decreased the swelling pressure at same dry density. Ca-type bentonite also represented that the swelling pressure became lower in the case of smaller elastic modulus of the constraining material.

FEBEX AND FEBEX-DP PROJECTS AT THE GRIMSEL TEST SITE

The aim of the FEBEX project was to study the behaviour of near-field components in a repository for high-level radioactive waste in granite formations. 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). The thermal effect of the wastes was simulated by means of two 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. The clay barrier was formed by blocks of compacted FEBEX bentonite. The blocks had initial dry densities of 1.69-1.70 g/cm^3 which, taking into account the probable volume of the construction gaps, gave an average barrier dry density of 1.60 g/cm^3.

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. In the following months this heater and all the bentonite and instruments preceding and surrounding it were extracted. A large number of bentonite samples were also taken for analysis in different laboratories. 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. The test continued running until April 2015, when heater #2 was switched off. The concrete plug was demolished and the buffer, heater and instruments were removed. An exhaustive bentonite sampling program was designed and the water content and dry density of the bentonite were determined on site.

The physical state of the barrier after 18 years of operation was very much affected by the processes to which it had been subjected: 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:

- All the construction gaps between blocks were sealed, both those among blocks of the same section and the gaps between bentonite slices..
- 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.
- 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.

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. 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. 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 years.

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