EUROPEAN COMMISSION

Community research

Long-term Performance of Engineered Barrier Systems

Long-term Performance of Engineered Barrier Systems PEBS

EB dismantling
Synthesis report

(DELIVERABLE-N°: D2.1-8)

Contract (grant agreement) number: FP7 249681

Authors:

Juan Carlos Mayor (ENRESA) and Manuel Velasco (GOLDER)

Date of issue of this report: **28/07/2014**

Start date of project: 01/03/10 Duration: 48 Months

Project co-funded by the European Commission under the Seventh Euratom Framework Programme for Nuclear Research &Training Activities (2007-2011)		
Dissemination Level		
PU	Public	**PU**
RE	Restricted to a group specified by the partners of the [acronym] project	
CO	Confidential, only for partners of the [acronym] project	

PEBS

EURATOM

INDEX

---

1. INTRODUCTION

The Engineered Barrier Emplacement Experiment (EB experiment), dismantled after almost eleven years of operation, has been a long, well monitored, and full-scale demonstration of the use of a Granular Bentonite Material (GBM) as clay barrier. The experiment was carried out, with a dummy canister resting of bentonite blocks, in a 6 m long gallery section (EB niche) excavated in the Opalinus clay (OPA) of the Mont Terri Underground Research Laboratory (URL). The longitudinal and cross sections of the EB niche are shown in Figure 1.

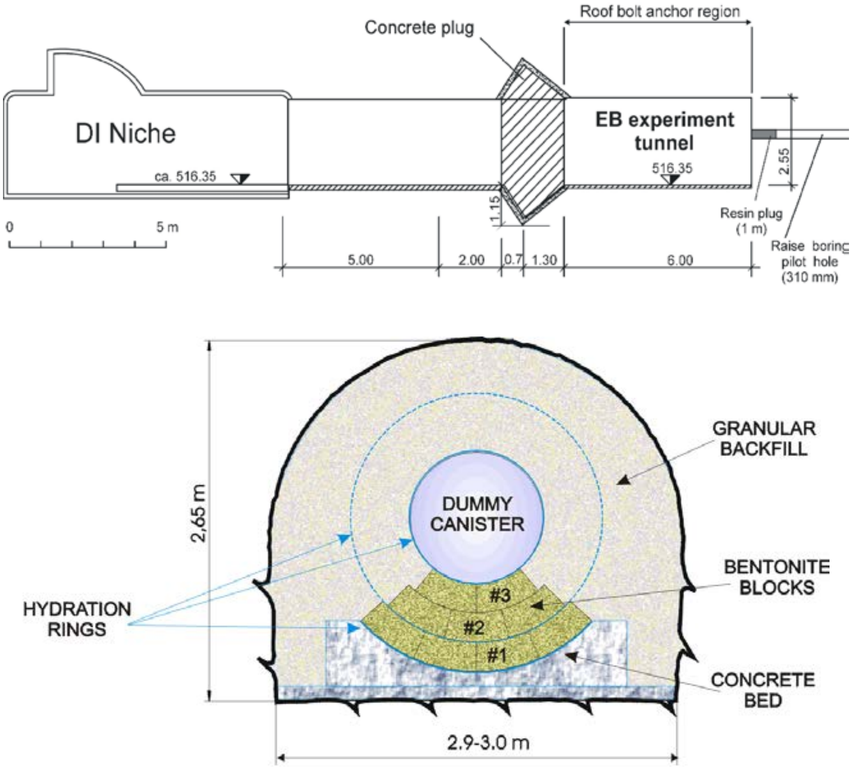

Figure 1: EB niche at Mont Terri URL, longitudinal and cross sections

The main objective of the controlled dismantling of this experiment has been to evaluate the actual state and properties (specially the hydraulic conductivity) of the emplaced bentonite barrier after its complete isothermal saturation (using an artificial hydration system). Therefore, the dismantling operations have been carefully coordinated with and extensive sampling programme: more than 500 samples have been taken for on-site an 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.

From March 2010, the EB experiment operations (specifically, the last years of its monitoring, its dismantling and post-mortem analyses) were included in the PEBS[1] project, forming part of the FP7 Euratom programme. Previously, the first phase of this experiment (years 2000 to 2003) was co-financed by the European Commission (contract nº FIKW-CT-2000-00017) and ENRESA, NAGRA and BGR; and between 2003 and 2010 the monitoring continued under the support of the Mont Terri Consortium (project 32.015 : EB, phases 10 to 15).

The present synthesis report of the dismantling has been elaborated mainly summarizing the data and conclusions included in more detail in the following deliverables of the PEBS project and pertinent documents:

- ***Deliverable D2.1-1:*** *"Horizontal borehole results (geophysics, hydro test, laboratory tests)". Prepared by BGR. Results of two pilot boreholes drilled through the test section 14 months before the dismantling operation.*

- ***Deliverable D2.1-4:*** *"As-Built of Dismantling Operation", written by AITEMIN. This deliverable includes, as Appendix III, the last "Sensors Data Report (No. 30)" with the complete monitoring data from the EB experiment, registered along the period 1st May 2002 to 14th January 2013.*

- ***Deliverable D2.1-6:*** *"EDZ seismic results-seismic transmission measurements", elaborated by BGR.*

- ***Deliverable D2.1-7:*** *"Laboratory Post-Mortem Analyses Report", elaborated by CIEMAT.*

- ***Deliverable D2.1-9:*** *"Geoelectrical Monitoring of Dismantling Operation", elaborated by BGR.*

- ***Deliverables D3.1-1 and D3.1-2:*** *"Modelling and interpretation of the EB experiment hydration", and "Interpretation of the final state of the EB experiment barrier". These two deliverables, elaborated by CIMNE-UPC, have been merged in a single document, to present an integrated view of the modelling of the EB experiment.*

- ***Publicación Técnica ENRESA 02/2005:*** *"Engineered Barrier Emplacement Experiment in Opalinus Clay for the Disposal of Radioactive Waste in Underground Repositories". Elaborated by ENRESA in 2005, it describes the objectives and design of the EB experiment, its actual construction and the experimental results gathered up to the end of year 2003.*

Information from other documents (cited in the References, section 7) has also been used.

---

[1] PEBS: Long-term Performance of Engineered Barrier Systems.

2. BACKGROUND: DEVELOPMENT OF THE EXPERIMENT

2.1 DESIGN AND CONSTRUCTION

The EB experiment was designed in order to demonstrate a new emplacement technique of the bentonite barrier and also to represent the end of the so-called “transient phase” of the barrier, when it will be almost fully saturated and its temperature will be practically equal to the initial one of the host rock. To achieve these general objectives, isothermal conditions and artificial hydration of the barrier are sufficiently appropriate.

As it is show in Figure 1, this full-scale experiment has been performed in a horseshoe tunnel section 6 m-long (and about 2.6 high and 3.0 m wide), located near the DI niche of the Mont Terri URL[2], excavated in Opalinus clay (in the period April to June 2001) with a road header.

A steel dummy canister (similar dimensions and weight as the ENRESA and NAGRA reference canisters) was placed on top of a bed of highly compacted FEBEX bentonite blocks (in turn lying on a concrete bed). The rest of the clay barrier volume (~ 28.4 m^3) was backfilled with the chosen GBM, made of a bi-modal mixture of pellets also of FEBEX bentonite (coming from Almería, Spain), 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.

Previously (November 2001 to March 2002), the designed instrumentation to monitor the barrier and the near-field Opalinus clay (16 hygrometers, 20 piezometers, 8 pressure cells, 7 extensometers, seismic sensors and electrode chains), and the artificial hydration system were installed. Besides, initial geophysical and hydraulic measurements in the rock were performed, to characterize its Excavation Disturbed Zone (EDZ). From them, it was estimated that the EDZ reached a depth of around 0.7 m in the roof of the test section, while at the sidewalls only extended to 0.1 m depth.

The aspect of the test layout (concrete and bentonite block beds, dummy canister and hydration system) just prior to the GBM emplacement and sealing of the section is shown on the following Figure 2.

The GBM emplacement was done in four days (April 2002) using an auger. An auxiliary retaining wall, with an open window, was first erected. The auger had to move through this window; with restricted movements and non-good working conditions due to the presence of the hydration tubing in the test section. Nevertheless, 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

---

[2] URL: Underground Research Laboratory.

obtained average dry density of the emplaced GBM was 1.36 t/m^3 (only 3% lower than the target value, equal to 1.40 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. Also, it should be pointed out that the bentonite blocks below the canister (see Figure 1) had a higher initial average dry density, equal to 1.69 t/m^3.

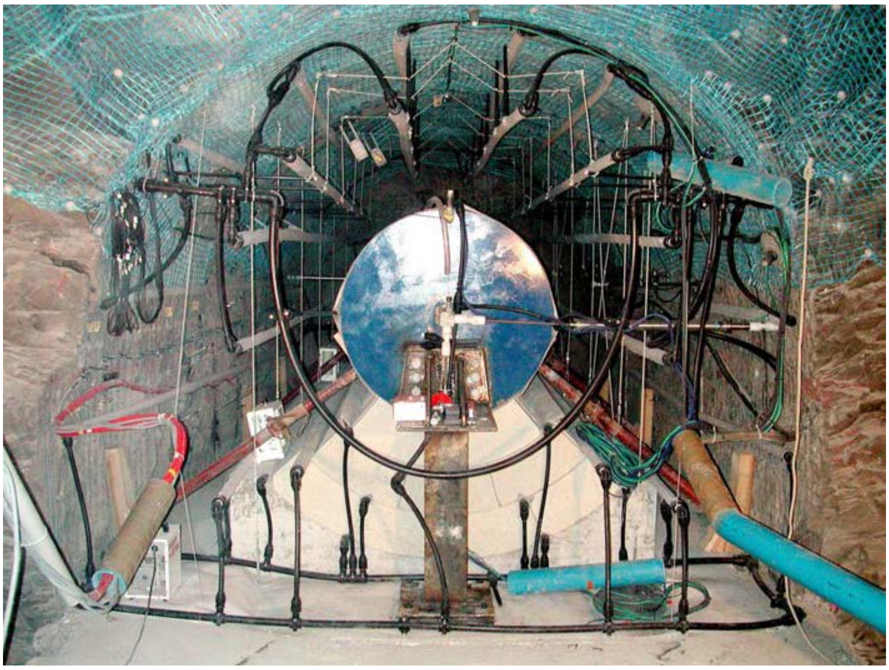

Figure 2: Test elements prior to GBM emplacement and sealing

It can be reasonably expected that, without the physical obstructions of the hydration system (specific of the EB experiment but not of a real repository setting) a higher dry density of the GBM would be achieved using similar procedures to those proven in the experiment. Moreover, fully automated production of a GBM is feasible. Large quantities can be produced with the required quality; and properly emplaced with standard techniques.

The test section was finally sealed with a 2.0 m-long concrete plug (cast on the 0.2 m-long auxiliary retaining wall previously erected in direct contact with the GBM).

2.2 HYDRATION AND LONG-TERM MONITORING

The artificial hydration of the barrier spanned approximately 5 years, starting in May 2002 and ending in June 2007 (5.3 years before the dismantling). The bentonite saturation was fairly quick: in the first 1.5 year-period the recorded water intake was equal to 15.2 m^3 (while the estimated available air volume in the test section was lower, around 12.5 m^3); although during the first days of the hydration some water leakage (not quantified) did occur through the concrete plug bottom (water stains were observed). Nevertheless, despite this leakage, it is assessed that in this 1.5 year-period almost full saturation (at least higher than 90%) of the GBM was achieved. In fact, all the hygrometers installed showed full saturation (except one, saturated later, after 3 years), and also total pressures in the barrier as high as 1.7 MPa were recorded.

Along the remaining water injection period (~ 3.5 years) the additional water intake was much slower: only 3.7 m^3 were injected, up to a total registered water intake of 18.9 m^3 in 5 years. During the last phase (May 2006 – June 2007), the injection was done at atmospheric pressure, with a noticeable decrease of the water flow. Moreover, during the last half a year before the closing of the injection valve of the hydration system negligible water intake was registered, although it cannot be discarded that during this last phase and afterwards an additional and very small water volume from the rock massif could still have been flowing towards the bentonite barrier.

In fact, some of the eight total pressure cells installed registered small increases of the swelling pressures until the start of the dismantling operations (October 2012), reaching at that date values in the range 1.5 to 2.2 MPa, greater than initially expected.

The rest of the monitoring data gathered along the eleven years of the EB experiment operation can be summarized as follows:

- **Temperature and relative humidity.** The average temperature value of the barrier at the end of the experiment operation was 16.2°C, and it has been practically stable most of the recorded time. Only, at the beginning of the bentonite hydration a sudden rise of the temperature was recorded, with a peak value of 28°C. The temperature did recover the initial value after few months. On the other hand, the capacitive hygrometers installed in the near-field Opalinus clay recorded saturation after only one year of hydration; and the ones placed in the bentonite barrier after three years.

- **Canister movements.** The extensometers installed at the front and rear ends of the canister (anchored to the rock massif) did register before dismantling a maximum total heave of the canister front of almost 1 cm. Also, looking from the concrete plug, the canister front moved around 6 mm towards the left, while the rear moved approximately 17 mm towards the right.

- **Rock movements.** The three pairs of extensometers anchored to the test section rock surface (one at the ceiling and the other two at the side walls), and to depths of 1 and 2 m, have registered negligible rock movements; and they were almost stabilized since the end of year 2004. The accumulated movements registered show an elevation of the ceiling of less than 1.2 mm; and a closing of around 1.5 mm in the left sidewall and of 1.0 mm in the right one.

- **Rock pore pressures.** The twenty piezometers available were installed in the rock massif at depths ranging from 0.3 to 3.0 m. At the end of the experiment operation, all the piezometers (18) placed at depths greater than 0.3 m were registering supratmospheric porewater pressures, with a maximum value (absolute) of 1.06 MPa, in one located at 3.0 m depth. The other two piezometers, placed near the rock-bentonite interface, at 0.3 m depth, were registering 0.1 MPa (almost equal to the atmospheric value). It is also worth to indicate that the excavation in year 2008 of the nearby Gallery 08 caused some perturbations to the pore pressure measurements. Also, the piezometers detected the drilling in 2011 of two horizontal pilot boreholes along the EB test section.

On the other hand, hydraulic testing, carried out in five stages during the first year of the experiment (period between October 2001 and October 2003), has shown that, due to the bentonite swelling, the rock hydraulic conductivity measured in a ring 80 cm thick around the test section decreased by approximately two orders of magnitude. Geophysical measurements also confirmed the favourable EDZ evolution during the clay barrier saturation process. It has been concluded that the EDZ parameters after the saturation are practically the same than those of the intact rock.

3. DISMANTLING AND SAMPLING OPERATIONS

3.1 GENERAL

The main purpose of the EB experiment dismantling have been the visual observation of the clay barrier and the other test elements, and to perform an extensive sampling (focused on the bentonite but also taking some samples of the other test elements, such as the concrete plug); for on-site and external laboratory analyses. Samples have been sent to CIEMAT, AITEMIN, BGR, NAGRA and ANDRA. Also, some of them are kept in reserve.

Geophysical (seismic and geoelectrical) investigations have also been performed to better evaluate the state of the bentonite and surrounding rock before dismantling (see following section 3.2).

Specifically, the scope of the sampling, the on-site and external laboratory analyses, and of the geophysical investigations, has been the following:

- 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.

- Assessment of the EDZ evolution during the dismantling.

- Recovery of other elements of the test, such as concrete samples, used sensors of the instrumentation and samples of the geotextile mats and tubing of the hydration system.

The dismantling and sampling operations[3] began on October 19th, 2012 and were finished on February 1st, 2013 (approximately a period of 100 days). The dismantling has not been complete: the canister, concrete bed, a length of 80 cm of the bentonite blocks and 120 cm of the GBM have been left on place as a demonstrator for the visitors of the EB experiment concept.

AITEMIN and CIEMAT have performed the sampling and most of the identification and hydromechanical analyses of the bentonite (GBM and blocks) while other organizations (BGR, NAGRA and ANDRA) have performed additional tests (such as microbiological and gas permeability).

3.2 PREVIOUS WORKS

Related with and as backup of the dismantling objectives, before the beginning of the work the following previous investigations were also performed:

- In August 2011, drilling of two horizontal pilot boreholes through the concrete plug and into the saturated GBM; in order to obtain samples of the GBM, perform geoelectrical and ultrasonic measurements and to try to carry out an hydro test. The description and results of this task are reported in the Deliverable D2.1-1.

- In July 2012, the seismic monitoring was resumed to assess the rock and barrier changes during the dismantling (Deliverable D2.1-6).

- In September 2012, a geoelectrical circular profile was reactivated, to evaluate the rock and bentonite barrier states (Deliverable D2.1-9).

3.2.1 Horizontal boreholes

The two horizontal pilot boreholes (BEB-PB1 and BEB-PB2) were drilled in August 2011 with their mouths at the points B1 and B2 on the concrete plug face shown on Figure 3.

The BEB-PB1 reached a length (borehole depth) of 4.24 m; and the BEB-PB2 of 4.19 m. The first one was planned for sampling the bentonite barrier and to perform geoelectrical and ultrasonic measurements. The second one was drilled for an hydrotest (although it could not be performed, see comments in a following paragraph).

---

[3] AITEMIN has been in charge of the works.

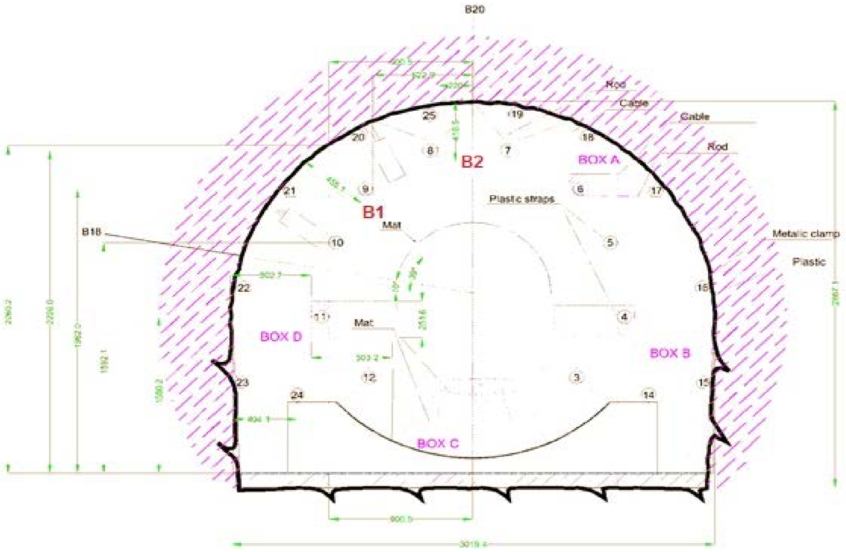

Figure 3: Borehole mouths (B1 and B2) of the boreholes BEB-PB1 and BEB-PB2

Drilling was done with a Hilti equipment operated by BGR staff; and diameters ranging from 112 to 86 mm. Sampling of the bentonite was tried pushing a Dames & Moore sampler. The GBM was more resistant and sticky than expected, and also the borehole walls were affected by the drilling (warming and drying out). In consequence, it is believed that the seven bentonite samples taken (M-1 to M-4 and B-1 to B-3) in borehole BEB-PB1 cannot be considered undisturbed: most probably, they dried out to some extent and were artificially compacted due to the drilling and sampling operations. Hydraulic tests were done at the CIEMAT laboratory with six of these samples, and values of the hydraulic conductivity[4] ranging from 9.3×10^{-12} to 3.1×10^{-13} m/s obtained (average value = 2×10^{-12}); but these results should be taken with caution due to the suspected sampling disturbance.

Nor the planned hydrotest could be performed in borehole BEB-PB2. After installing the designed casing with a packer system and a filter section inside, the expected convergence of the borehole wall, closing the gap bentonite-casing, did not occur (the borehole diameter remained rather stable during several months); and the hydro testing had to be cancelled.

On the contrary, the geophysical measurements in borehole BEB-BP1 could be done properly because the techniques used allow to "look behind" the disturbed wall thickness. In the following Figures 4 and 5 the results of the two geoelectrical measurements carried out are shown.

---

[4] See Table 2 of Deliverable D2.1-1.

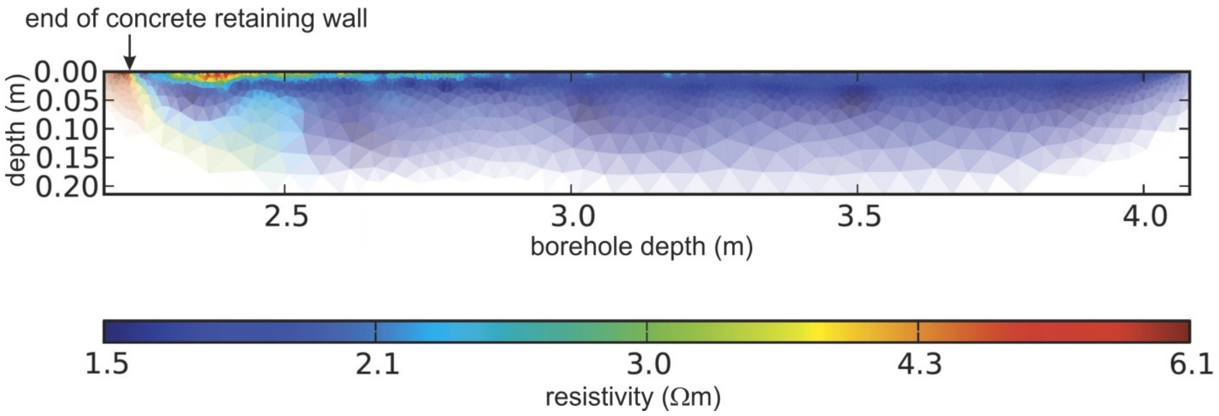

Figure 4: Inverted resistivity. BEB-BP1 first measurement (downwards)

In Figure 4, the concrete wall is clearly marked with higher resistivity values (>20 Ω m). Up to 2.9 m depth, a small zone of higher resistivities was detected: it can be interpreted as the borehole damaged thickness. Behind 3 m, the medium (GBM) looks very homogeneous.

Figure 5 shows the inversion results of the second measurement, displayed with a smaller resistivity range than the one of the first measurement. The borehole damaged zone is clearly detected and has a thickness of approximately 2 cm into the GBM. On the other hand, the undisturbed GBM is characterized by resistivities below 2 Ω m.

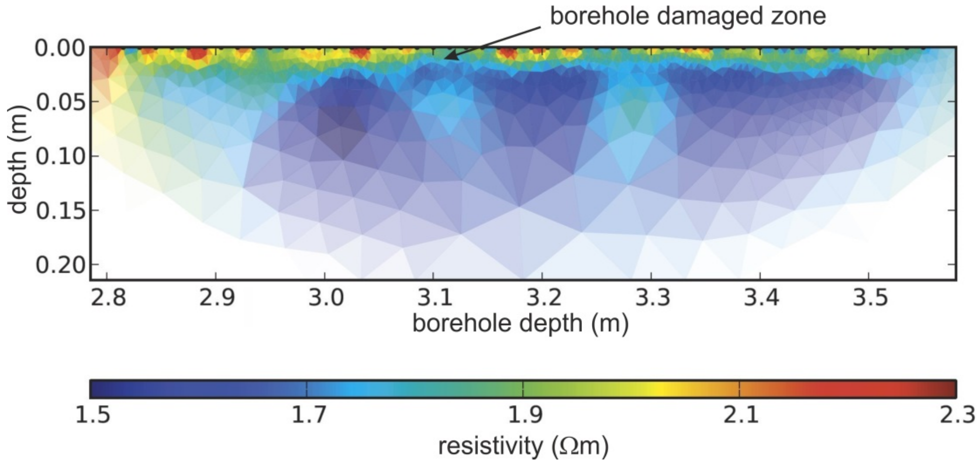

Figure 5: Inverted resistivity. BEB-BP1 second measurement (downwards)

Representative results of the two ultrasonic measurements (performed with a 5-hour difference) are shown on Figure 6.

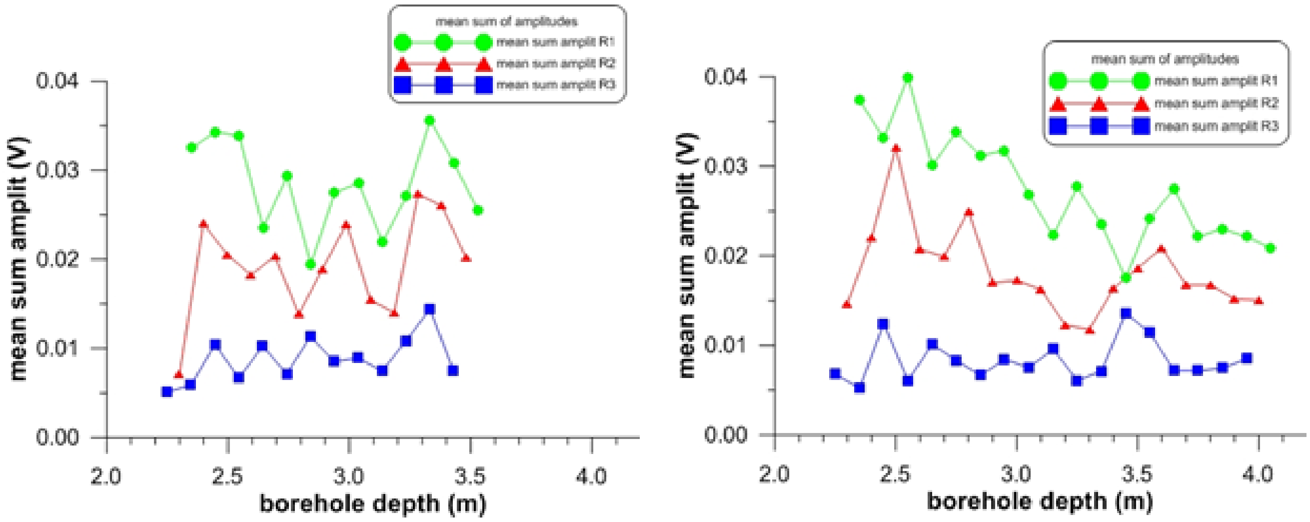

Figure 6: Arithmetic mean of the sum of amplitudes for different emitter – receiver distances (green: R1, red: R2, blue R3). Left: B data (morning). Right: C data (afternoon).

There are remarkable differences between the morning and afternoon data, implying noticeable changes in the BEB-BP1 borehole wall. The derived borehole disturbed zone (BdZ) corrected ultrasonic velocities seem to be reasonable when comparing them with seismic data registered eight years before during the initial phase of the GBM saturation. Moreover, according to the ultrasonic measurements in this borehole, the GBM appears quite homogeneous, with only some small lateral changes.

3.2.2 Seismic monitoring

A phase II of the seismic monitoring was initiated in July 2012, using the piezoelectric transducers installed for the Phase I of this monitoring in year 2002: twenty in the Opalinus clay (in four boreholes, about two meters long, and a distance of 1 m to each other at the corners of a square) and four in the GBM, at a distance of 20 cm of the rock surface. The previous Phase I of the seismic monitoring was concluded in December 2003, having reached the conclusion that the EDZ of the rock was self-sealing after about 1.5 years of the bentonite barrier hydration process.

The time span between the end of Phase I and the start of Phase II has been approximately 8.6 years. According to the new measurements of Phase II, obtained some months before the dismantling operation start, in this time span an increase of the seismic P-wave velocities in the rock near-field of approximately 10% did occur. This higher seismic velocity in the rock probably is due to the slow bentonite swelling pressure growth applied on the bentonite-rock interface.

On the other hand, it should be pointed data that two of the transducers (emitters) placed in the GBM could not be reactivated for the Phase II, and then only seismic measurements in the Opalinus clay are available in this phase.

3.2.3 Geoelectrical circular profile

A geoelectrical profile (see Figure 7) previously installed (year 2001) in the rock surface after the EB niche excavation was reactivated, to assess the spatial resistivity distribution just before the EB dismantling operations.

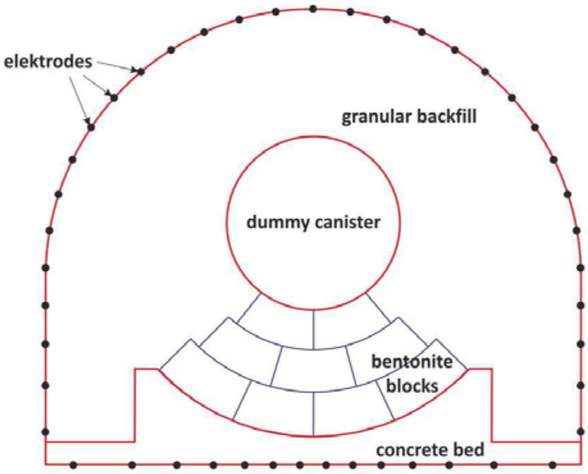

Figure 7: Electrode positions of the reactivated geoelectrical profile

On September 30th 2012, approximately three weeks before the start of the dismantling works, one geoelectrical measurement was done using this profile. The model of the spatial resistivity distribution deduced is shown in the following Figure 8.

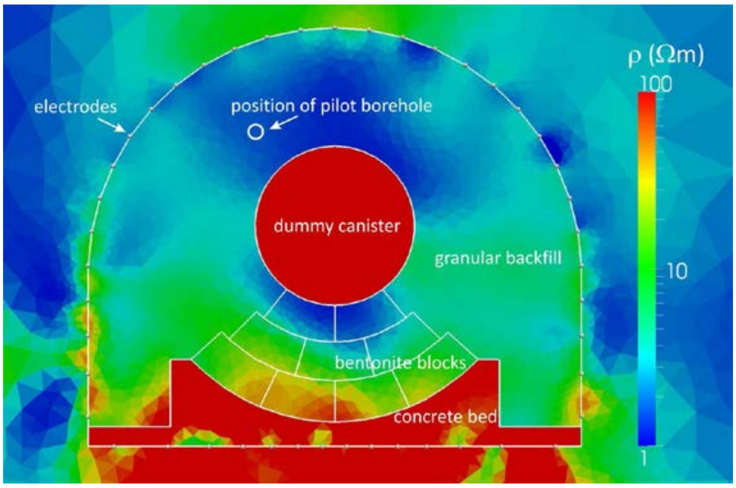

Figure 8: Model of the spatial resistivity distribution on September 30th 2012

The main conclusions obtained from this geoelectrical measurement are the following:

- The concrete elements and the dummy canister do appear as high resistivity structures (> 100 Ω m).

- The lowest resistivities (below 3 Ω m) are displayed above and directly below the canister.

- In the GBM, there is a resistivity vertical gradient, and the higher values in this material are recorded near the test section floor.

- No contrast has been detected between the original bentonite blocks and the GBM.

The results are also coherent with those previously obtained at one of the horizontal boreholes (see Figures 4 and 5).

On the other hand, according to calibration laboratory tests performed with bentonite samples (see following section 4.4.2), the higher the resistivity the higher the water content. In these laboratory tests (performed without confinement) it could be deduced that for electrical resistivity values higher than 1.8 Ω m, the water content of the bentonite is in general greater than 40%.

3.3 CONCRETE PLUG DISMANTLING

After protecting the existing Data Acquisition System (DAS) and the seismic cables, and the removal of the water tank formerly used for the hydration, the breaking up of the concrete plug (2.2 m thick including the inner initial retaining wall) began on the 23rd of October, 2012. The hydraulic splitter method was selected for this task. It consists of drilling with a pneumatic hammer horizontal boreholes in the concrete (diameter ≈ 55 mm) around an initial bigger diameter hole (200 mm), previously drilled using water as refrigerator in most of its length (2.5 m), and acting as an inner free surface (see Figure 9). Then, a DARDA hydraulic splitter was introduced in the boreholes (the distance between them was no longer than 30 cm) to break the concrete, towards the big-diameter hole.

The dust from the drilling was collected by an industrial vacuum cleaner, and the concrete debris in big bags, transported with a forklift to a dump near the Mont Terri Site main entrance.

After the first days of the work, it was found that due to the high resistance and toughness of the concrete, the initially planned method had to be complemented using an additional pneumatic hammer operated by a small backhoe. Doing so, the bentonite face was reached on the 14th of November, through a relative small area (see right picture below, Figure 9).

Figure 9: Plug dismantling process (holes around the main one and bentonite reached)

After reaching the bentonite and beginning its digging, the plug breaking up continued, now with the help of expansive cement poured in holes drilled along the lateral faces of the opening of the plug. The effects of the expansive cement were noticed after ~72 hours, and the concrete plug removal continued using also hand tolls (such as a Hilti percussion hammer, a mallet and a pick). Although initially it was planned to completely remove the plug, finally it was decided to leave in place approximately one third of its right half, as part of the demonstration for visitors of the EB experiment.

Wet areas were observed in the lower part of the plug during the dismantling.

Concrete samples were collected and its water content measured on-site (see following sections 3.5.2 and 4.2).

3.4 EXCAVATION AND SAMPLING OF THE BENTONITE

3.4.1 Methodology

The removal of the bentonite began on the 14th of November 2012; using hammers (geologist and electric percussion ones), with a flat-end bit tool to extract irregular pieces of GBM; or a pointy bit, when removing the bentonite blocks (as whole pieces) underlying the canister (see Figure 10).

The bentonite removal was done with a team of two people, trying to keep the excavated face as much parallel as possible to the original plug. The average progress of the removal was of around 25 cm per day.

It was observed in the first days a relatively fast drying process in the bentonite front; so, it was decided to place a protection plastic after every working day. (see Figure 11). When the work had to be interrupted more than two days, it was tried to keep the following sampling section as far as possible form the working face, leaving at least 30 cm of thickness from the face till the next sampling section.

Figure 10: Removal of GBM and bentonite blocks

Figure 11: Drying of bentonite (after 5 days) and plastic for protection

As the dismantling moved forward, auxiliary elements of the experiment such as hydration pipes, sensors, and casing from the horizontal boreholes were also removed. Bentonite debris was collected in big bags and transported to the dump site.

After finishing the planned removal of the bentonite (end of January, 2013), the remaining one for the demonstrator was covered with a plastic, to keep its humidity as much as possible (see following Figure 12).

Figure 12: Bentonite (blocks and GBM) and canister left in place for future demonstrator

3.4.2 Final canister support

A custom-made metallic beam was manufactured for the final support of the canister, and placed at the end of the dismantling works. Previously, temporary auxiliary support elements, such as metallic extensible rods and a sawhorse were used. The final metallic beam was welded to the front face of the canister and fixed to the floor as well as to the concrete bed. Also, as extra safety measure, two metallic sawhorses were placed along the concrete bed below the canister (see Figure 13).

Figure 13: Final metallic beam and sawhorses supporting the canister

3.4.3 Bentonite sampling

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 14.

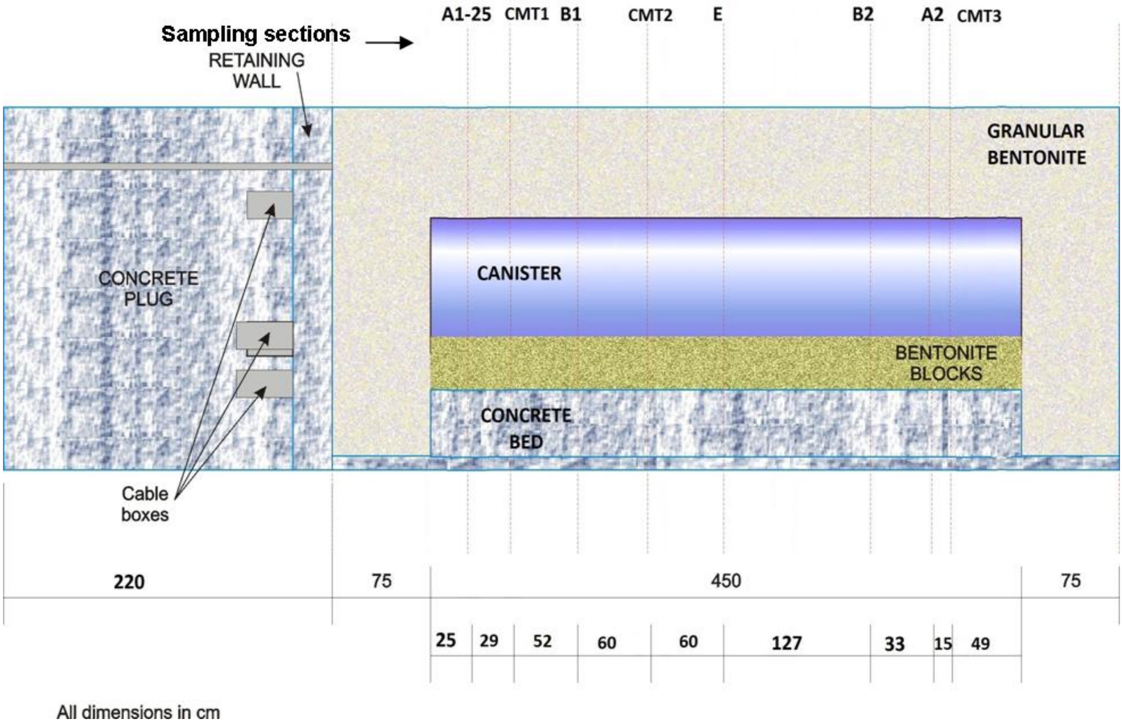

Figure 14: Position of the bentonite sampling sections

For the sampling, it was first tried to push into the bentonite (with the help of a backhoe or with a rotating crown attached to a Hilti machine) a steel tube of 38 mm in diameter, but this procedure did not work properly, due to the resistance and high plasticity of the material, and to the sample disturbance by the heat generated during the rotation. Then, it was decided to use flat-end hammers to extract less-disturbed samples of GBM (although irregular); of approximately 300 g for the on-site analyses and weighting over 500 g if possible for the ones sent to the external laboratories. The bentonite blocks sampled were removed as whole pieces if feasible.

The location of the samples in each sampling section is shown on the following Figures 15 thru 22.

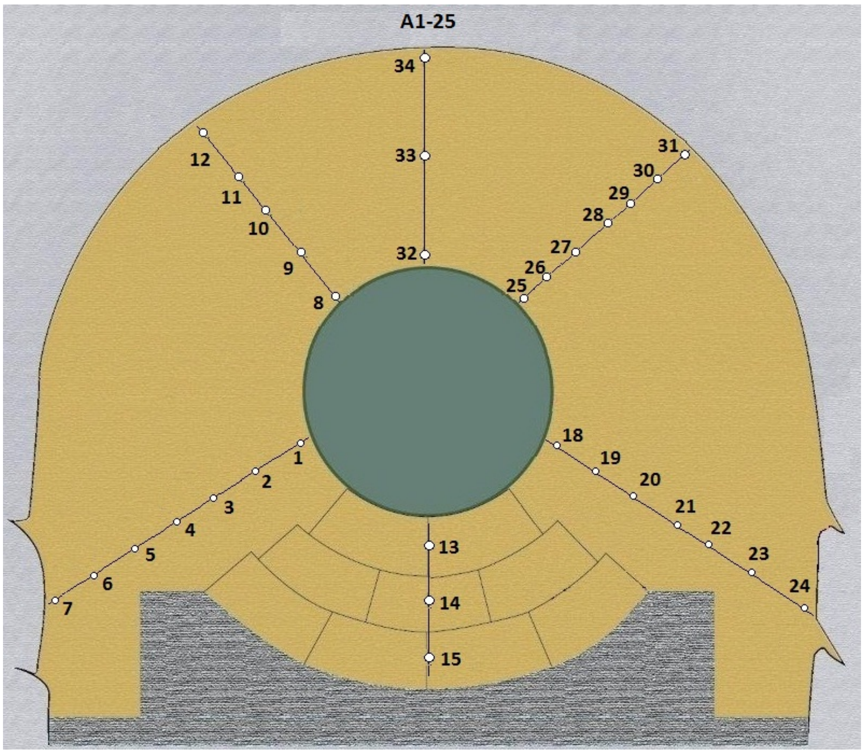

Figure 15: Samples in section A1-25

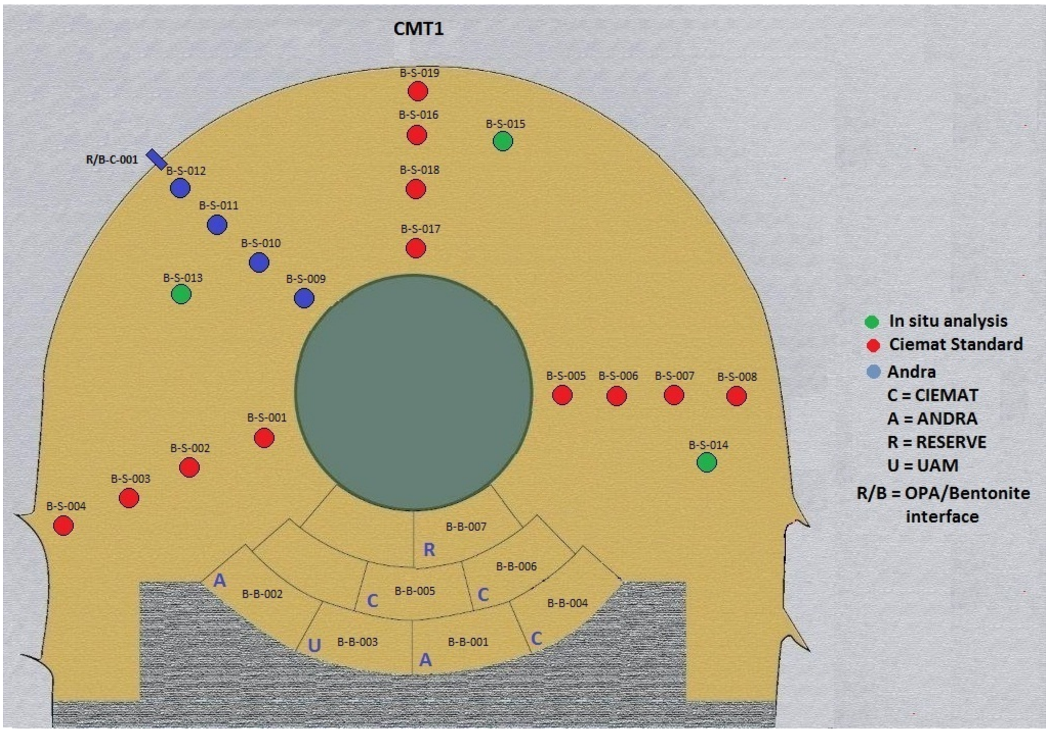

Figure 16: Samples in section CMT1

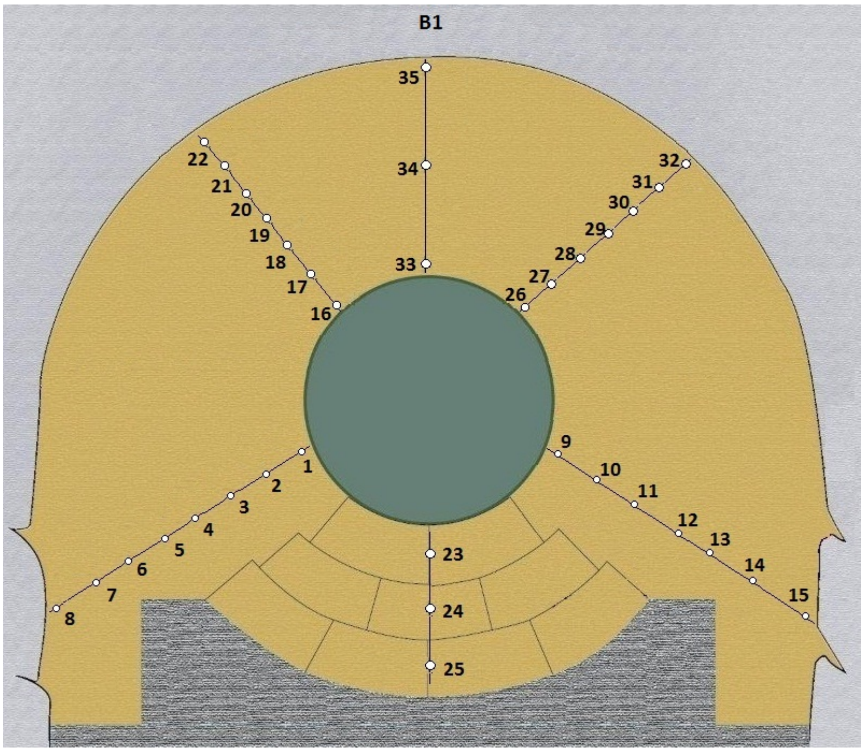

Figure 17: Samples in section B1

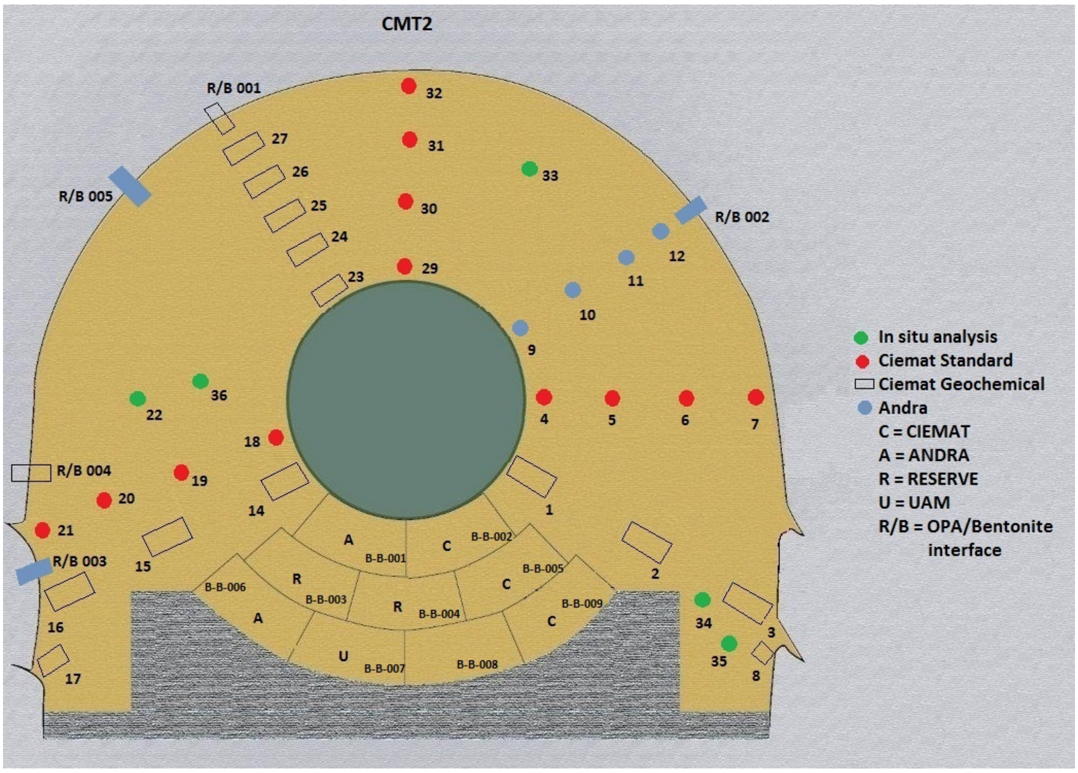

Figure 18: Samples in section CMT2

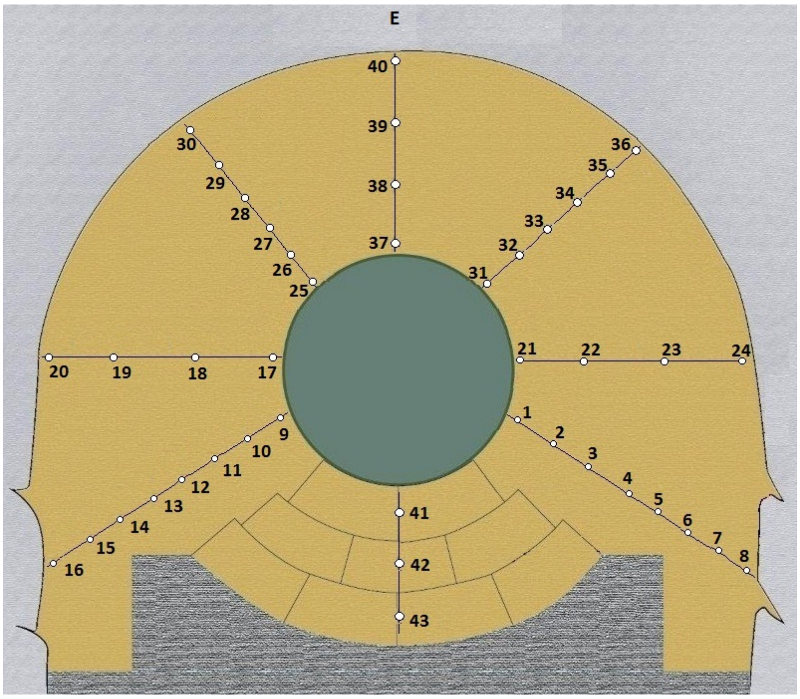

Figure 19: Samples in section E

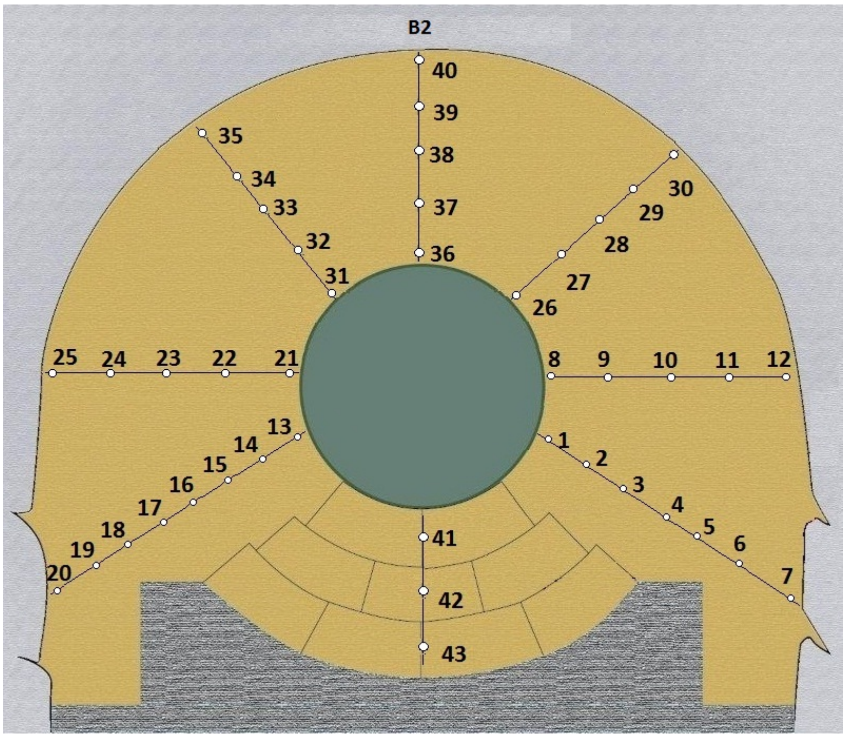

Figure 20: Samples in section B2

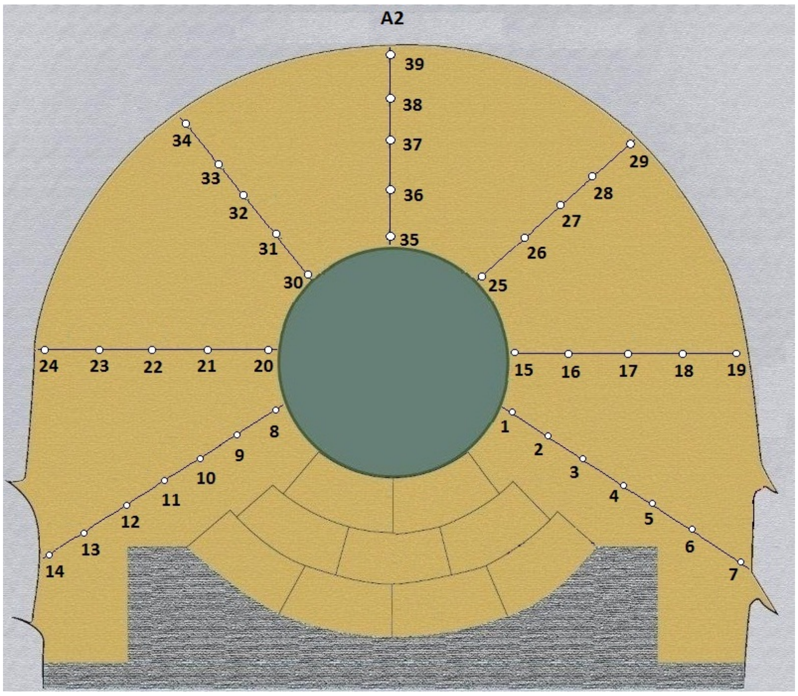

Figure 21: Samples in section A2

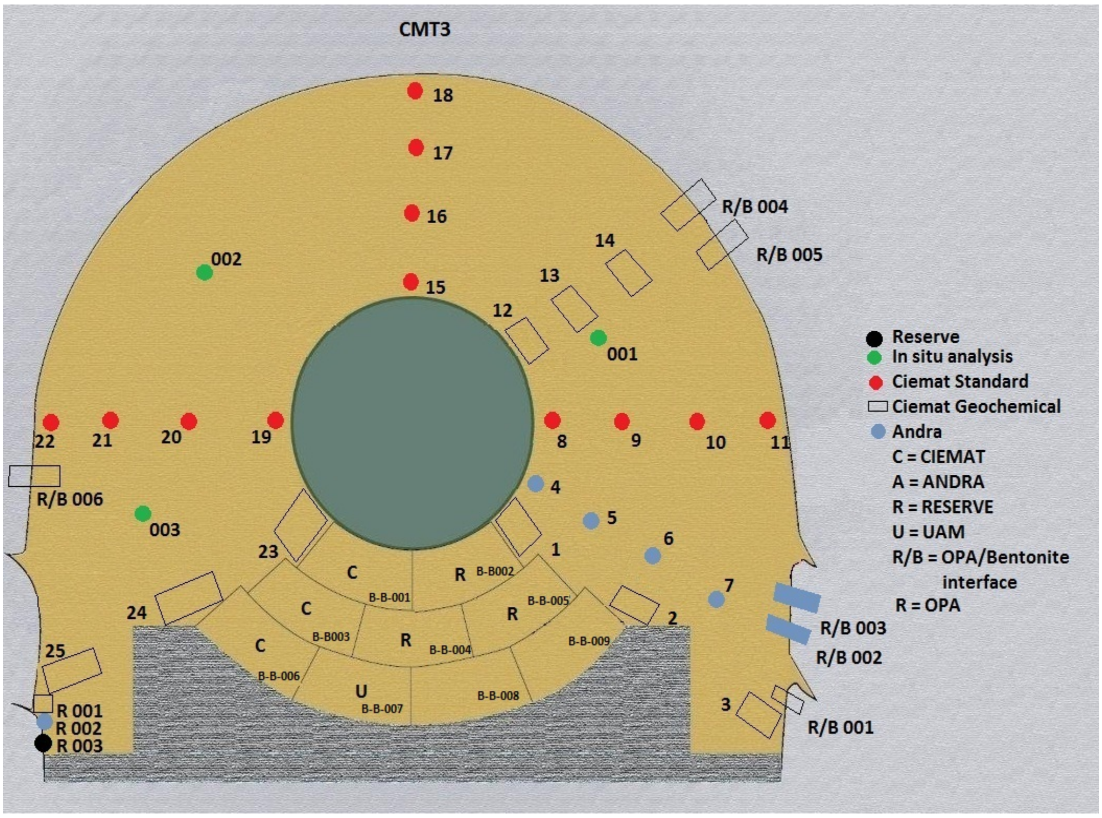

Figure 22: Samples in section CMT3

Every sample was immediately measured and weighted after the collection. The ones to be sent to the different organizations were packed in wooden boxes for their transport.

3.5 REMOVAL AND SAMPLING OF OTHER ELEMENTS

3.5.1 Removal of the DAS

The Data Acquisition System (DAS) was disconnected at the last moment of the dismantling works, in order to have data from as many sensors as possible during the operation. The cables of the sensors were cut as close as possible to the data logger cabinet, and then the computer cabinet was also disconnected. Both cabinets were packed and sent to AITEMIN.

3.5.2 Sampling of the concrete elements and water

Samples from the concrete elements (plug, retaining wall and bed) were taken. The positions of the samples from the plug and wall (taken with the tools used for the dismantling) are shown in Figure 23. They were irregular and between 75 and 150 cm^3 in volume. Samples from the bed were taken using a circular saw.

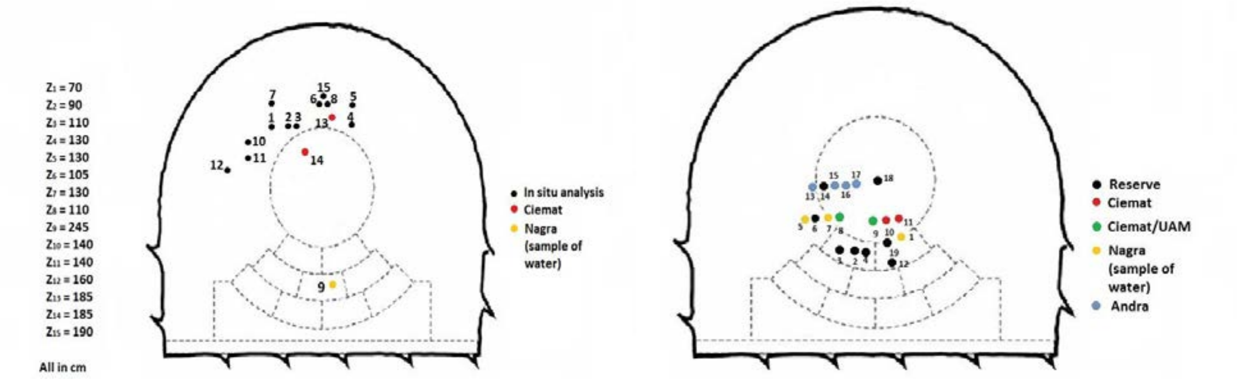

Figure 23: Samples form plug (left) and retaining wall (right)

The "z" coordinate in the plug (centimetres) is measured from the defined origin of coordinates, located on the floor, and in the centre of the original outer face of the concrete plug.

Most of these concrete samples were used for on-site analysis (moisture content), although some of them were properly packed and sent to external laboratories.

Also, in Figure 23 it is indicated the collection of samples of water, taken from the hydration pipes, behind the inner retaining wall face.

3.5.3 Sampling of interfaces

Twenty samples of the retaining wall-bentonite interface were taken, using a rotating coring equipment and a steel pipe; or in blocks (with the help of hand tools and then cutting the block in several pieces).

Also, sixteen samples of the Opalinus clay-bentonite interface were collected, pushing a steel pipe into the bentonite and then coring the rock with a rotating device. Each sample was packed as a whole one keeping the interface in contact.

3.5.4 Sampling of sensors and other elements

Twenty sensors (such as extensometers, hygrometers and pressure cells) and their cables were recovered and sent to the external laboratories as planned. The cables were cut as far as possible from the body of the sensors. In some cases, a change in color in the bentonite around the sensor was observed, due to slight corrosion (not significant). Besides, the welding points to attach in section E the pressure cells to the canister were affected by some corrosion, with corrosion stains also on the geotextile surrounding the sensor.

Finally, seventeen samples of other auxiliary elements of the experiment such as pieces of the geotextile mats and tubes of the hydration system were collected.

4. POST-MORTEM OBSERVATIONS AND ANALYSES

4.1 GENERAL ASPECTS

The visual aspect of the bentonite barrier all along the dismantling work was homogeneous and no risks of slide failures in the excavated bentonite front were appreciated. Also, the newly exposed rock massif of the test section seemed visually to have kept intact its physical properties. The other auxiliary elements of the experiment (pipes, cables, geotextile, etc.) were in good conditions. The geotextile always looked clean, with no intrusions of bentonite. Only small stains were observed in the sensors: the corrosion effects on metallic elements can be considered negligible.

One of the main objectives of the EB dismantling has been to determine the dry density and moisture content of the bentonite barrier. Unfortunately, due to the unavoidable time lags during the sampling operations, prior to the actual sampling collection and analysis, some small changes in the bentonite state could not be avoided and should be kept in mind when assessing the available analyses results.

Specifically, visual observations indicated that the excavated front of the bentonite dried relatively quickly, with a noticeable effect in 1-2 days after exposure. Moreover, tests were done on-site in order to evaluate the impact in the analysis results of the time spent handling the samples. A big bentonite sample was taken and divided in seven subsamples; and water content measured after 2, 15, 30, 60, 120, 240 and 360 minutes.

The average results are presented in the following Figure 24.

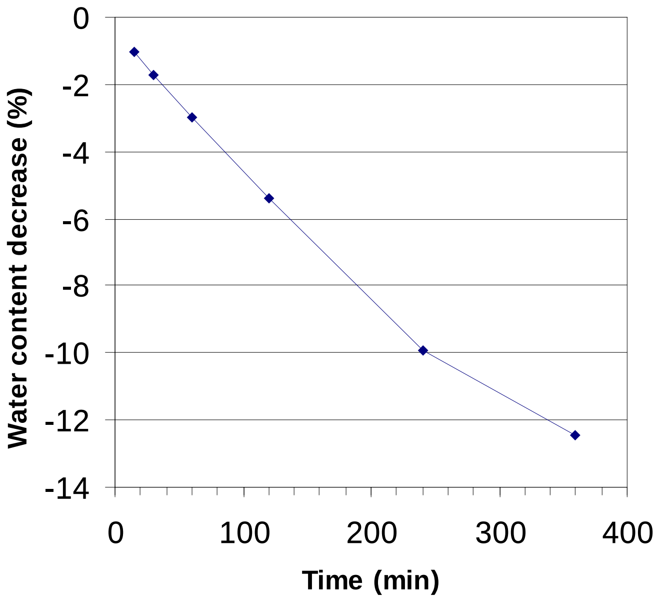

Figure 24: Time evolution of the average water content decrease (after sample collection)

These results show an average water content loss of 1.2% after 20 minutes of sample exposure to air conditions. This is the approximate time period spent trimming and handling the samples to be analysed on site.

On the other hand, during the dismantling, some expansion of the bentonite barrier along the longitudinal axis of the test section (z axis) did occur, also related with the decreasing trend of the recorded values by the total pressure cells as the dismantling work was advancing (see Figure 25).

Besides, related with the former, canister movements have been observed during the dismantling operation. Specifically, during this operation the canister did move approximately 4 cm in the longitudinal direction. Also, an uplift of the canister of around 3 cm has been registered. This uplift occurred when the digging of the GBM was in advance respect to the bentonite blocks removal: those left in place swelled and the distance from the canister centre to the floor (previously measured at the beginning of the dismantling) increased.

This bentonite swelling (also unavoidable) occurring before carrying out the analyses could also affect their results, as the obtained dry density values probably are minor to some extent (not quantified) than the actual values of the undisturbed barrier.

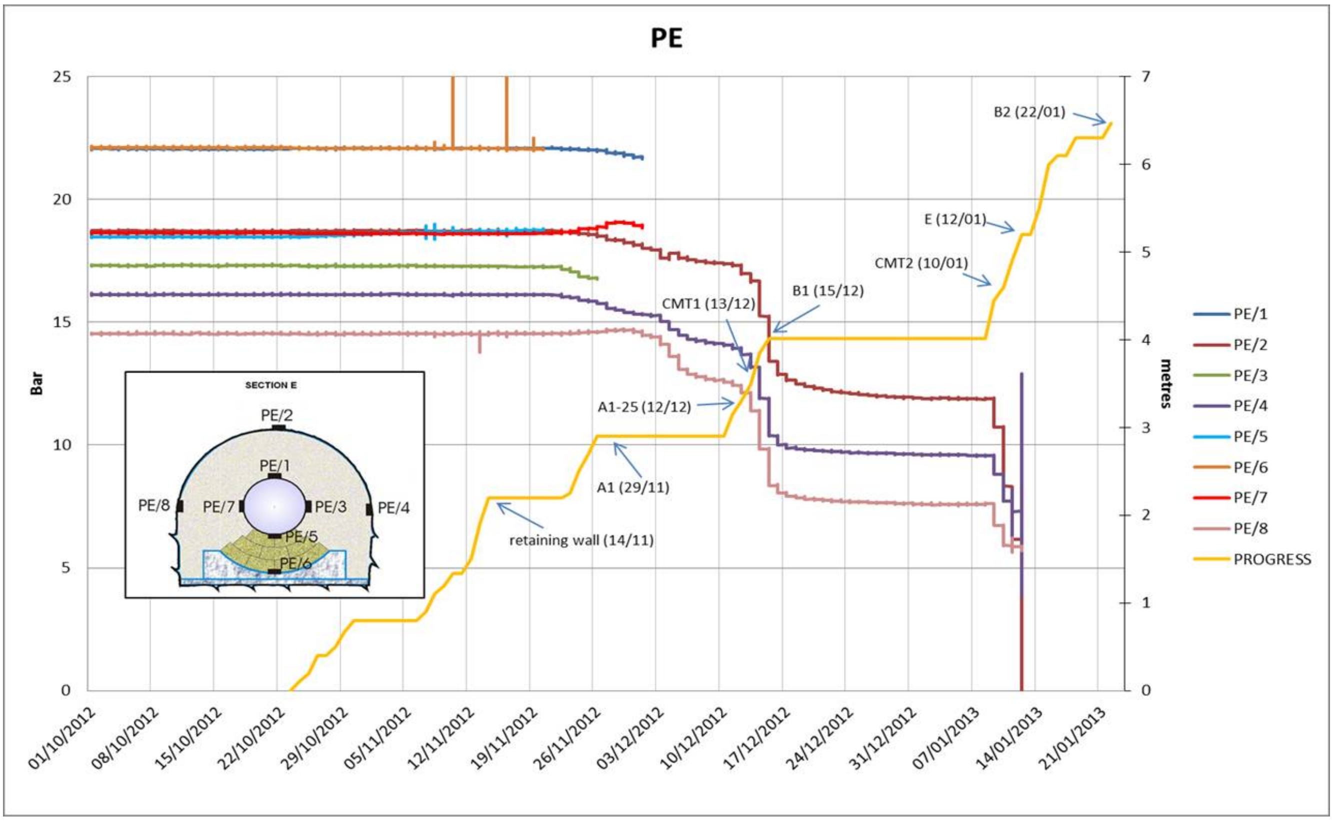

Figure 25: Total pressure decrease as dismantling was progressing

As explained in more detail in Deliverable D2.1-4, it is proposed as tentative correction of the on-site analysis results to raise by 1.2% the obtained water content values, and to recalculate accordingly the degree of saturation deduced values (while keeping without correction the obtained in the analyses dry density values).

4.2 ON-SITE TESTS

A field laboratory was installed (see Figure 26) in a clean and ventilated area close to the EB experiment site, with the needed items (oven, balances, mercury, cutting tools, etc.) to perform water content and dry density determinations with concrete and bentonite samples, as soon as possible after their collection.

Figure 26: On-site laboratory

Water content values were obtained in twelve concrete samples from the plug. They range from 3.9 to 4.7% (average value = 4.4%). It can be concluded that the plug was fully saturated.

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.

The results of all the on-site analyses are presented in detail in the deliverable D2.1-4. As they were progressing, it became clear that the bentonite samples from the lower parts of the test section were wetter and with dry densities lower than those collected in the upper parts. Also, the water content tends to be higher and the dry density lower in the sections farther away from the plug. As a representative summary of the on-site results, Table 1 shows the average water content, dry density and calculated degree of saturation (without the correction for sample drying during handling) for five of the eight sampling sections[5]. The average values are grouped according to the test section part (lower, intermediate and upper) and the original type of the bentonite (GBM and blocks).

---

[5] In sampling sections CMT-1, CMT-2 and CMT-3 only 5 or 3 samples were taken for on-site analyses, and are not included in Table 1.

Position		Amount of samples	Water content (%)	Dry density (g/cm^3)	Degree of saturation (%)
A1_25	GBM Lower	14	36.8	1.32	95
	GBM Upper	15	31.8	1.42	96
	Blocks	3	34.4	1.33	90
B1	GBM Lower	15	40.0	1.29	99
	GBM Upper	17	32.8	1.40	96
	Blocks	3	34.0	1.38	96
E	GBM Lower	16	39.8	1.28	96
	GBM Intermediate	8	35.4	1.35	95
	GBM Upper	16	34.0	1.38	96
	Blocks	3	33.0	1.38	93
B2	GBM Lower	15	41.5	1.26	98
	GBM Intermediate	10	37.2	1.32	96
	GBM Upper	15	33.9	1.39	96
	Blocks	3	34.4	1.36	94
A2	GBM Lower	14	41.9	1.24	96
	GBM Intermediate	10	37.5	1.31	96
	GBM Upper	15	34.0	1.38	96

Table 1: Average values of the on-site analyses

Without correction for the sample drying during handling the mean value (all on-site results) of the water content is 36%; and of the dry density 1.34 g/cm^3. Then, assuming G = 2.70, the calculated mean degree of saturation would be 96%.

In general, no relevant saturation differences have been detected between areas in the same section or between sections. Also, the GBM and the blocks had become relatively homogeneous. In fact, due to the blocks swelling along the experiment (and partly during the dismantling) their original dry density (1.69 g/cm^3) had decreased to values ranging from 1.30 to 1.39 g/cm^3 (average = 1.36 g/cm^3).

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, although the calculated degrees of saturation from the CIEMAT’s results tend to be slightly higher than those from the on-site analyses (see details in Tables 6, 11 and 13 of deliverable D2.1-4).

On the other hand, if the effect of sample drying during handling is taken into account, the degree of saturation might be reasonably corrected. It is proposed (see former section 4.1) as correction to assume that the actual water content is 1.2% higher than the obtained values in the on-site analyses. Doing so, the calculated degrees of saturation increase between 2 and 4 points in percentage. In the following Figures 27 thru 31 interpreted isolines of the corrected calculated degree of saturation in five sampling sections are presented (red numbers refer to the identification of the samples). These graphs have been elaborated with the Surfer mapping program and they should be considered only approximate.

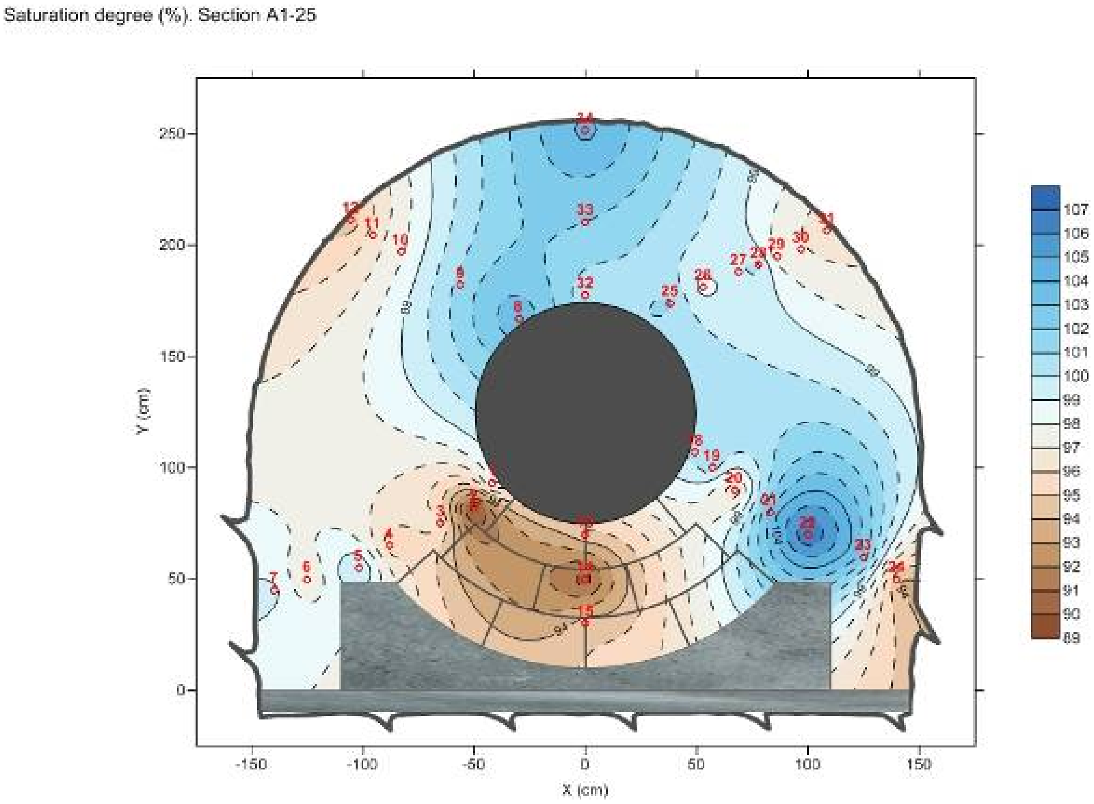

Figure 27: Isolines of the corrected degree of saturation (Sampling section A1-25)

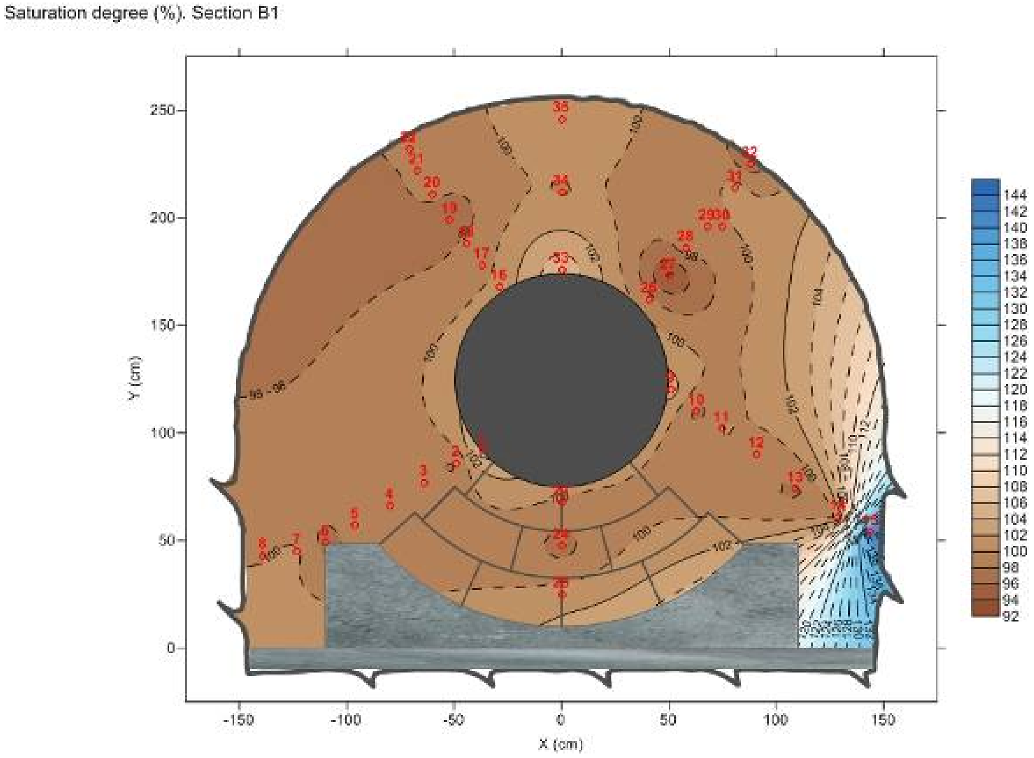

Figure 28: Isolines of the corrected degree of saturation (Sampling section B1)

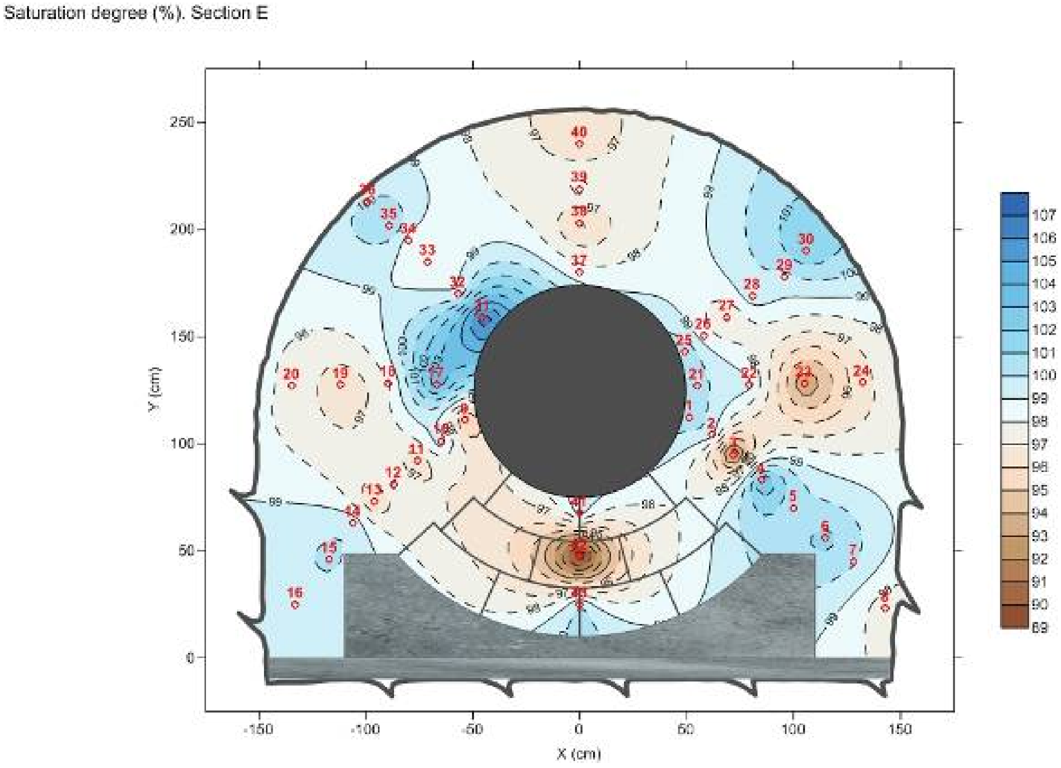

Figure 29: Isolines of the corrected degree of saturation (Sampling section E)

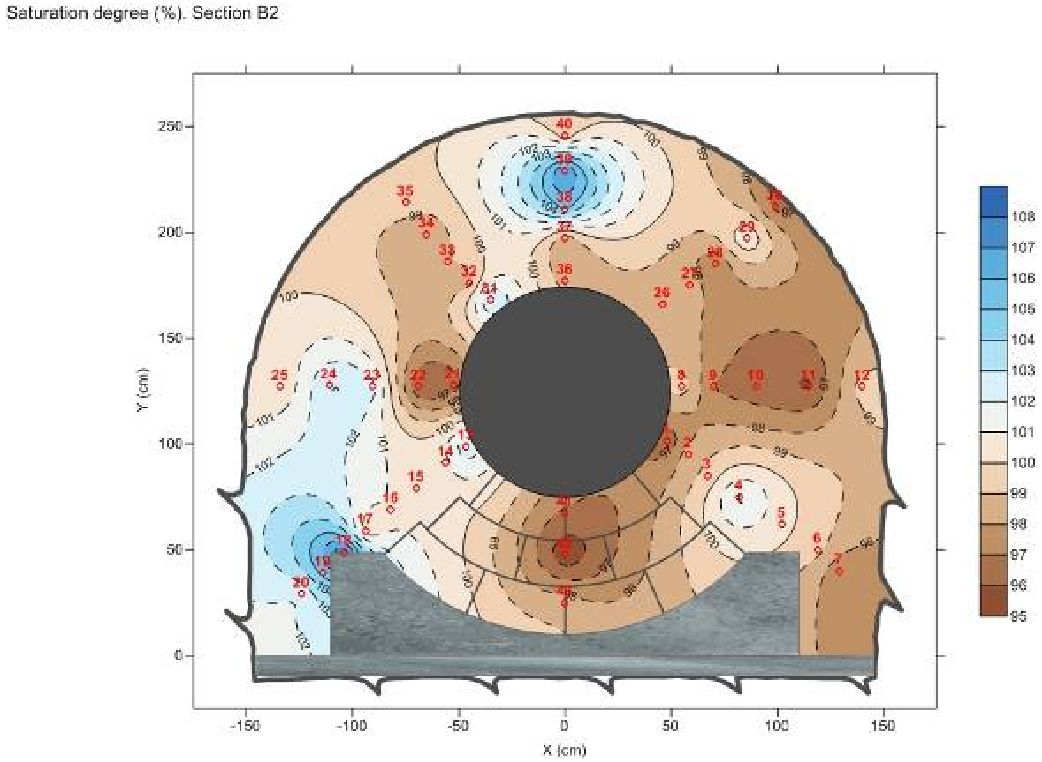

Figure 30: Isolines of the corrected degree of saturation (Sampling section B2)

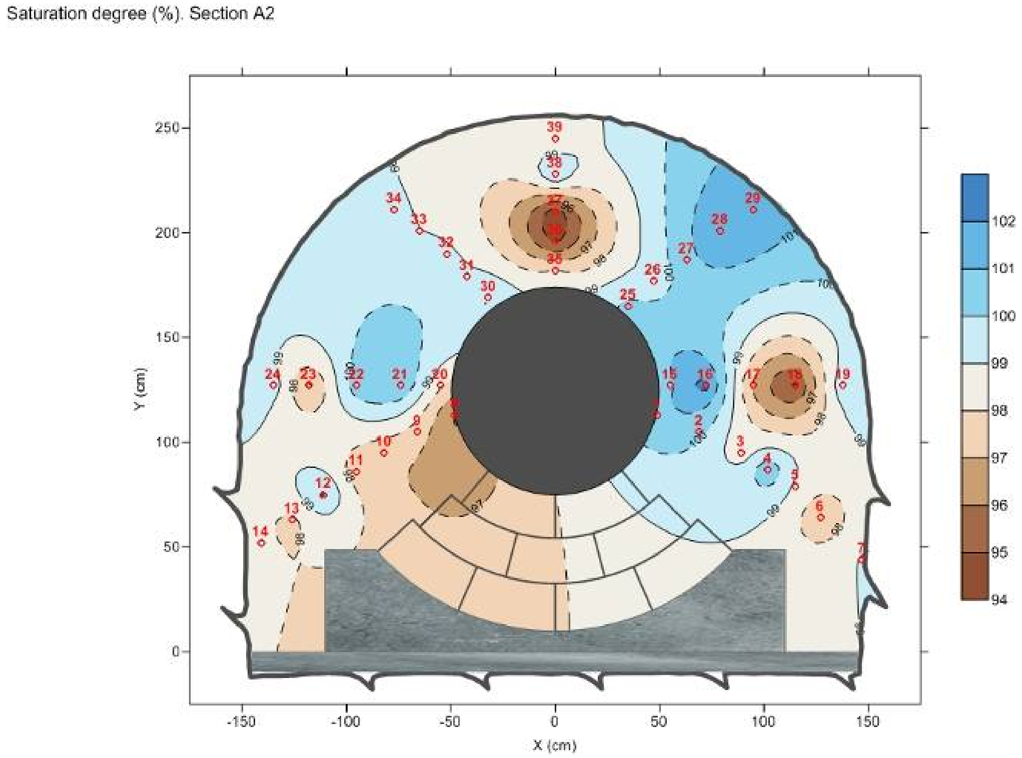

Figure 31: Isolines of the corrected degree of saturation (Sampling section A2

4.3 EXTERNAL LABORATORY ANALYSES

4.3.1 General

Samples of the GBM (166), bentonite blocks (18), concrete of the plug (2), interfaces (31), sensors (20) water (2), and of other auxiliary elements (17) have been sent to the laboratories of the following PEB's partners: CIEMAT, AITEMIN, BGR, UAM, NAGRA and ANDRA. Following, the analyses performed are summarized.

4.3.2 CIEMAT laboratory analyses

Most of the bentonite samples sent to external laboratories have been analyzed by CIEMAT (reported in the deliverable D2.1-7, and also in Villar 2013). They came from the sampling sections A1-25; CMT1; CMT2; E; B2 and CMT3; and were quickly packed and sent to CIEMAT facilities, where they were stored in a room which temperature range between 7 and 16^{o}C and the relative humidity from 70 to 90%. As in the on-site laboratory, auxiliary tests were first performed to assess the drying during the sample handling. In the CIEMAT's laboratory, the sample preparation for water content and dry density measurements usually took less than 20 minutes; and from the auxiliary tests could be concluded that the decrease of water content during sample handling generally ranges between 0.7 and 1.5%. This means that the calculated degrees of saturation can be up to 2% lower than the actual ones.

Besides, as part of the previous tasks in the laboratory, the dimensions of some of the bentonite blocks received were measured upon unpacking (they had also been measured on-site just after their dismantling). The comparison of the final block dimensions with the original ones shows[6] the following:

- The blocks have clearly swelled, both during the experiment life and also along and after the dismantling, when the test confinement (plug) was removed. The measurements of the blocks taken at the laboratory are larger than those performed on-site.

- The blocks closer to the concrete plug (section CMT1) swelled mainly in the longitudinal direction (up to 56%). Blocks from sampling sections CMT2 and CMT3 had swelled an average of 7% in the vertical direction, which confirms the canister uplift observed during the dismantling.

The laboratory analyses performed at the CIEMAT facilities are related to the physical state of the bentonite (water content, dry density, suction, pore size distribution and basal spacing), and to its thermo-hydro-mechanical behavior (thermal and hydraulic conductivities and remanent swelling

---

[6] See details in section 5.2 of Villar 2013.

capacity, after the saturation during the experiment). Following, the most significant findings from these analyses are presented.

Water content and dry density tests have been done on eighty three GBM samples (two specimens analyzed for each sample) and nine block samples (at least six specimens analyzed for each block). The obtained average values are presented in Table 2, grouped according to the sampling section part and type of original bentonite.

Position		**Amount of samples**	**Water content (%)**	**Dry density (g/cm^3)**	**Degree of saturation (%)**
A1_25	GBM Lower	7	37.2	1.34	99
CMT1	GBM Lower	4	37.5	1.33	99
	GBM Intermediate	4	35.9	1.36	98
	GBM Upper	4	33.4	1.42	99
	Blocks	3	35.4	1.36	97
CMT2	GBM Lower	5	43.0	1.24	98
	GBM Intermediate	5	36.6	1.35	98
	GBM Upper	5	33.4	1.41	98
	Blocks	3	34.7	1.38	98
E	GBM Lower	4	41.3	1.27	99
	GBM Intermediate	5	35.2	1.37	98
	GBM Upper	8	34.2	1.39	98
B2	GBM Lower	8	42.2	1.25	98
	GBM Upper	5	35.2	1.37	97
CTM3	GBM Lower	6	44.1	1.24	100
	GBM Intermediate	8	37.9	1.32	97
	GBM Upper	5	35.0	1.39	99
	Blocks	3	35.5	1.36	98

Table 2: Average water content and dry density values (CIEMAT laboratory)

The average water content values for the different GBM parts and blocks range between 33% and 44%; and for the dry density between 1.24 and 1.42 g/cm^3. Again, as on the on-site analyses, there is a clear trend for the water content of the GBM to increase and the dry density to decrease towards the lower part of the test section. The blocks had water contents similar to those of the immediately adjacent GBM, and dry densities also similar to the intermediate and upper parts of the GBM.

Taking all the available results from CIEMAT, the mean value of the water content is 37%, and of the dry density 1.34 g/cm^3; practically equal than those deduced from the on-site analyses (see previous section 4.2). Also, the calculated degrees of saturation (even without any correction for sample drying during handling) are high, as an average approximately equal to 98%.

Although the samples of bentonite were almost fully saturated, still they had some suction (remaining capacity to absorb distilled water). Measurements done in seventeen samples using psychrometers (other determinations done with capacitive sensors were considered not reliable enough) provided suction values ranging from 2.1 to 4.7 MPa.

According to the pore size analyses performed (45), except for some samples of dry density lower than 1.30 g/cm^3 a relevant percentage of the porosity (between 40% and 55%) is included into the microporosity size (diameter smaller than 7 nm). Besides, in the GBM samples a macropore family (sizes between 3 and 35 μm) had appeared, which did not exist in the original GBM pellets.

X-ray profiles were registered in forty seven samples to determine the smectite basal spacing. For most of the samples the basal spacing obtained indicate the presence of three water layers in the smectite interlayer space.

To evaluate the hydraulic conductivity (K) of the emplaced GBM (after its saturation) has been one of the main purposes of the EB experiment and its dismantling. The permeability tests (15) performed at CIEMAT do confirm that a GBM barrier, even if emplaced with relatively low average dry density (1.36 g/cm^3 in this experiment), has a low enough permeability. In general, the obtained values of K are equal or lower than 5×10^{-12} m/s, except one[7]. The mean deduced value of K is 2×10^{-12} m/s. (These tests were done with saline Pearson water, which slightly increases permeability if compared with tests done using deionised water.)

The thermal conductivity was measured on eight bentonite blocks and on twelve GBM samples. Due to the bentonite saturation, the obtained values are relatively high, ranging from 0.90 to 1.35 W/m·K.

After dismantling, the GBM has some swelling potential: in the four swelling tests performed, a maximum swelling strain value of 22.5% was obtained. Other four swelling pressure tests were also performed, and the measured swelling pressures values ranged from 0.33 to 0.69 MPa.

---

[7] $K = 8 \times 10^{-12}$ m/s, obtained with a very low dry density sample (1.18 g/cm^3), less representative of the overall barrier.

It is also worth to note that, after the additional water intake along the permeability and swelling tests, in general saturation degrees higher than 100% (in some cases higher than 110%) have been calculated for the tested specimens (assuming that the pore water density is 1.00 g/cm^3).

4.3.3 NAGRA laboratory analyses

Sixteen samples from sections CMT1 and CMT2 were taken for microbial analyses (Stroes-Gascoyne et al., 2013), using sterilized Shelby tubes. They were packed in plastic bags (under N_2) and afterwards in Mylar bags under vacuum, and kept at 4^{o}C.

In the Environmental Microbiology Laboratory of the EPFL[8] the samples were cut into subsamples under anoxic and sterile conditions. No obvious drying or change in appearance was observed during sample storage.

At the EPFL laboratory, besides auxiliary tests such as water content and dry density determinations, cell culturing analyses (heterotrophic aerobic and anaerobic bacteria, and sulphate reducing bacteria) have been performed. Furthermore, subsamples were shipped on ice to the Whiteshell Laboratories of the AECL[9] in Pinawa (Canada) for water activity measurements.

The main results of these microbial analyses may be summarized as follows:

- The samples analyzed had water activities higher than 0.96.
- Relatively high culturability levels for heterotrophic aerobes have been obtained, from 2×10^3 to more than 4.5×10^5 CFU/g.
- Although there was evidence of discrete Sulphate Reducing Bacteria (SRB) growth, their culturable levels are generally low and similar to those naturally present in the Febex bentonite.
- The already observed in other experiments somewhat higher culturable levels near rock-bentonite interfaces had also been noticed in the EB experiment.
- The now obtained water activity results are comparable to previous ones for Wyoming MX-80 bentonite, with only small shifts towards higher values for the Febex bentonite (for similar dry densities).

---

[8] Ècole Polytechnique Fèdèrale de Lausanne, Switzerland.

[9] Atomic Energy of Canada Limited.

If low levels of culturable bacteria (e.g. 10^2 CFU/g) are desirable to lower the risk of microbially influenced corrosion, microbial evaluation may be required for any type of bentonite considered as potential buffer material; and its required dry density further assessed.

4.3.4 ANDRA laboratory analyses

Samples of the GBM and the blocks were sent to ANDRA, in order to perform with them laboratory tests at the Ècole Centrale de Lille. The complete results and findings will be reported in a Mont Terri Technical Note (in preparation). With the now available data, it can be advanced that the most relevant results and conclusions are the following:

- The GBM is well saturated. Samples near the interface with the Opalinus clay appear not affected by the proximity to the rock. Their degree of saturation is higher than near the canister. On the other hand, lower water contents have been measured, in the GBM in contact with the concrete retaining wall. All these results are consistent with those obtained on-site.

- In a GBM sample with a degree of saturation close to 100%, a swelling pressure of 1.4 MPa was measured after putting the sample in contact with water.

- Tentatively, on the same sample gas breakthrough pressure has been estimated. Discontinuous gas breakthrough at 1.05 MPa and continuous one at 2.05 MPa have been measured. Other tests will be performed to have a better estimation of this property.

- Four gas permeability tests have been done, under a confining pressure of 0.5 MPa. Three of them with GBM samples with high water contents (between 32% and 36%). Their measured gas permeability values were relatively low and homogeneous, ranging between 1.4 to 6.4×10^{-22} m^2. On the contrary, the fourth test was performed with a sample taken close to the concrete wall, with a lower water content (23.7%). Its measured gas permeability (7.4×10^{-18} m^2) is more than three orders of magnitude higher than the other values, due to the lower degree of saturation.

- Suction has been determined as a function of water content using several samples. The results are shown in the following Figure 32.

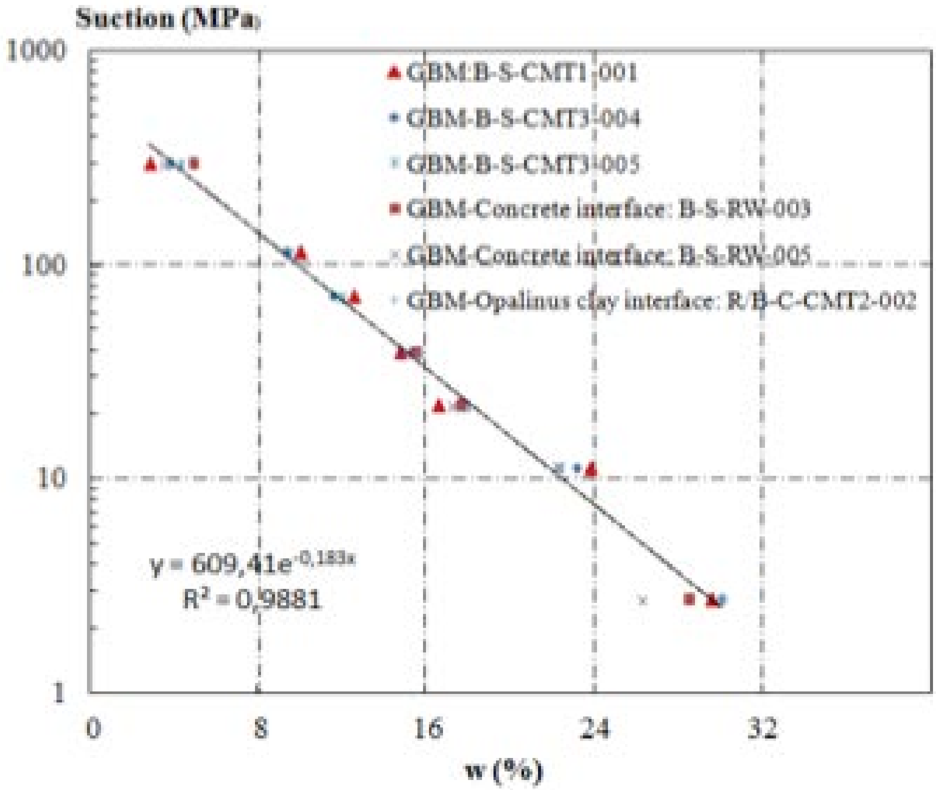

Figure 32: Suction versus water content (GBM samples)

4.4 GEOPHYSICAL DATA

4.4.1 Seismic data

Phase II of the seismic measurements began on July 12th, 2012; 134 days before the removal of the concrete plug of the experiment section. In Figure 33 the P-wave velocities (v_p) estimated between three pairs of emitters (E) and receivers (R) are shown. One of the pairs (E04-R03) it is located in the rock at a distance of 38 cm from the interface with the bentonite; and the other two at 138 and 208 cm. The dismantling was finished about 205 days after the start of Phase II.

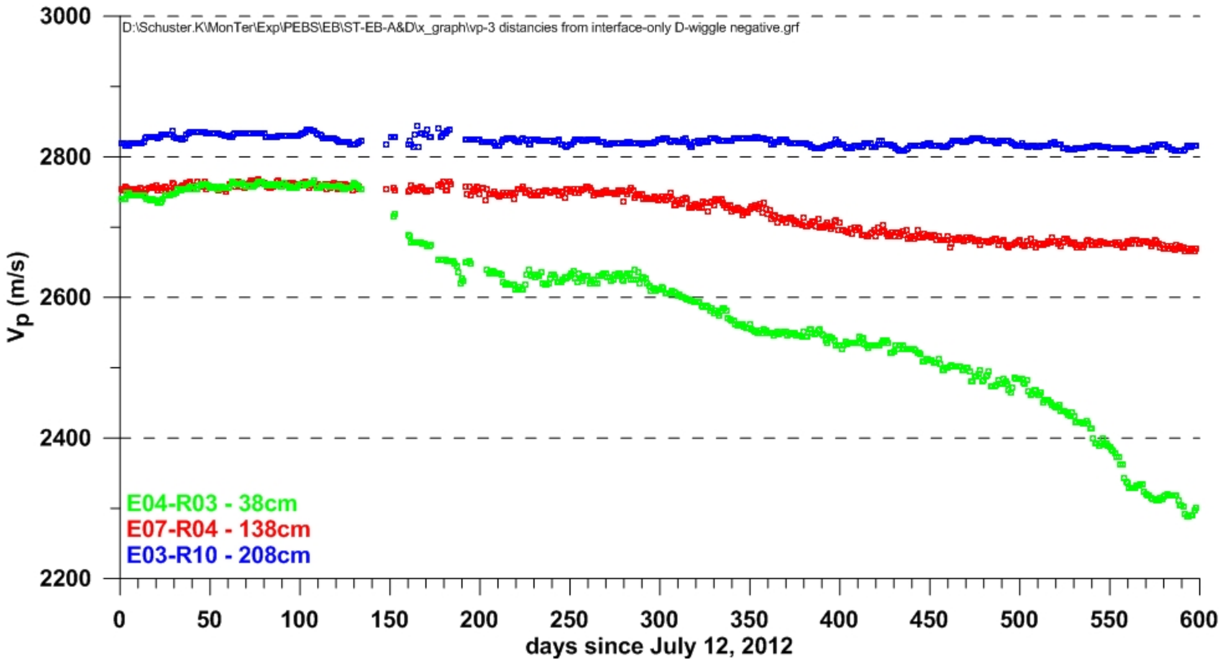

Figure 33: Velocities in the rock at three distances from the interface during the dismantling and afterwards

From the data shown in Figure 33, it can be deduced that the effect of the rock unconfinement due to the bentonite barrier removal it is clearly reflected in the v_P drop at a distance 38 cm from the rock surface; while the effect is much smaller at 138 cm; and almost negligible at 208 cm. It can be interpreted (as it could be expected) that after the EB experiment dismantling the rock state is practically the same as the one in the excavated niche before the bentonite barrier emplacement; including the gradual recreation of the initial EDZ.

4.4.2 Geoelectrical data

Six bentonite samples were taken during the dismantling in the section E and sent to the BGR laboratory, in order to calibrate the relationship water content-electrical resistivity. All of these samples were first fully saturated (without confinement) and then allowed to progressively dry at free air. The resistivity was measured at different stages. The results are shown in Figure 34. They confirm that resistivity increases as water content does.

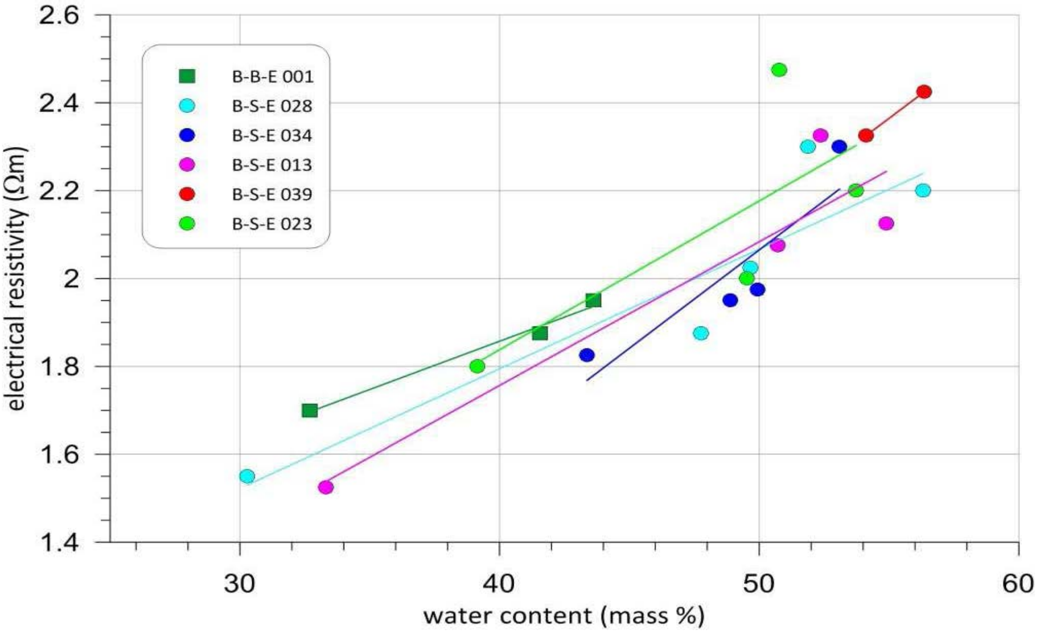

Figure 34: Electrical resistivity as a function of water content

On the other hand, after finishing the bentonite removal, the reactivated geoelectrical circular profile (see previous section 3.2.3) was used again for measuring the Opalinus clay electrical resistivity around the EB test niche. In Figure 35 the resistivity registered in the rock massif is shown, for two dates: February 16th 2013 (approximately half a month after the end of the dismantling) and May 23rd 2013 (about three months later).

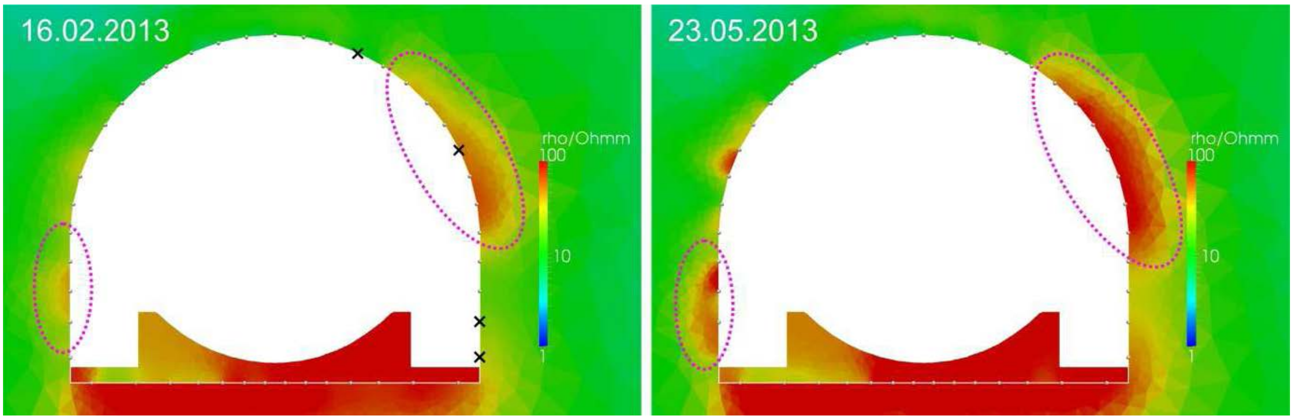

Figure 35: Electrical resistivity in the rock on February 16th (left) and May 23rd, 2013 (right)

The concrete elements (floor and bed) do appear as high resistivity structures. In the rock massif, and close to the newly exposed surface, two areas with higher resistivities (> 40 Ω m) were detected (denoted by dashed magenta ellipses in Figure 35). They might correspond to areas of high deviatoric stress that could enforce the formation of microcracks in the Opalinus clay.

5. MODELLING AND INTERPRETATION

5.1 GENERAL

Coupled numerical analyses have been performed by CIMNE-UPC (reported in deliverables D3.1-1 and D3.1-2), addressing the hydration and final state of the bentonite barrier in the EB experiment. The finite element computer code CODE-BRIGHT has been used, assuming isothermal conditions and consequently employing an hydromechanical (HM) formulation. Specifically, for the modelling of the GBM behaviour, a double structure approach has been adopted.

The details of the formulation and constitutive equations are included in section 3 of D3.1-1 and D3.1-2. The balances of water, gas, solid and momentum (equilibrium) are considered. The mechanical response of the bentonite blocks is described by the elastoplastic Barcelona Basic Model (BBM); while the hydro-mechanical response of the GBM during the hydration is modelled through a double porosity approach, considering that the total deformation has contributions by the microstructure and the macrostructure. This last one can be described by equations for unsaturated non-expansive soils. The microstructural behaviour is controlled by physico-chemical phenomena at clay particle level. It is assumed that microstructure is saturated and its deformation is reversible, volumetric and independent of macrostructural effects. The coupling between the two structural levels takes into account irreversible macrostructural strains when elastic microstructural strains occur. Furthermore, irreversible macrostructure deformations are assumed to be proportional to elastic microstructural strains according to interaction functions. On the other hand, the hardening law for the double-structure formulation considers the dependency of the saturated isotropic yield locus on the total plastic strain (arising from the activation of the loading-collapse yield curve and/or the micro-macro coupling).

Because gas pressure is assumed as being constant, only the advective flow of liquid water is considered, and computed using the generalized Darcy's law. The dependence of intrinsic permeability on pore structure is considered in terms of total porosity; and the relative permeability of the liquid phase is made dependent on the degree of saturation. The relation degree of saturation-suction (retention curve) follows the formulation proposed by van Genuchten. On the other hand, using the double porosity model it is possible to track the values of the macro and microporosity along the hydration process. It is also assumed that the flow of water takes place only through the macropores and then the intrinsic permeability is a function of the macroporosity (through an exponential law).

5.2 MAIN FEATURES OF THE CALCULATIONS

The two-dimensional plain strain model geometry, and the initial and boundary conditions are shown in Figure 36. One half of the domain is simulated, assuming symmetry. The adopted initial stress state in the rock is anisotropic, with the vertical stress equal to 6.0 MPa and the horizontal one to 4.8 MPa. A liquid pressure value of 1.0 MPa has been prescribed along the boundaries of the mesh, and also as the initial water pressure into the rock mass prior to the EB niche excavation.

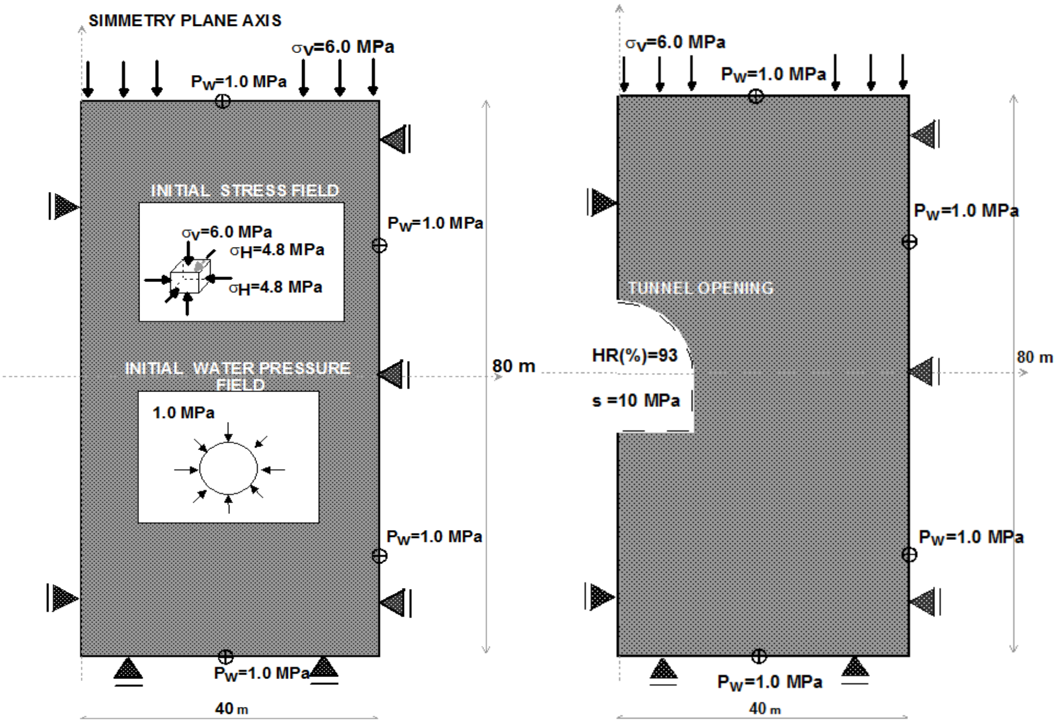

Figure 36: Model geometry and initial and boundary conditions

The niche excavation has been modelled by a relaxation of the total stresses and imposing on the inner niche surface a constant suction of 10 MPa, which corresponds to a relative humidity of about 93% (see right side of Figure 36). Also, the effect of EDZ has been taken into account considering a modelled material around the niche (5 m width) with the same properties of the intact rock except for its initial porosity (increased from 0.12 to 0.14), permeability (increased five times) and air entry suction (decreased from 18 to 9 MPa).

The emplacement of the EB experiment main elements (concrete bed, bentonite blocks, canister and GBM) was assumed as instantaneous, and the hydration tubes were simulated by 34 injection points over the whole modelled cross section. (Also, the geotextile mats were modelled through very thin lines of finite elements.) The initial suction of the GBM was set as 300 MPa, and for the bentonite blocks as 150 MPa. The initial stress state of the bentonite materials was assumed to be isotropic and with a value of 0.3 MPa.

To approximately follow the actual history of the injection process (see appendix III of deliverable D2.1-4) the following phases have been considered in the model:

- First phase: Injection of 6.7 m^3 of water during the first two days, through the 34 injection points.
- Second phase: Period of 126 days without water inflow.
- Third phase: Period of 1,741 days. At this model stage, a variable water pressure was applied in the injection points closely reproducing the actual injection pressure evolution registered during that period.
- Fourth phase: No further water was injected after June 18th, 2007. Then, in this last model phase no inflow was prescribed through the injection points.

The model parameters adopted (physical properties, hydraulical and mechanical ones) of the Opalinus clay (both intact and EDZ) and of the GBM, bentonite blocks, concrete bed, geotextile mats and canister are presented in detail on Tables 1 thru 6 of deliverables D3.1-1 and D3.1-2. Parameters required for the double structure model, retention curve, and the relationship permeability-degree of saturation of the GBM were calibrated from the interpretation an numerical modelling of laboratory tests performed at the UPC as part of the EB experiment. Laws and parameters for the bentonite blocks were taken from available previous studies carried out during the FEBEX project; and those for the Opalinus clay from the recently updated dataset provided by the HE-E experiment.

5.3 MODELLING RESULTS: HYDRATION PHASE

5.3.1 Evolution of the relative humidity

The comparison of the computed relative humidity (RH) in the bentonite barrier with the actual data registered in sampling sections B1 and B2 it is shown on Figure 37.

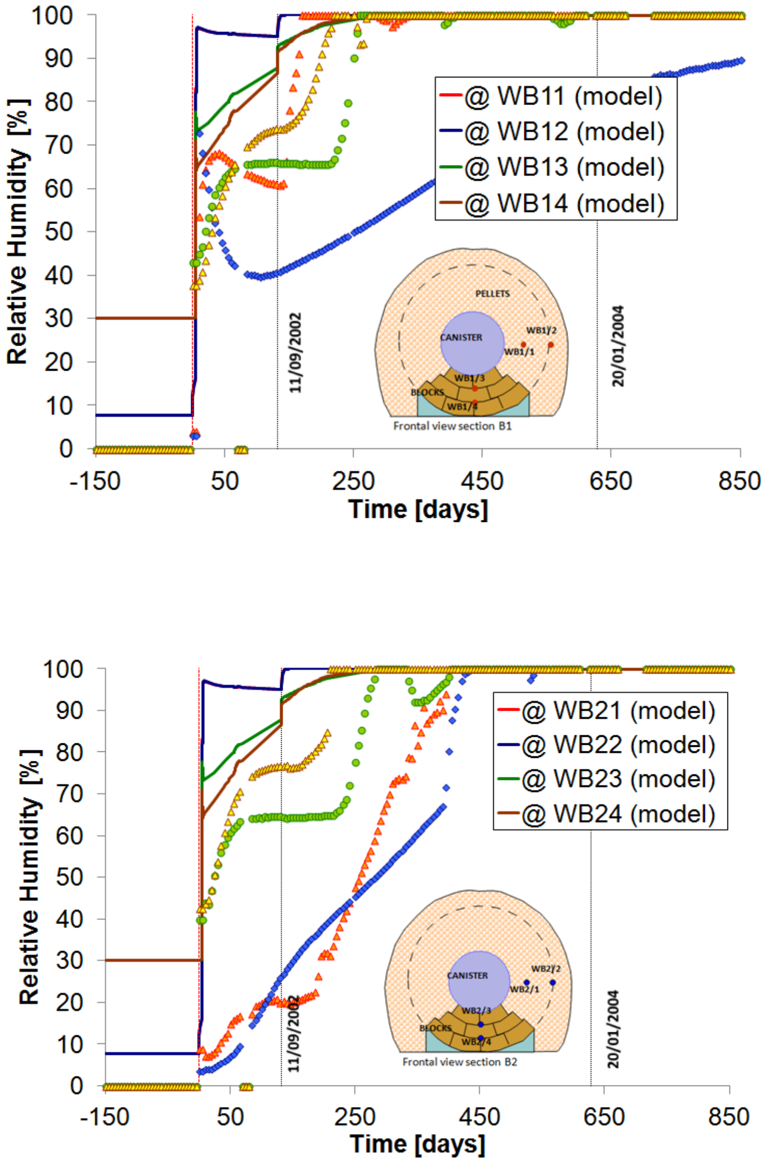

Figure 37: Computed (full lines) and measured (symbols) relative humidity in the barrier (sampling sections B1 and B2)

Significant discrepancies can be observed between the RH model results and the experimental real data, especially concerning the GBM hydration; although the fast initial saturation of the barrier predicted by the model may be a consequence of the model assumption that a high volume of water (6.7 m^3) was initially and completely absorbed by the bentonite while in fact it has been reported that some water losses (not quantified) did occur through the concrete plug. On the other hand, RH model predictions for the bentonite blocks agree better with the experimental data.

In the rock massif and near to the interface with the bentonite, the RH sensors registered an episode of desaturation followed by a fast resaturation (between days 150 and 450 of the hydration period). Although this episode is not well predicted by the model, the numerical results for the sensors WB0_01 and WB1_01 (placed in sampling section A1), and WB23_01 and WB24_01 (in section A2) do show a similar response: a small reduction of RH (due to excavation effects) followed by a complete resaturation of the rock once the GBM is almost saturated (see Figure 38).

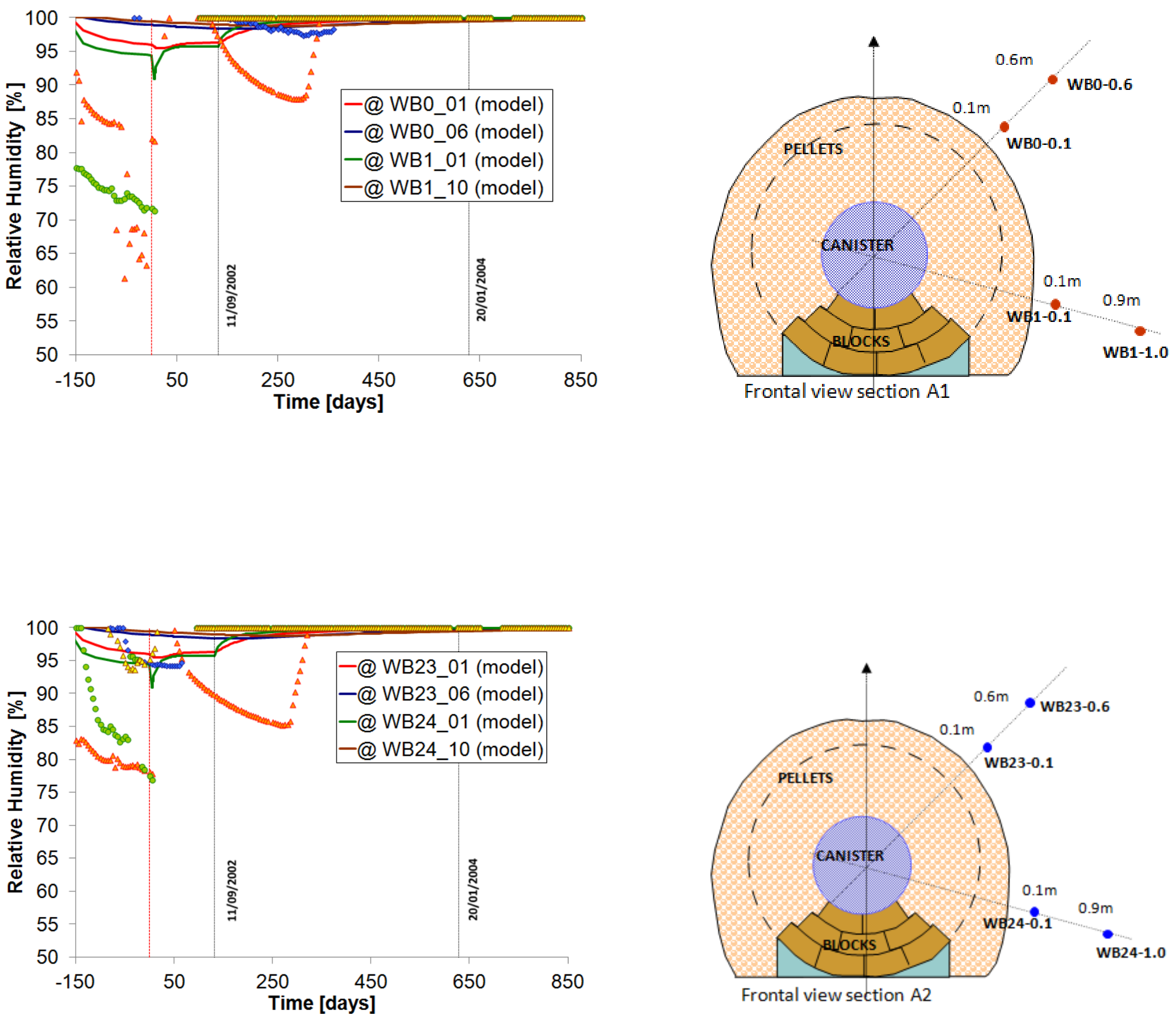

Figure 38: Computed (full lines) and measured (symbols) relative humidity in the rock (sampling sections A1 and A2)

5.3.2 Evolution of pore water pressure in the rock near-field

The measured and computed values of the pore water pressure in the rock near-field show a good agreement. They also confirm the saturated condition of the rock. The model does predict the drainage effect due to the niche excavation; the pore water pressure decrease in the early stage of the experiment (due to the flow of water towards the bentonite barrier); and the tendency of the pore water pressure towards supratmospheric values as the bentonite becomes saturated. The computed and pore water pressures values measured by the sensors in the rock around the sampling sections B1, B2, C1 and C2 are presented in the following figures 39, 40 and 41.

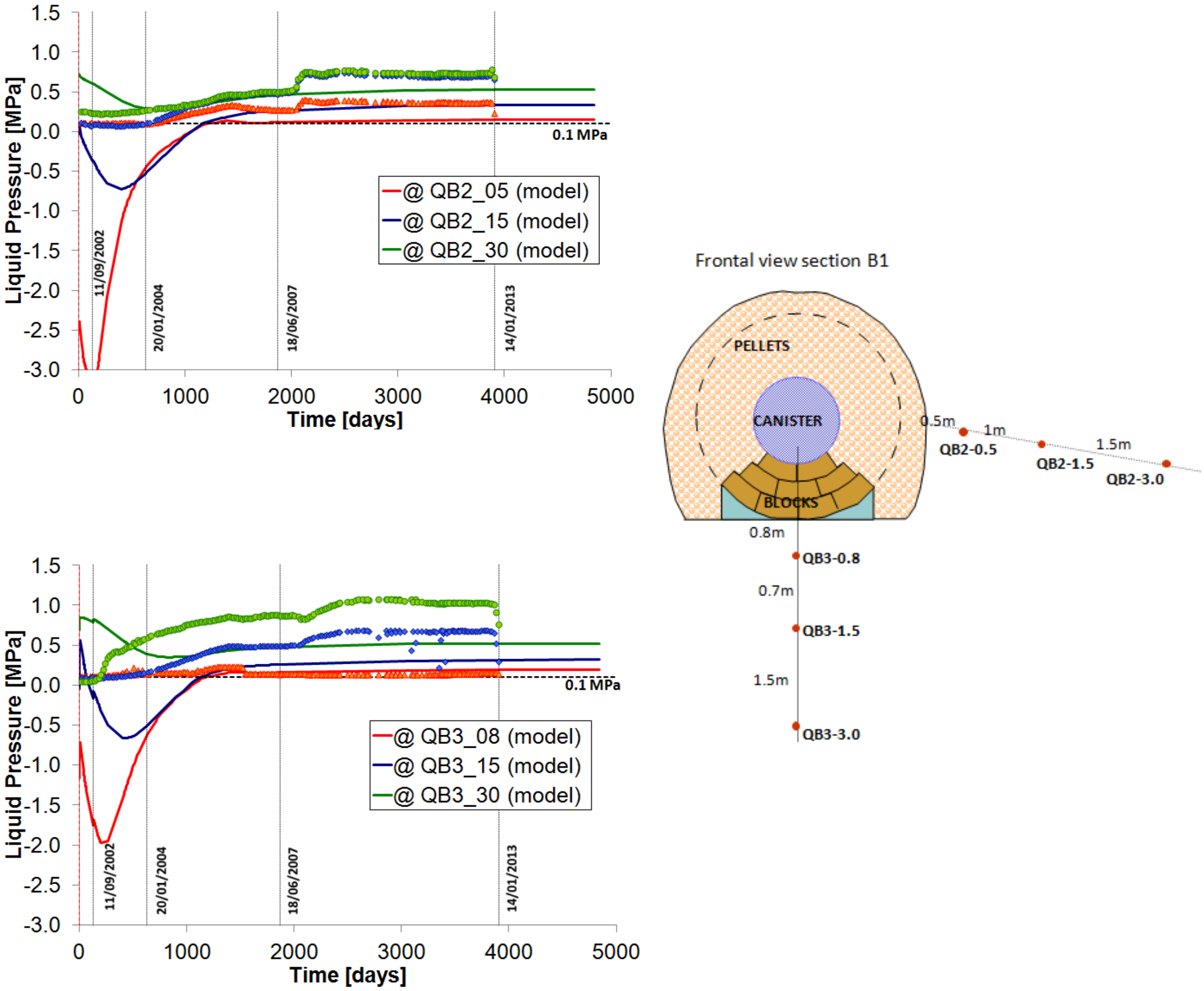

Figure 39: Computed (full lines) and measured (symbols) rock pore water pressures (section B1)

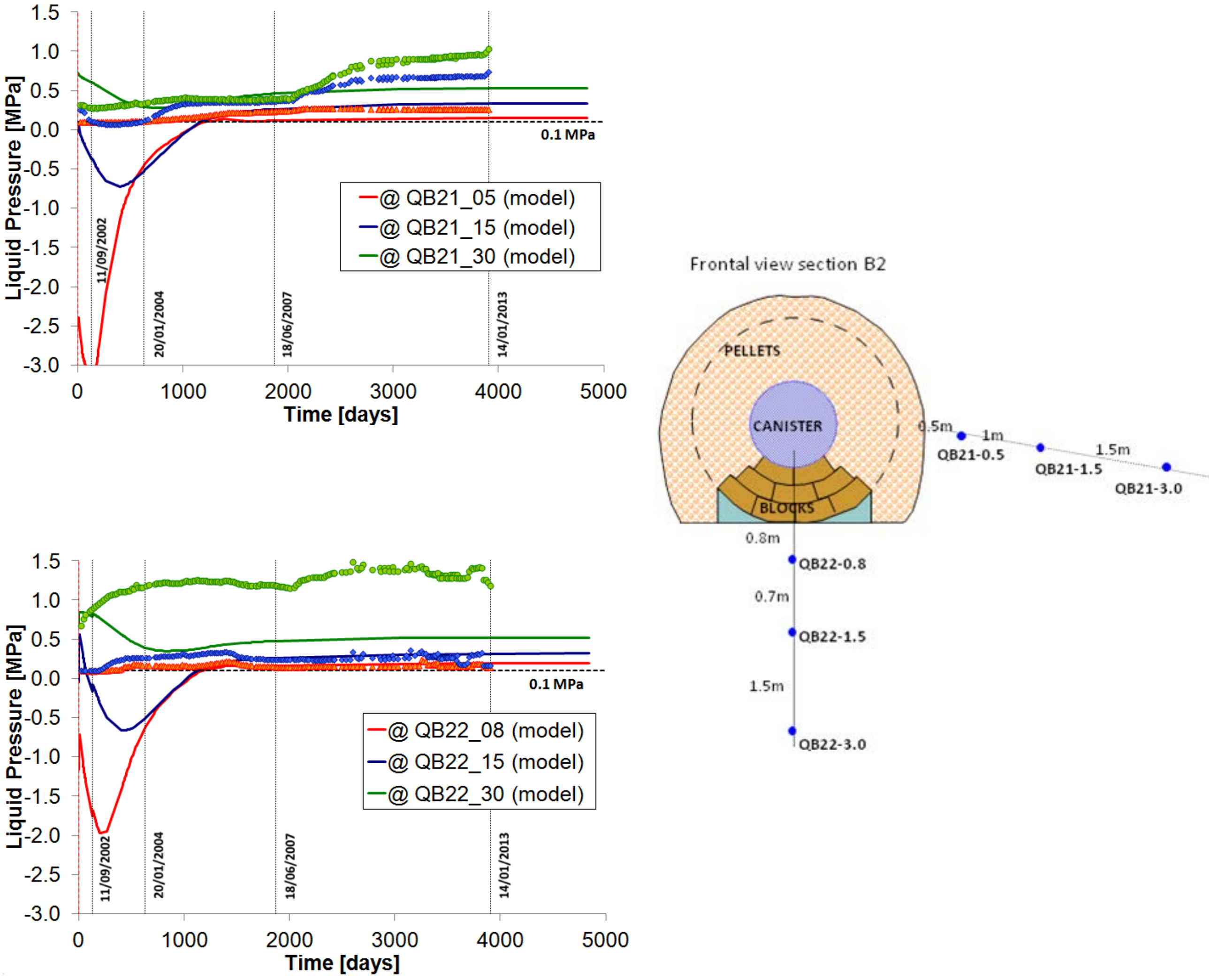

Figure 40: Computed (full lines) and measured (symbols) rock pore water pressures (section B2)

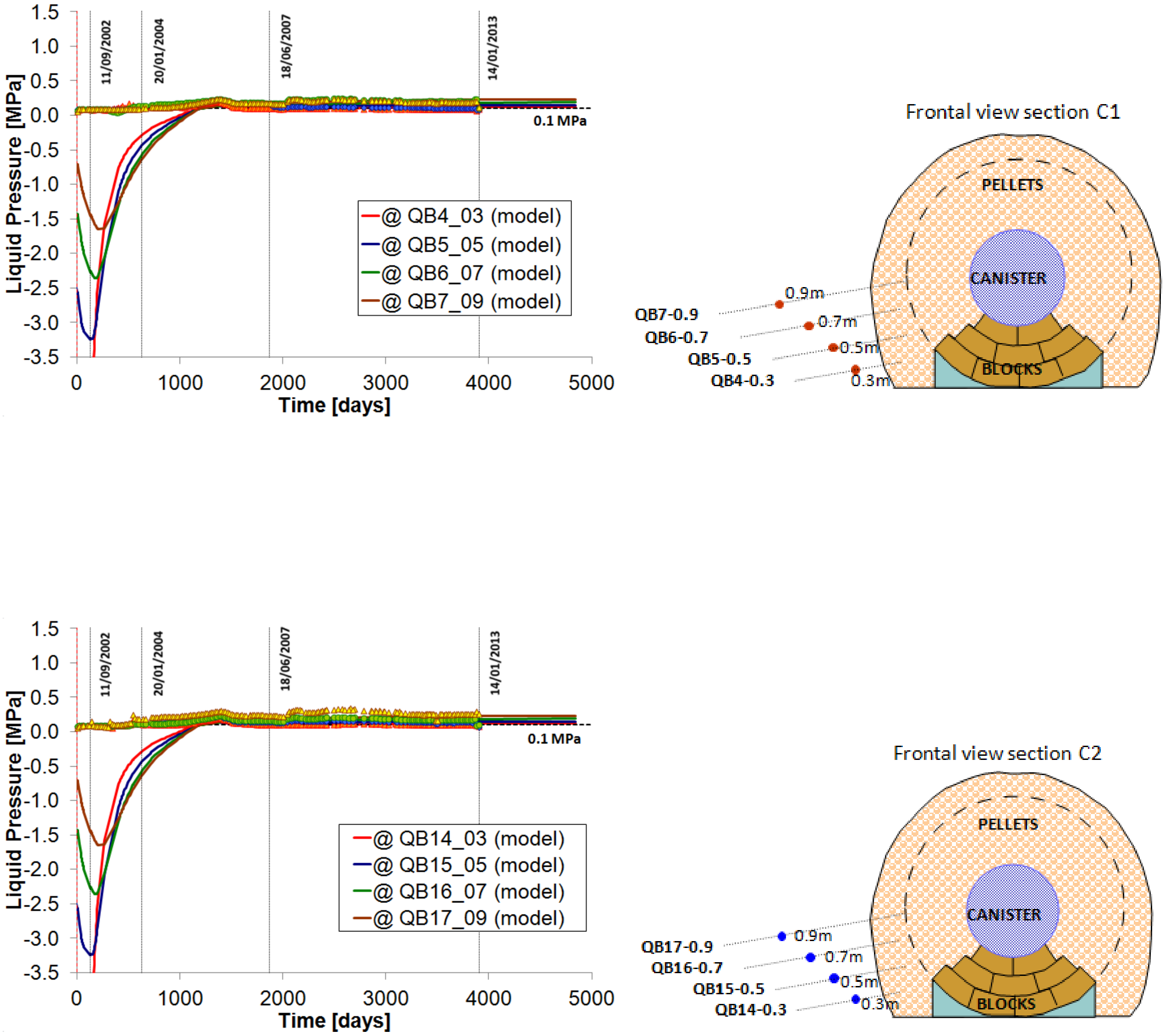

Figure 41: Computed (full lines) and measured (symbols) rock pore water pressures (sections C1 and C2)

5.3.3 Displacement of the canister

Due to the symmetry conditions assumed in the model, only vertical movements of the canister are predicted. A maximum upward movement of 11 mm has been calculated, for the period between the end of the first phase of hydration and the dismantling start. (The maximum real canister upward movement registered by the installed extensometers was about 1 cm, practically equal to the calculated one.) The canister heave is due to the higher swelling capacity of the bentonite blocks compared with that of the GBM (of lower initial dry density).

5.4 MODELLING RESULTS: FINAL STATE OF THE BARRIER

The model predicts an almost full saturation of the bentonite barrier. Specifically, all the computed values for the GBM are higher than 98.5%. These results agree very well with the obtained real data after dismantling.

Also, Figure 42 illustrates the comparison of computed porosity (ϕ) from the model and the isolines of the bentonite dry density (ρ_{dry}) interpreted from the on site analyses during the dismantling. (Note that, for practically saturated soils, $\rho_{dry} = \rho_S (1-\phi)$. A value of $\rho_S = 2.70$, specific weight, can be assumed for the bentonite.)

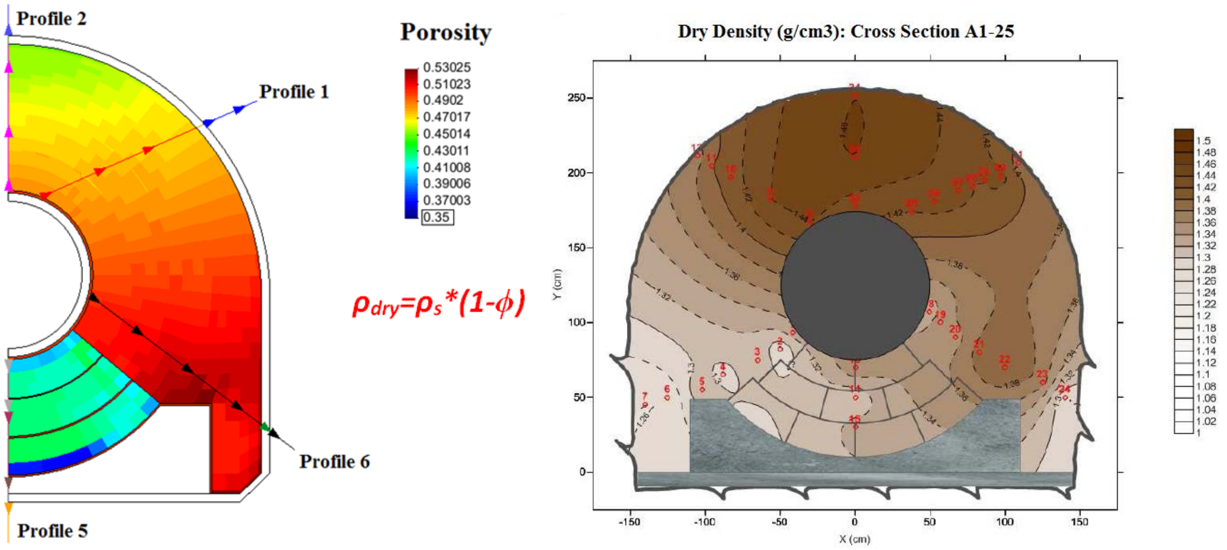

Figure 42: Computer contours of porosity and isolines of the dry density (from real data) in sampling section A1-25

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 homogeneization 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.

6. MAIN CONCLUSIONS FROM THE DISMANTLING

The dismantling works of the EB experiment (visual observation, monitoring, extensive post-mortem analyses and geophysical investigations) have clearly confirmed the following significant information about a bentonite barrier (emplaced using bentonite blocks and GBM) hydrated under isothermal conditions:

- The barrier was practically fully saturated.

- 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 has been shown that this key safety indicator falls between the acceptable limits considered in the Performance Assessment of the repository concepts.

- Homogenization between the two types of bentonite emplaced (blocks and GBM) has taken 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.

- The measured values of the thermal conductivity of the saturated bentonite (from 0.90 to 1.35 W/m·K) are high enough.

- Self-sealing of the EDZ in the Opalinus clay had been observed during the experiment, due to the swelling pressure developed in the barrier. As it could be expected, after the dismantling the seismic data do suggest the gradual recreation of the EDZ.

- The dismantling has provided the opportunity to perform microbial analyses of the bentonite emplaced more than ten years before. Samples analyzed had water activities higher than 0.96; relatively high culturability levels for heterotrophic aerobes; and low culturable levels of sulphate reducing bacteria.

- In general, the obtained gas permeability values of the saturated bentonite are low and homogeneous (from 1 to 6×10^{-22} m^2).

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

Modelling results using the CODE-BRIGHT code concerning the hydration process and the final state of the EB bentonite barrier are in reasonable agreement with the actual findings after the dismantling. Moreover, the real data obtained in this operation is a sound basis for a better formulation of the numerical models; reducing their uncertainties and providing more clear criteria to be conservatively applied in the Performance Assessment of engineered barriers.

Acknowledgment

The research leading to the results summarized in this deliverable has received funding from the European Atomic Energy Community's Seventh Framework Programme (FP/7 2007-2011) under Grant Agreement nº 249681 (the PEBS project).

7. REFERENCES

7.1 PEBS PROJECT DELIVERABLES

Deliverable D2.1-1.“Horizontal borehole results (geophysics, hydro test, laboratory tests)”. BGR (April 2014).

Deliverable D2.1-4.“As-built of dismantling operation”. AITEMIN (September 2013).

Deliverable D2.1-6.“EDZ seismic results – seismic transmission measurements”. BGR (June 2014).

Deliverable D2.1-7.“Laboratory post-mortem analyses report”. CIEMAT (January 2014).

Deliverable D2.1-9.“Geoelectrical monitoring of dismantling operation”. BGR (March 2014).

Deliverables D3.1-1 and D3.1-2. “Modelling and interpretation of the EB experiment hydration” and “Interpretation of the final state of the EB experiment barrier”. CIMNE-UPC (June 2014, presented in a single document).

7.2 ADDITIONAL REFERENCES

ENRESA 2005. “Engineered barrier emplacement experiment in Opalinus clay for the disposal of radioactive waste in underground repositories”. Publicación Técnica ENRESA 02/05 (February 2005).

Stroes – Gascoyne, S., M. Frutschi, C. Hamon, A. Bagnoud, O. Leupin, and R. Bernier – Latmani. “Microbiological analysis of samples from the engineered barrier experiment at Mont Terri rock laboratory”. TN 2013-56 (July 2013).

Villar, M.V. “EB experiment, Contribution of Ciemat to EB dismantling report, physical state of the bentonite”. CIEMAT (June 2013).