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In-situ experiments on bentonite-based buffer and sealing materials at the Mont Terri rock laboratory (Switzerland)

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Abstract Repository concepts in clay or crystalline rock involve bentonite-based buffer or seal systems to provide containment of the waste and limit advective flow. A thorough understanding of buffer and seal evolution is required to make sure the safety functions are fulfilled in the short and long term. Experiments at the real or near-real scale taking into account the interaction with the host rock help to make sure the safety-relevant processes are identified and understood and to show that laboratory-scale findings can be extrapolated to repository scale. Three large-scale experiments on buffer and seal properties performed in recent years at the Mont Terri rock laboratory are presented in this paper: The 1:2 scale HE-E heater experiment which is currently in operation, and the full-scale engineered barrier experiment and the Borehole Seal experiment which have been completed successfully in 2014 and 2012, respectively. All experiments faced considerable difficulties during installation, operation, evaluation or dismantling that required significant effort to overcome. The in situ experiments show that buffer and seal elements can be constructed meeting the expectations raised through small-scale testing. It was, however, also shown that interaction with the host rock caused additional effects in the buffer or seal that could not always be quantified or even anticipated from the experience of small-scale tests (such as re-saturation by pore-water from the rock, interaction with the excavation damaged zone in terms of preferential flow or mechanical effects). This led to the conclusion that testing of the integral system buffer/rock or seal/rock is needed.

Keywords Engineered barrier system · In-situ experiments · Bentonite · Sand–bentonite mixture · Nuclear waste disposal

1 Introduction

Operation of nuclear power plants creates heat-generating radioactive waste which, according to international consensus (OECD-NEA 2008) and to the concepts most countries using nuclear power are developing, should be disposed of in deep geological formations. In different countries, different host rocks are considered owing to their respective geological situations. The geological disposal concepts for radioactive waste are generally based on a multi-barrier system, which comprises the host rock formations and engineered barrier systems (EBS), such as sealing structures for boreholes, galleries, and shafts, as well as the backfill of remaining voids and the waste containers or canisters themselves. The overall objective of nuclear waste disposal in geological formations is to ensure permanent containment

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of the waste, concentrating and isolating it for a very long time from the biosphere. Owing to the different types of host rock (clay, salt, or crystalline rock) and repository concepts, the roles and requirements of the engineered barriers are different. In the existing concepts for clay or crystalline host rock, bentonite-based materials are widely used for buffer or sealing purposes. For constructing a repository and for ensuring the safe containment of the nuclear waste over a very long time period, profound knowledge about the material behaviour of the coupled system of waste containers, EBS, and the rock is indispensable. In addition to theoretical and laboratory-scale work, some countries run underground rock laboratories (URLs) in order to obtain this knowledge, following the guidelines of OECD-NEA (2001).

The Mont Terri rock laboratory is a unique facility where international repository research is performed in a claystone environment. It is located in the Jurassic Opalinus Clay in the Swiss Canton of Jura. Figure 1 shows a geological cross-section including the rock laboratory.

Besides many other experiments, large-scale investigations on the combined system of EBS and clay rock have been performed in recent years. Some of the respective experiments are presented here. These comprise

- The HE-E heater experiment
- The EB engineered barrier experiment
- The SB borehole seal experiment

A key project addressing the long-term performance of the engineered barrier system was the European Commission co-financed PEBS project ("Long-term performance of the engineered barrier system", Schäfers et al. 2014), which used a comprehensive approach of experimental, modelling and evaluation exercises to address the issue. The HE-E experiment and the final phase of the EB experiment were performed in the frame of PEBS. An overview of the experiment locations and the geological setting is given by Bossart et al. (2017).

2 The role of bentonite-based buffer and sealing materials

Some of the disposal concepts in clay or crystalline rock (e.g., the Swiss, Swedish, or Spanish concepts) involve a so-called buffer which surrounds the waste containers and fills the void between the containers and the host rock. The buffer generally consists of bentonite or bentonite-bearing material and is re-saturated over time by water from the host rock. This results in the development of a swelling pressure, an increase in thermal conductivity and a decrease in hydraulic conductivity. Thus, the buffer provides containment of the waste, limits advective flow, and enables heat dissipation into the rock. It also provides chemical buffering and long-term retardation of radionuclides in case of a leak. The detailed safety functions of the buffer in various disposal concepts are compiled in Deliverable D1.1/D1.2 of the PEBS project (PEBS 2012). Despite the differences in the concepts, they can be summarized as follows:

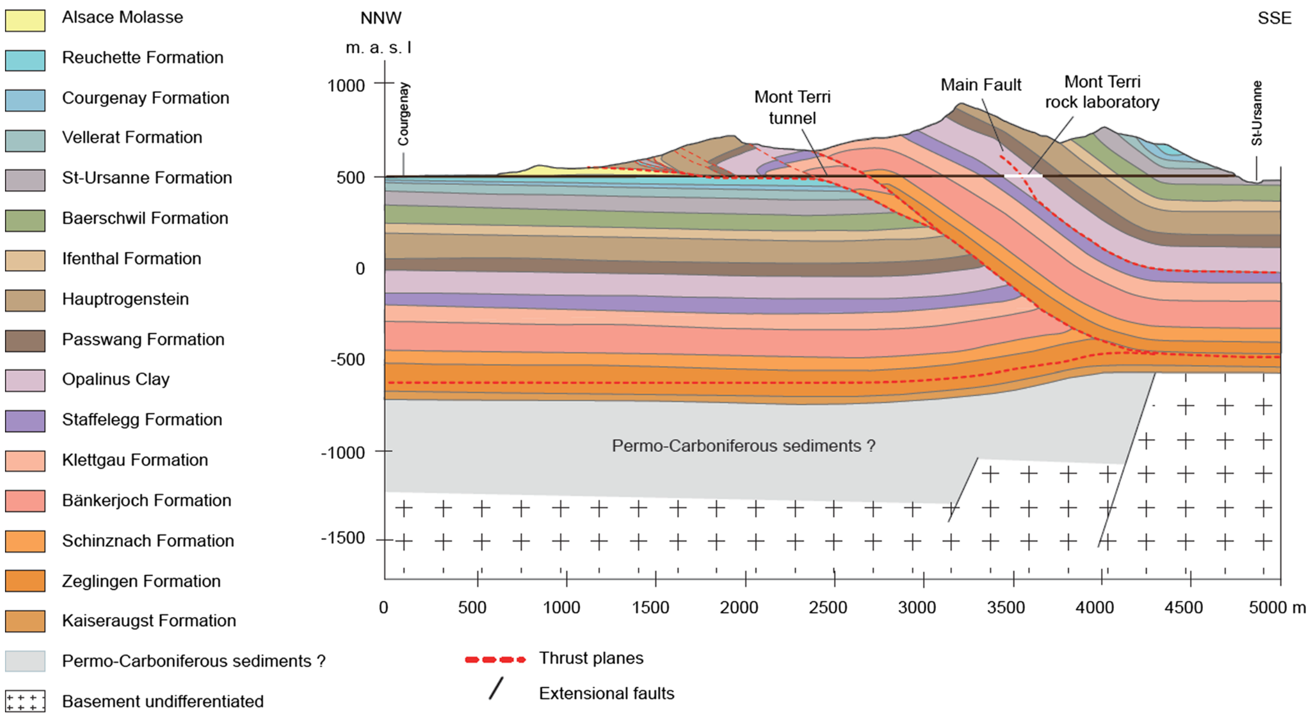


Fig. 1 Geological cross-section of the Mont Terri anticline and location of the Mont Terri rock laboratory (Nussbaum et al. 2017)

- Limitation of advective transport by achieving a low hydraulic conductivity after re-saturation
- Limitation of deformation of the host rock and reduction of the excavation damaged zone (in clay host rock) by achieving sufficient swelling pressure
- Prevention of canister sinking and damping of shear movements in the rock (in crystalline host rock)
- Suitable heat conduction to avoid excessive temperature
- Reduction of microbial activity and related corrosion by high buffer density
- Sorption of radionuclides
- Filtering of colloids
- Resistance to mineral transformation to maintain required properties

Seal elements for boreholes, galleries and shafts are part of all repository concepts. Their safety functions are very similar to those listed for the buffer, although they can also be less stringent. Heat conduction and, obviously, prevention of canister sinking play a minor role for these components. Depending on the concept, the backfill of the remaining voids in the repository provides mechanical support and may also take the role of a barrier in the long term. Currently, in all concepts clay-bearing materials are candidate materials for seal elements and backfill taking a barrier function.

While bentonite has the fundamental properties to fulfil the requirements for the buffer or seal, its coupled thermo-hydro-mechanical–chemical (THMC) behaviour under repository conditions is highly complex. A thorough understanding of buffer and seal evolution is required to provide evidence that the safety functions are fulfilled in the short term and the long term. Especially with respect to the thermo-hydro-mechanical (THM) evolution, experiments in the real or near-real scale under relevant conditions, taking into account the interaction with the host rock, are necessary to identify and better understand the safety-relevant processes as well as to show that laboratory-scale findings can be extrapolated/upscaled to the repository scale.

3 The HE-E heater experiment

The HE-E experiment was started in 2011 as part of the 7th Framework EURATOM project “Long-term Performance of Engineered Barrier Systems” (PEBS). The idea of PEBS was to evaluate the sealing and barrier performance of the EBS with time, through development of a comprehensive approach, involving experiments, model development, and consideration of the potential impact on safety functions (Schäfers et al. 2014). The main objective of the HE-E was to gain insight in the early non-isothermal re-saturation period of the buffer and its impact on the THM behaviour. Particular objectives were to provide the experimental database required for the calibration and validation of existing thermal–hydraulic–mechanical models of the early re-saturation phase and to verify upscaling of the thermal conductivity of the partially saturated buffer from laboratory to field scale for two types of candidate buffer materials: pure bentonite and sand-bentonite mixture. The HE-E experiment is the first near-real scale in situ experiment involving granular buffer at high temperature.

The experiment was set up in a microtunnel of 1.3 m diameter which had been used earlier for the Mont Terri ventilation experiment VE (Mayor et al. 2007b), with the benefit of a comprehensive rock instrumentation that could be re-used. The location of the microtunnel in the Mont Terri rock laboratory can be found in the paper of Bossart et al. (2017). After completion of the PEBS project in 2014, the experiment partners Nagra, ENRESA, BGR, and GRS decided to continue the HE-E experiment with national funding. Detailed information about the HE-E, as available at the end of the PEBS project, is given in the HE-E final report (Gaus et al. 2014).

3.1 Design and construction

An overview of the HE-E configuration is given in Fig. 2. The experiment is set up in a 10 m long section of the 1.3 m diameter VE microtunnel. It consists of two sections separated by a concrete plug. Both sections are equipped with an electrical heater bedded on highly compacted bentonite blocks. The remaining void is backfilled with granular bentonite buffer (Sect. 1) or 65/35 sand/bentonite mixture (Sect. 2). Especially Sect. 1 represents Nagra’s

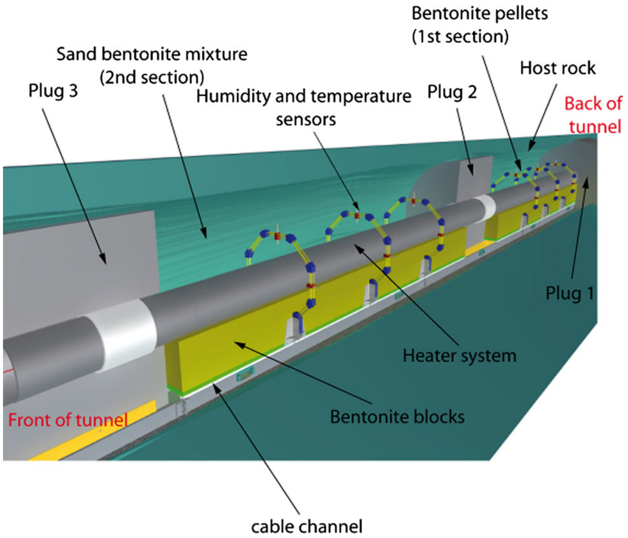


Fig. 2 Overview of the HE-E configuration (Teodori and Gaus 2012)

emplacement concept in a near 1:2 scale. The sand/bentonite mixture was chosen as an alternative potential buffer material after the experiences of the SB experiment (see Sect. 5). In the HE-E experiment, the bentonite used for all buffer types was sodium bentonite (Wyoming bentonite).

The Opalinus Clay around the microtunnel had already been instrumented for the VE experiment; sensors had been installed in different cross sections (Fig. 3): Temperature and pore pressure sensors (SA and SD), temperature and humidity sensors (SB), and extensometers (SD). In 2010/11, the rock instrumentation was completed by additional temperature and pore pressure sensors and a seismic array.

The spatial restrictions of the microtunnel proved a challenge for the installation of heaters, buffer, and instrumentation. The solution was to construct a unit of bentonite block support, heater liner, and sensor carrier outside the microtunnel which was then inserted into the tunnel as a whole (Fig. 4). The sensor carriers support temperature and humidity sensors at defined radial distances from the heater liner in six cross sections (Fig. 3). After installation of each block/liner/carrier package the heater was inserted and the remaining void backfilled with granular buffer material using an auger system (Fig. 5, left). An additional compaction of the buffer was not possible. The three buffer materials (blocks, granular bentonite, and sand/bentonite) were characterised in the laboratory in terms of their petrophysical, thermal and hydraulic properties. Table 1 summarizes the basic properties. On-site measurements gave slightly different values for the granular materials. Emplacement density was estimated by comparison to the total emplaced buffer mass and the microtunnel volume obtained from a 3D scan of the microtunnel geometry (Fig. 5, right).

Installation of the HE-E was finished by mid 2011, and on June 30, 2011 the heaters were started. Since then, the experiment has been running without major problems. Three main heating phases can be distinguished: A first phase of 3 months with a linear liner temperature increase to 80–90 °C, a second phase with linear temperature increase of another 9 months to reach 140 °C on the liner, followed by the third phase with a constant liner temperature which has been maintained to date.

3.2 Monitoring results to date

An example of the temperature evolution in the buffer is shown in Fig. 6. The results shown have been measured in the heater midplane of the sand/bentonite section; temperature evolution in the pure bentonite section is very similar due to similar thermal properties of the two granular materials. The temperatures in the bentonite blocks (7Bt and 5Bl) are slightly higher than those at comparable distance from the heater in the granular buffer (12C and 12M) because of the higher thermal conductivity of the blocks. Due to the overall low thermal conductivity of the dry buffer the thermal gradient is quite high (from 140 °C on the heater surface to 45 °C on the microtunnel surface, 12H). Heating results in a drying of the buffer close to the heater, illustrated by a drop in relative humidity as depicted in Fig. 7 for the sand/bentonite section. Water vapour is expelled to the outer and cooler parts of the buffer, where full saturation and 100% relative humidity are reached after 5 months of heating. Similar results are obtained for the pure bentonite buffer, although it takes about one year to reach 100% humidity.

With the seismic long-term monitoring the evolution in the Opalinus Clay as well as in the sand/bentonite (S/B) buffer is characterised with seismic parameters (Schuster 2014b). One focus is on the evolution of the S/B, where three piezoelectric transducers are located, one emitter, 5 cm from the S/B-Opalinus Clay interface and two

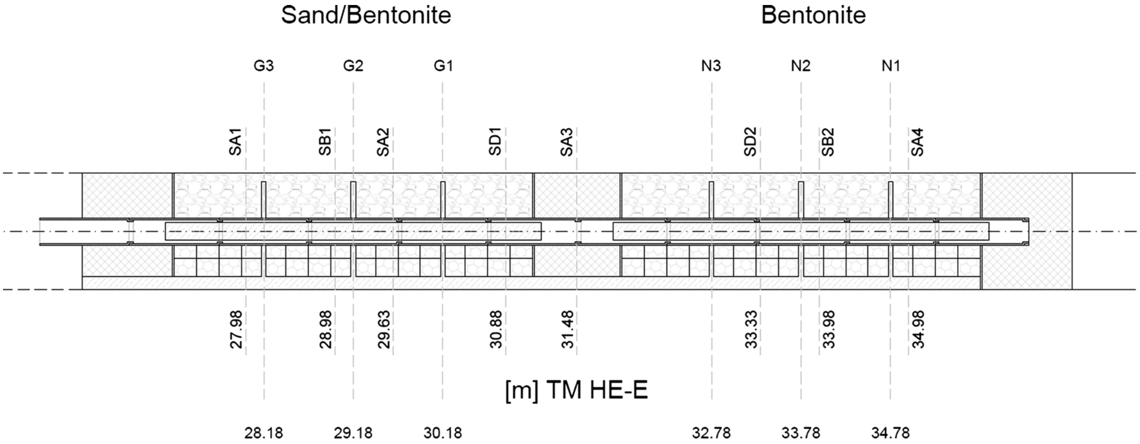


Fig. 3 Longitudinal section of the microtunnel showing the instrumentation cross sections (Gaus et al. 2014). Sections SA, SB, SD denote rock instrumentation, sections N1–N3 and G1–G3 denote buffer instrumentation

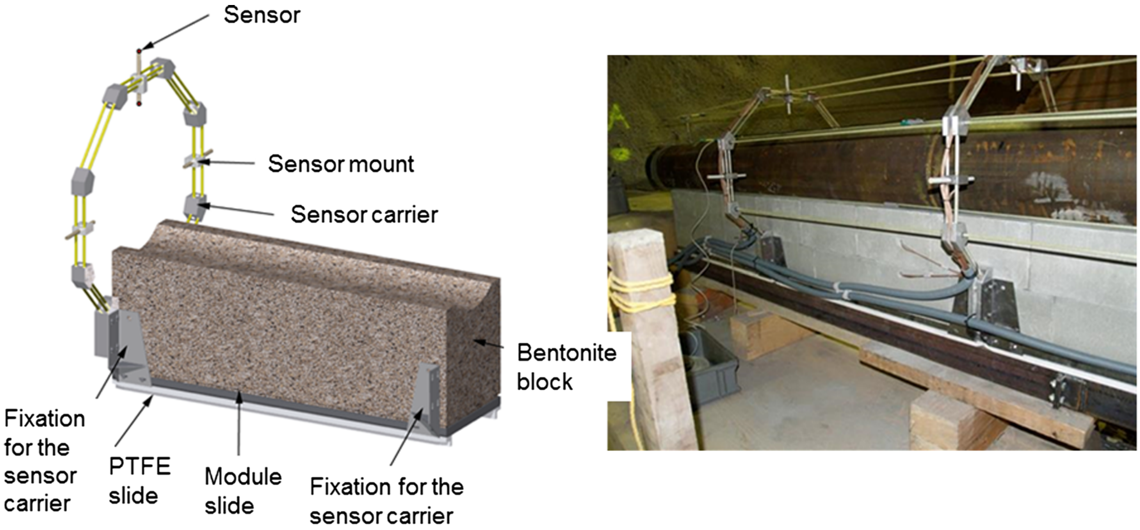


Fig. 4 Integrated buffer installation and instrumentation. *Left* design of a buffer instrumentation module, *right* complete bentonite block/liner/sensor carrier module before insertion into the microtunnel (Gaus et al. 2014)

Fig. 5 *Left* Granular buffer emplacement using an auger system, *right* 3D image of the microtunnel test section before installation for volume calculation (Gaus et al. 2014)

Table 1 Basic properties of HE-E buffer materials (Gaus et al. 2014)

	Bentonite blocks	Granular bentonite	Sand/bentonite
Water content (% by mass)	10.34	5.4	4.1
Bulk density (kg/m^3), preceding laboratory measurement	1993	1595	1440
Dry density (kg/m^3), preceding laboratory measurement	1806	1513	1383
Bulk density (kg/m^3), samples prepared as during emplacement		1543	1500

receivers at 5 and 10 cm distance from the interface. In Fig. 8 the evolution of the derived and normalised P-wave velocities (v_p) for the first 550 days is illustrated. The normalised v_p evolution reflects changes of material parameters of the S/B at different stages and with different gradients. In general, a higher v_p indicates a more competent (more compacted) material.

The first recognisable P-wave phases could be observed immediately after backfilling and closure of the microtunnel on day 52 for the distance 7.5 cm (emitter at 5 cm, receiver at 10 cm) and 50 days later for the 5 cm distance. This difference could be related to the denser initial compaction of the S/B (small initial gap in the roof). Heating started on day 109. There are at least four pronounced bending points in both graphs as a result of different compaction/saturation stages of the S/B (for the 7.5 cm distance: around days 100, 190, 290, and 490). The latest one was 20 days after the heater reached the

Fig. 6 Temperature evolution in the buffer at the heater midplane of the sand/bentonite section (G2). Data from the granular buffer (12H, 12M, 12C) and from the bentonite blocks (7Bt, 5Bl)

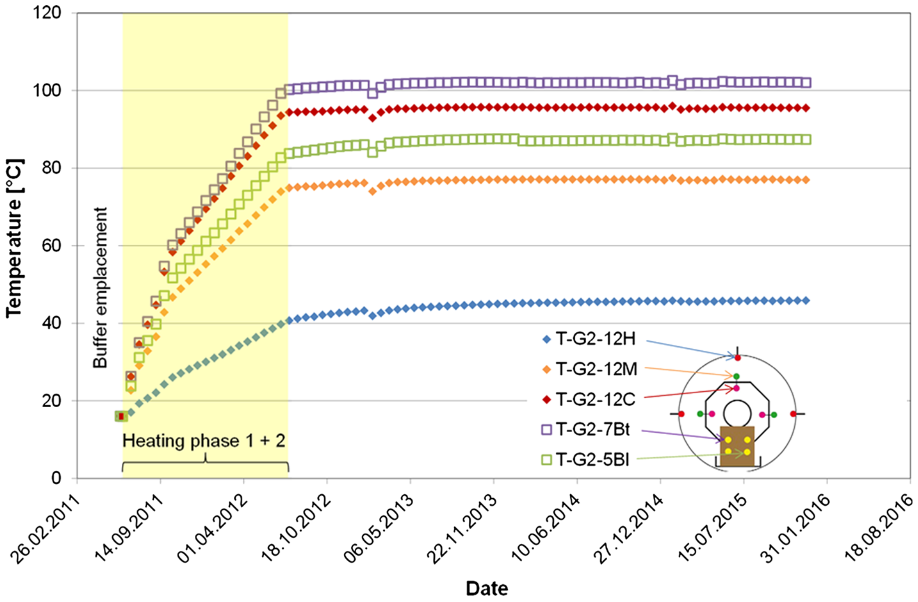
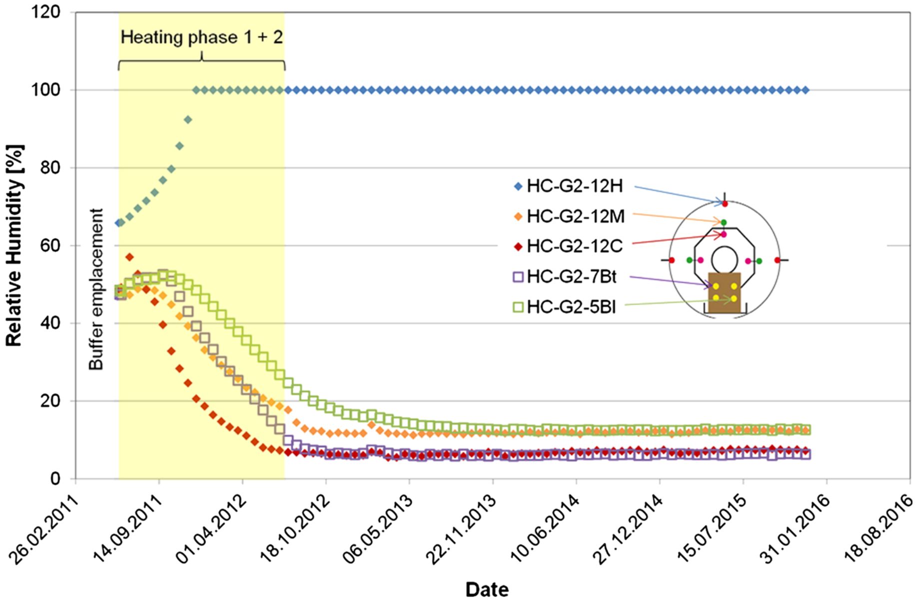


Fig. 7 Relative humidity evolution in the buffer at the heater midplane of the sand/bentonite section (G2). Data from the granular buffer (12H, 12M, 12C) and from the bentonite blocks (7Bt, 5Bl)



maximum temperature. Between days 200 and 290, when the RH sensors at the interface reached 100% relative humidity, a constant stage for the 7.5 cm distant travel paths is observed. For the 5 cm distance, closer to the interface, this trend is slightly negative between days 200 and 280, whereas for the following 20 days a remarkable decrease in v_p is observed. Due to the heating a vapour front moves towards the interface. A temporary accumulation of vapour/water close to the interface could reduce the v_p. This interpretation is supported by slight variations in the frequency content of the first arrival phases. Between days 260 and 280 the centre frequency of the sum spectrum is slightly higher than for day 281 to day 300. A further conspicuity is the v_p notch around day 539 which results from a 14 h power failure of the heaters (summer storm).

Monitoring is continued and a continuous gradual increase of normalised v_p between days 800 and 1200 was observed in a first analysis, meaning compaction/swelling of the material is progressing.

3.3 Interpretation

Integral part of the measurement interpretation is model simulation, which was performed in different cycles. During designing the HE-E, scoping calculations (Czaikowski et al. 2012) were performed for planning the

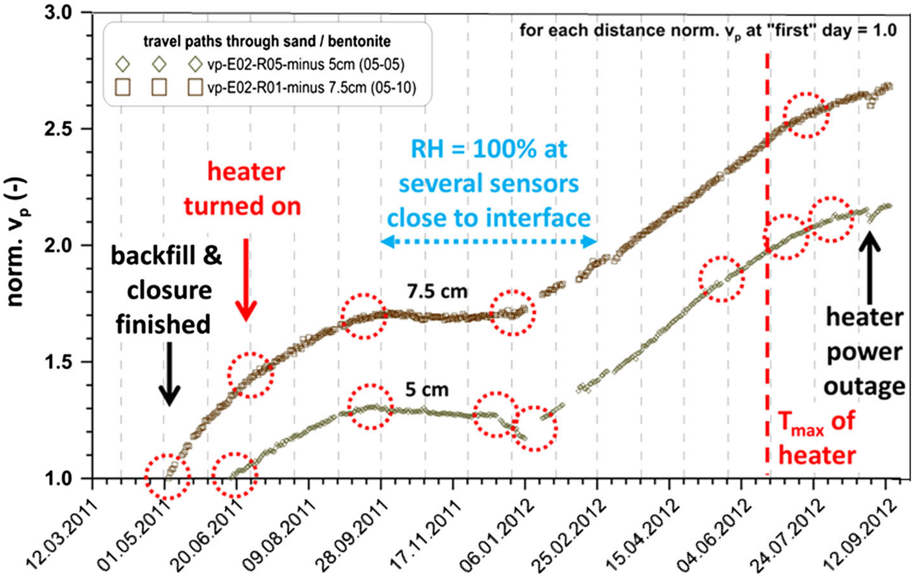


Fig. 8 Normalised P-wave velocity evolution in the sand/bentonite material

experiment execution and to make sure the instrumentation met the requirements. Parallel to performing the experiment, TH- and THM-coupled model calculations were performed with the actual material parameters and boundary conditions of the experiment (Gaus et al. 2014) to reproduce the observed behaviour and to predict future evolution. Despite the conceptual and geometrical restrictions of the different models, the modelling results showed that the temperature and humidity evolution in the buffer could be well reproduced. More detail regarding the modelling of the HE-E and other experiments is given in by Gens et al. (2017).

Re-saturation of the buffer is slow, as it is governed by pore-water supply from the surrounding clay. As mentioned earlier, the microtunnel was not excavated for the HE-E, but had undergone a complex de-saturation/re-saturation history during the preceding ventilation test. Pore pressure measurements in the rock close to the microtunnel show that the near-field was and still is in suction, and only at distances over 1 m from the tunnel surface positive pore-water pressures are observed. Therefore, more time will be needed until a significant re-saturation inside the buffer can be expected. With increased saturation, on the other hand, the thermal conductivity of the buffer will increase and extenuate the temperature gradient.

The hydraulic conductivity and swelling pressure of the buffer materials cannot be evaluated in the in situ test, since the buffer is still very dry. Still, some information is gathered from the seismic measurements. The pure granular bentonite buffer could be installed with a density of more than 1500 kg/m^3, which makes acceptable hydro-mechanical (HM) properties after re-saturation probable. The emplacement density of the sand/bentonite buffer, however, is very poor (1383 kg/m^3). This is a result of the narrow grain distribution of the material which was chosen to avoid segregation during the emplacement, and of the impossibility of additional compaction after emplacement. Consequently, laboratory measurements showed insufficiently low permeability (Wieczorek and Miehe 2013) and too low swelling pressure (Villar et al. 2014b) of this material at the density achieved on site, making modifications necessary.

4 The EB experiment

The HE-E focuses on the early post-closure phase with high temperature gradients and low buffer saturation. The buffer evolution at a later stage, when heat production has diminished and the buffer is re-saturated and pore pressure evolves, was addressed by the Engineered Barrier emplacement experiment (EB) which started in 2002. The experiment location is shown in Bossart et al. (2017).

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

- Define a buffer material and demonstrate its production at semi-industrial scale
- Characterise HM properties of the buffer
- Design and demonstrate the emplacement and backfilling technique
- Assess the quality of the buffer after emplacement
- Characterise the excavation damaged and/or disturbed zone in the rock and determine its influence on the HM behaviour of the system
- Investigate the evolution of the HM parameters in the buffer and the EDZ as a function of progressing hydration

- Develop a HM model of the complete system

Similar to the HE-E experiment, a dummy canister (in this case without heat production) was placed on highly-compacted bentonite blocks and the remaining space was backfilled with pure granular bentonite buffer (Fig. 9). In contrast to HE-E, the bentonite is a calcium bentonite from Serrata de Nijar in Spain. In order to achieve full saturation of the buffer in a realistic experimental duration, an artificial hydration system was installed. Regarding the tunnel and canister dimensions, the EB experiment is a full-scale experiment.

4.1 Construction

A new niche was excavated for the experiment in 2001, and geophysical and hydraulic measurements were performed for EDZ characterisation. Afterwards, the bentonite blocks and the dummy canister were emplaced. A hydration system consisting of a pipe system of 37 pipes (Fig. 9) and sensors for buffer monitoring in different cross sections (Fig. 10) were installed. Finally, the granular buffer was emplaced using an auger system which had proven to be the most suitable technique, and the experiment setup was sealed off with a concrete plug (Mayor et al. 2007a).

The bentonite blocks had a dry density of 1.69 g/cm^3 and an initial water content of 14%. The dry density of the granular backfill as determined from the total mass emplaced and the total available volume amounted to an average of 1.36 g/cm^3. Preceding laboratory tests had shown that at full saturation, hydraulic conductivities in the range of 10^{-12} m/s and a swelling pressure of about 1.3 MPa could be expected for such a dry density value (Mayor et al. 2007a).

4.2 Re-saturation phase and monitoring results

In May 2002, the injection of artificial pore-water (Pearson water) into the buffer via the hydration pipes was started. A total of about 19 m^3 were injected until June 2007. Afterwards, the buffer was only subject to further natural water uptake from the surrounding Opalinus Clay until October 2012, when dismantling of the experiment started.

The evolution of relative humidity as an indicator for suction/saturation in the buffer was monitored in different cross sections (Fig. 10). As an example, Fig. 11 shows the results in cross section B1. One year after start of water injection the granular buffer can be considered almost fully saturated, in the sense that relative humidity reached 100%, which means suction has disappeared. Only one sensor (WB1/2) takes longer to reach 100% humidity.

4.3 Dismantling and evaluation

An important part of the investigation programme was the dismantling and evaluation operation of the EB, which was performed in the frame of the PEBS project.

Between October 2012 and January 2013 the whole experiment was excavated and more than 500 samples of the buffer were taken from different cross sections (Fig. 12) for on-site and laboratory analyses of dry density and moisture content, suction, pore size distribution, basal spacing, thermal conductivity, hydraulic and gas conductivity, swelling strain and swelling pressure, and microbial analyses.

From on-site measurements taken directly after sampling, it was found that the average water content of the buffer (granular bentonite and blocks) was 36%, the average dry density 1.34 g/cm^3, and the average degree of saturation 95.5% (Palacios et al. 2013). As shown for cross section B1 as an example (Fig. 13), there is some degree of inhomogeneity in terms of dry density and water content distribution, although the large initial density contrast between blocks and granular buffer has practically vanished. Water content is lower and dry density is higher in the upper part of the granular buffer. Laboratory tests on

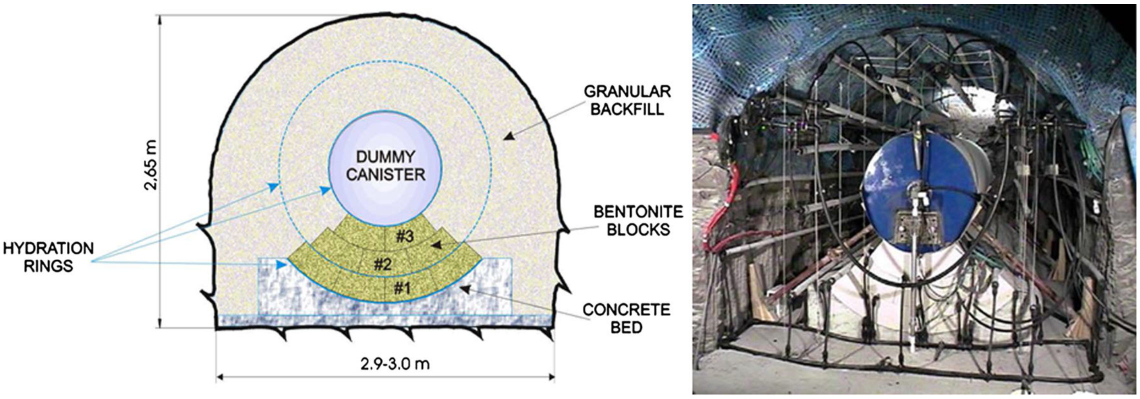


Fig. 9 EB experiment layout. Hydration pipes are arranged in rings around the central dummy canister (Mayor et al. 2007a, b)

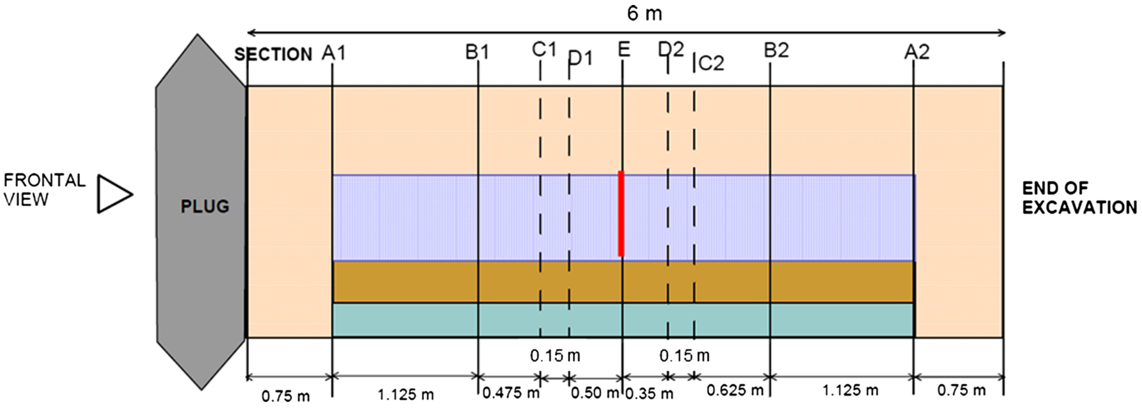


Fig. 10 EB longitudinal section showing the instrumentation cross sections (Vasconcelos et al. 2014)

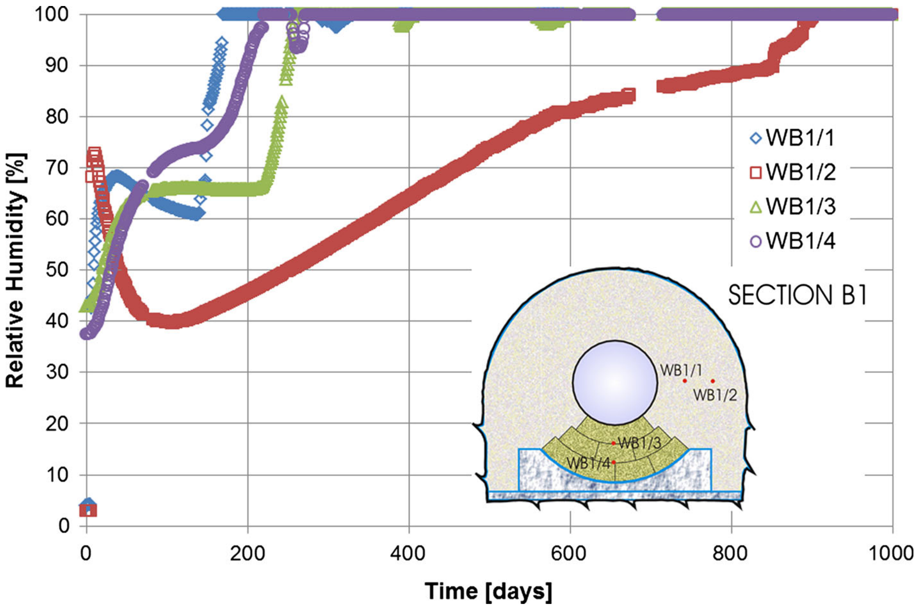


Fig. 11 Evolution of relative humidity in measurement cross section B1

buffer samples (Villar et al. 2014a) further confirmed an average degree of saturation of approximately 98%, a range of water content between 33 and 44%, and a dry density variation between 1.24 and 1.42 g/cm^3. The hydraulic conductivity proved to be in the range of 10^{-12} m/s for all of 15 tested samples.

4.4 Seismic long-term monitoring during the early phase of the EB and during dismantling

A total of 24 seismic sensors had been installed in the rock and in the buffer to monitor the performance of the system by P-wave velocity (v_p) measurements. The measurements were performed during the first 19 months of operation of the EB (between April 2002 and November 2003). More than eight years later, prior to dismantling of the experiment, the seismic array was reactivated (Schuster 2014a). The results of the measurements are discussed on the example of the normalised P-wave velocity evolution on a travel path of 1 m length parallel to the left wall of the niche, 38 cm in the Opalinus Clay (Fig. 14).

Reliable P-wave phases could only be detected from day 342 after closure of the niche. Earlier, strong attenuation due to a pronounced EDZ as a consequence of the construction of the EB niche precluded any reliable phase correlation. After that, v_p increased gradually by nearly 10%, which is interpreted as EDZ re-compaction/sealing. The total pressure at the interface between buffer and tunnel wall measured in the vicinity, which is also shown for comparison in Fig. 14, shows a similar evolution.

During the monitoring pause v_p increased further by 6% and continued increasing until start of dismantling. When the dismantling front approached the seismic sensors (buried 38 cm from the wall) v_p first increased slightly due to the stress concentration in the wall and then decreased with different gradients until it nearly reached the starting

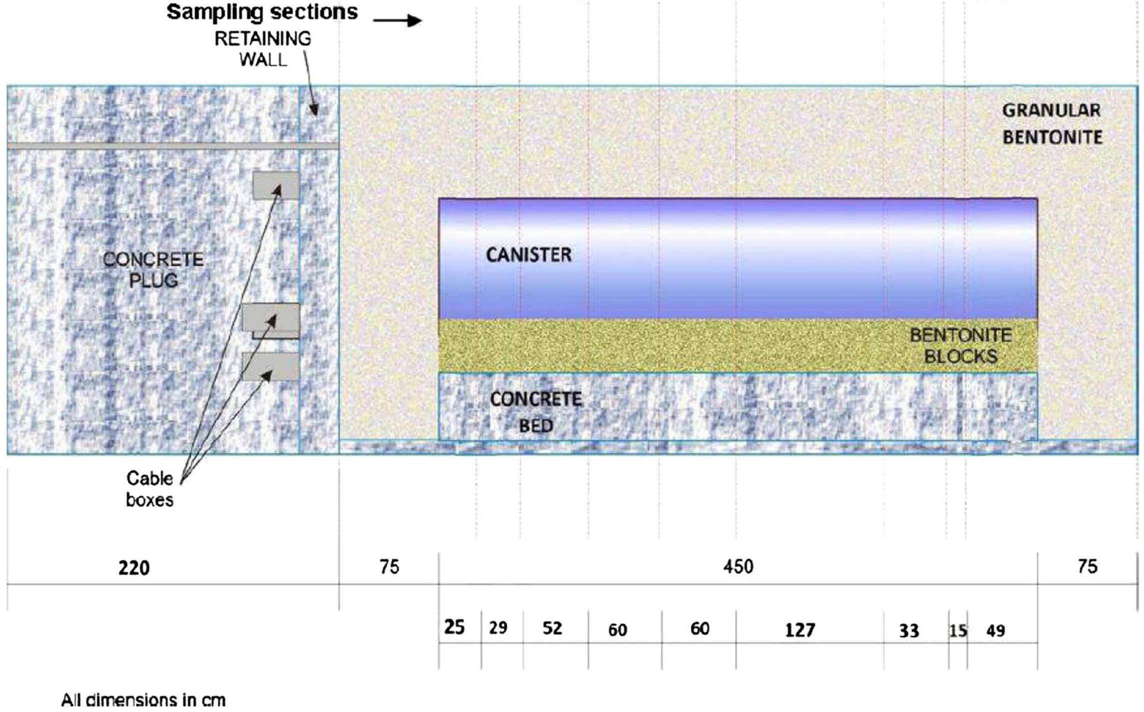


Fig. 12 EB longitudinal section showing the sampling cross sections (Palacios et al. 2013)

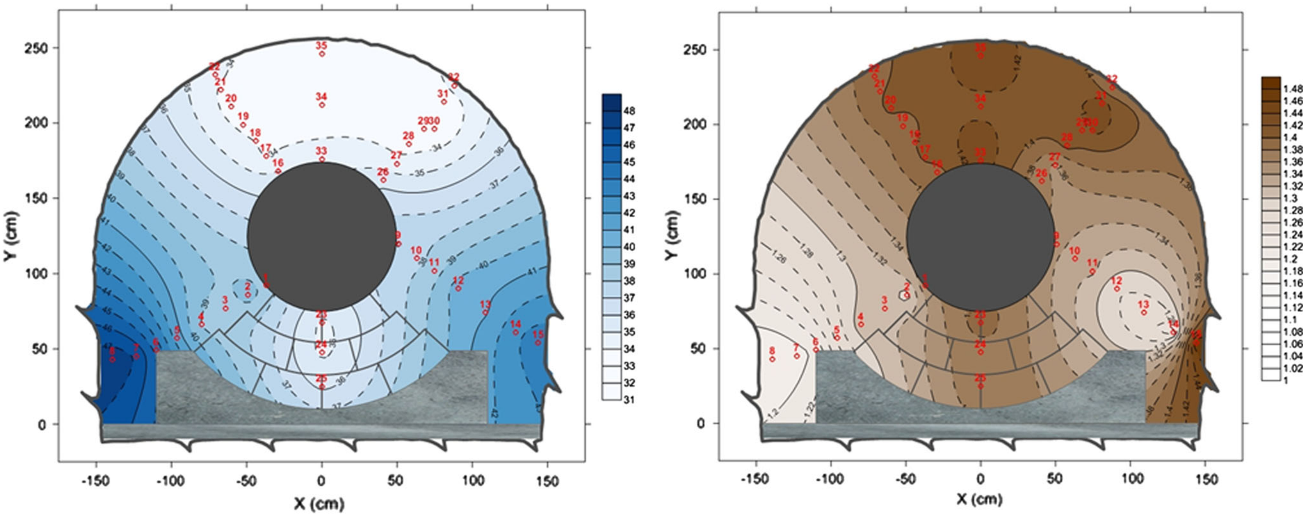


Fig. 13 Water content (*left*) and dry density (*right*) after dismantling in EB cross section B1. *Red marks* show the sampling locations (Palacios et al. 2013)

value around day 4320. This can be interpreted as a recreation of an EDZ. A similar evolution can again be observed for the total pressure which expectedly dropped when the excavation front approached.

A full cycle of a creation, sealing and recreation of an EDZ could be visualised with seismic methods. Swelling of the bentonite, together with the hydration process, resulted in a strong mechanical support of the neighbouring rock.

4.5 Conclusions of the EB

The dismantling works of the EB experiment have clearly confirmed the following significant information about a bentonite barrier (emplaced using bentonite blocks and granular bentonite) hydrated under isothermal conditions (Mayor and Velasco 2014):

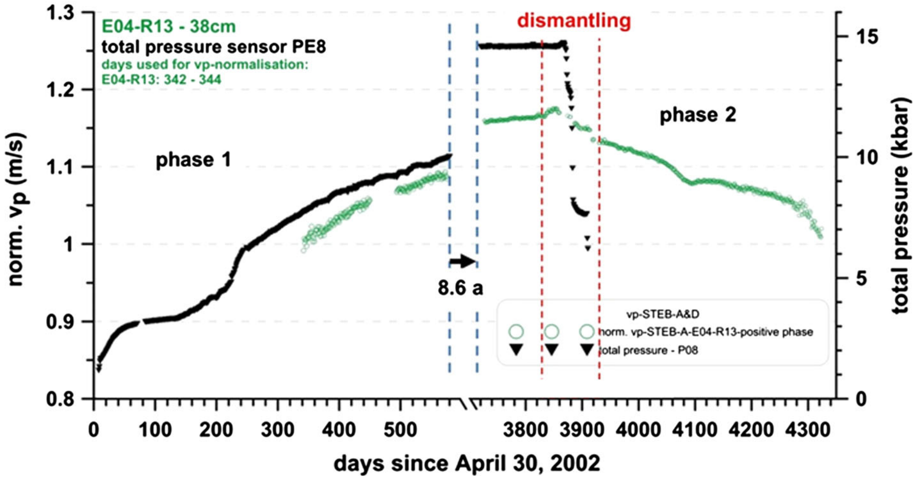


Fig. 14 Normalised P-wave velocity evolution and total pressure in the EB experiment

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

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

5 The SB borehole seal experiment

Depending on emplacement density and initial saturation, pure bentonite can develop very high swelling pressures and very low hydraulic conductivities after re-saturation. While these are favourable sealing properties, gas entry pressure may also be high. The idea of looking into sand/bentonite mixtures as a material for engineered barriers is to reduce cohesion and gas entry pressure to allow for discharge of corrosion gases while maintaining sufficiently low permeability to water and sufficiently high swelling pressure. The SB experiment (Rothfuchs et al. 2012) had the objective to qualify a respective barrier material. It was performed between 2003 and 2012, partially in the frame of the EC-financed ESDRED project.

5.1 The approach was to

- Determine material parameters of candidate sand/bentonite mixtures in the laboratory and select suitable compositions
- Perform scoping calculations for experiment design
- Conduct a large-scale laboratory mock-up experiment for testing installation techniques and instrumentation
- Perform an in situ experiment with four individual borehole plugs
- Perform interpretative modelling
- Dismantle the experiment and conduct post-mortem investigations

5.2 Preceding laboratory and mock-up tests

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

The mixture with 65/35 sand/bentonite ratio was chosen for two mock-up experiments in steel tubes of 300 mm diameter (Fig. 15), which represents a 1:1 scale with respect to the later in situ experiment. The test procedure was to

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

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

5.3 In-situ setup and results

After successful completion of the mock-up tests, the in situ experiment was set up at the Mont Terri rock laboratory in 2005/2006 (Fig. 16). Four boreholes were installed and instrumented similarly to the mock-up tests:

- Boreholes SB1 and SB2 are equipped with 1 m long seal sections of 65/35 sand/bentonite mixture
- Borehole SB15 is equipped with an 0.5 m long seal section of 50/50 sand/bentonite mixture (sealing length was reduced due to an expected slower re-saturation with the higher bentonite content)
- Borehole SB13 is equipped with 0.5 m long seal section of pure granular sodium bentonite for comparison

Figure 17 shows some stages of the construction. The bulk densities of the seals achieved at construction are shown in Table 2. Except for SB2, they are somewhat lower than those obtained in the laboratory.

The experimental procedure followed the one described for the mock-up tests. During re-saturation of the seals it was, however, found that in both boreholes SB1 and SB15 water bypassed the seal element. This can be due to a

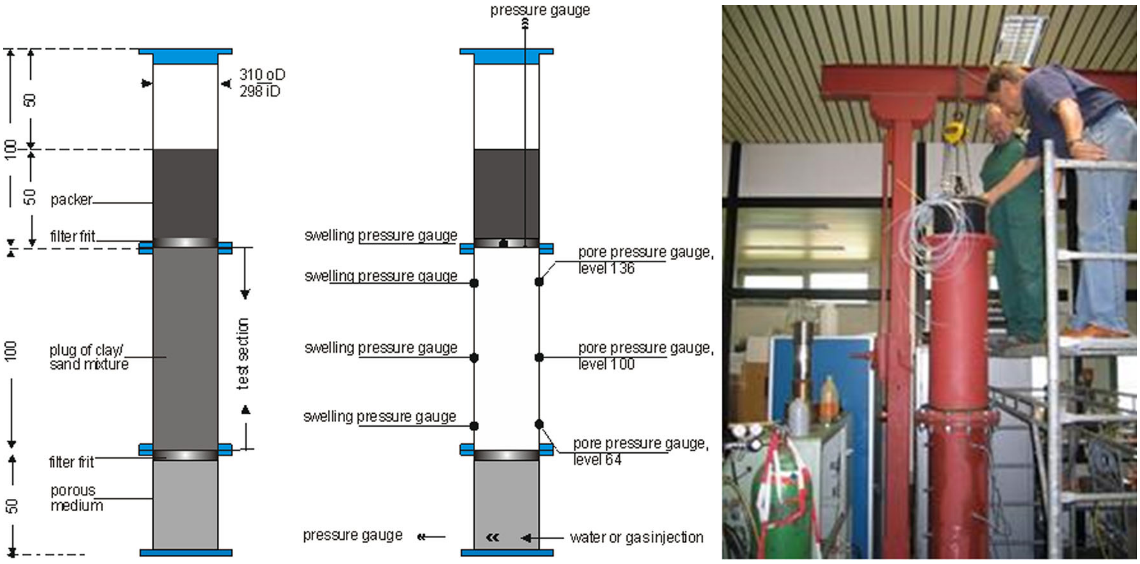


Fig. 15 Overview of SB mock-up design and instrumentation (Rothfuchs et al. 2012)

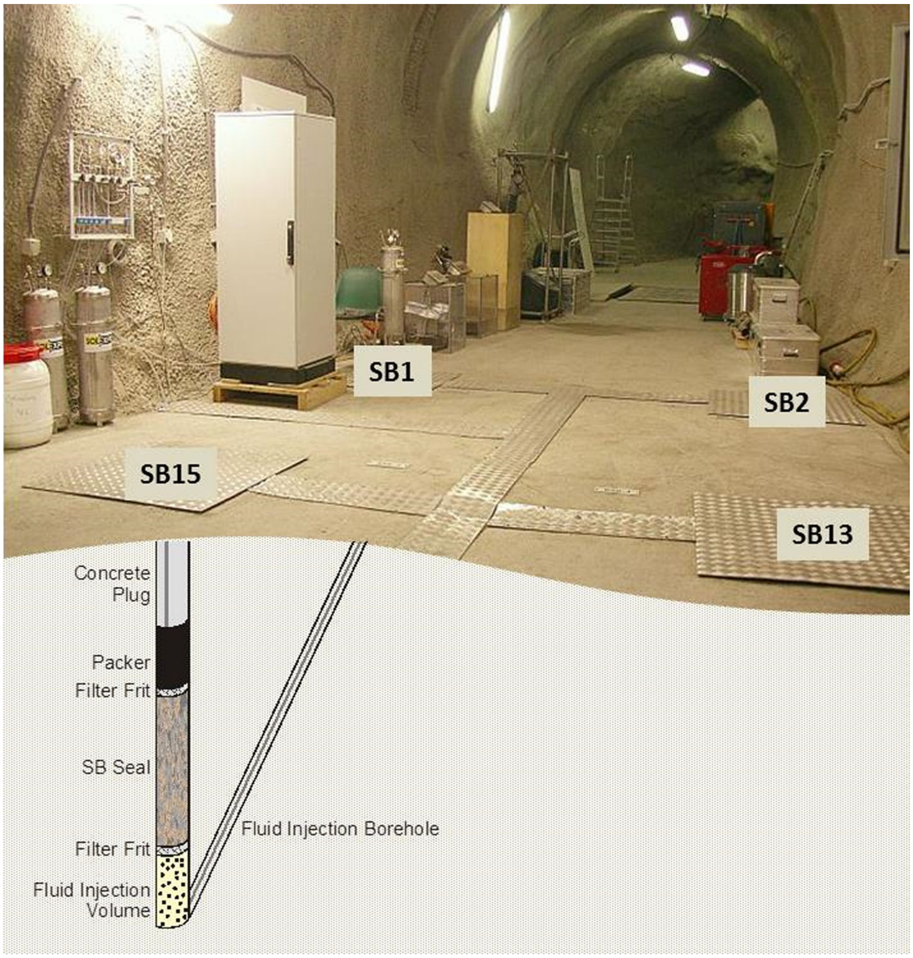


Fig. 16 Overview of SB in situ configuration. SB1 and SB2: boreholes with 65/35 sand/bentonite seal, SB15: borehole with 50/50 sand/bentonite seal, SB13: borehole with pure bentonite seal

Fig. 17 View into borehole SB2 (diameter 300 mm) after emplacement of sand/bentonite mixture (*left*), after installation of the packer (*centre*), and after grouting of the borehole cellar (*right*) (Rothfuchs et al. 2012)

pronounced borehole disturbed zone (BdZ) around the boreholes and is aided by the low installation density in these boreholes—the swelling pressure is not high enough to re-compact the EDZ. Since the swelling pressure sensors in these boreholes failed, too, they could not be evaluated further.

The test in SB2 ran more successful. Between February and April 2006 the injection pressure was increased stepwise to 0.38 MPa (Fig. 18). Swelling pressure showed a quick response and reached final values between 0.15 and 0.19 MPa within less than one year after start of injection. No outflow of water could, however, be observed even after more than 5½ years of re-saturation.

In order to investigate this problem and find a way to successfully complete the experiment, a new model simulation was performed taking into account a desaturation/pore pressure reduction in the gallery near-field which could be quantified by adjacent pore pressure

Table 2 Installation densities of the SB buffer materials (Rothfuchs et al. 2012)

	Buk density achieved in situ (kg/m^3)	Bulk density achieved in the laboratory (kg/m^3)
SB1 (65/35)	1720	1870–1930
SB2 (65/35)	1910	1870–1930
SB13 (50/50)	1640	n. d.
SB15 (0/100)	1690	1730–1820
Mock-up Test 2 (65/35) (for comparison)		2070

measurements. The result was that the applied injection pressure was not sufficient to induce an outflow at the top of the borehole. Increasing the injection pressure to 1.1 MPa led to measureable outflow at the seal top, and a water permeability of 4.2×10^{-18} m^2 was determined. Afterwards, gas injection resulted in a gas entry pressure of 0.45 MPa and a gas permeability at break-through around 10^{-16} m^2. All in all, the results of this test were quite in line with the preceding laboratory and mock-up tests, showing that the sand/bentonite mixture fulfilled the requirements.

The fourth test, SB13, involved pure granular bentonite as sealing material. As could be expected, much higher swelling pressures (>3 MPa) were obtained here, although it was not possible to completely re-saturate the sealing element within the experiment time.

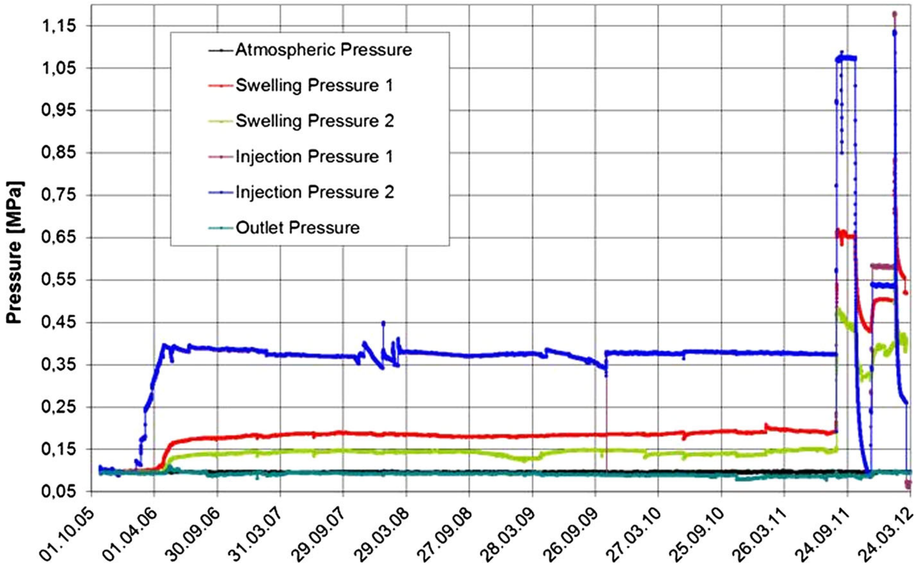
After finishing the experiment, samples were taken from all boreholes between November 2011 and March 2012. This involved retrieving of the concrete plug and the packer and drilling core holes into the seal and the surrounding rock (Fig. 19). The samples were evaluated in terms of water content. For the samples from SB2, the water content ranges between 16.1 and 20.5%, except for the sample with higher water content. This is in good agreement with the mock-up test. For SB1 and SB15, the water content values are much higher (23–35%), as a consequence of their low emplacement density. Water content measurement of SB13 (29.8% in average) showed that the pure bentonite seal was close to full saturation.

6 Conclusions and perspective

The experiments described here illustrate the effort that is put into in situ testing of bentonite-based buffer and sealing materials. All experiments faced considerable difficulties in installation, operation or evaluation. Still, in connection with laboratory and simulation work they either were successfully completed (EB and SB) or are on a very good way (HE-E).

It was shown that the experiments could mostly be set up at the required conditions and that, if so, both the bentonite and, in case of SB, the sand/bentonite material meet the requirements and perform as expected. Thus, the in situ experiments clearly show that buffer and seal elements can be constructed in a way to meet the expectations raised by small-scale testing. It was, however, also shown that interaction with the host rock causes additional effects in the buffer or seal that cannot always be quantified or even anticipated from the experience of small-scale tests (such as re-saturation by pore-water from the rock, interaction with the excavation damaged zone in terms of preferential flow or mechanical effects), so that testing of the integral system buffer/rock or seal/rock is required.

Fig. 18 Injection pressure and swelling pressure evolution at SB2 (Rothfuchs et al. 2012)



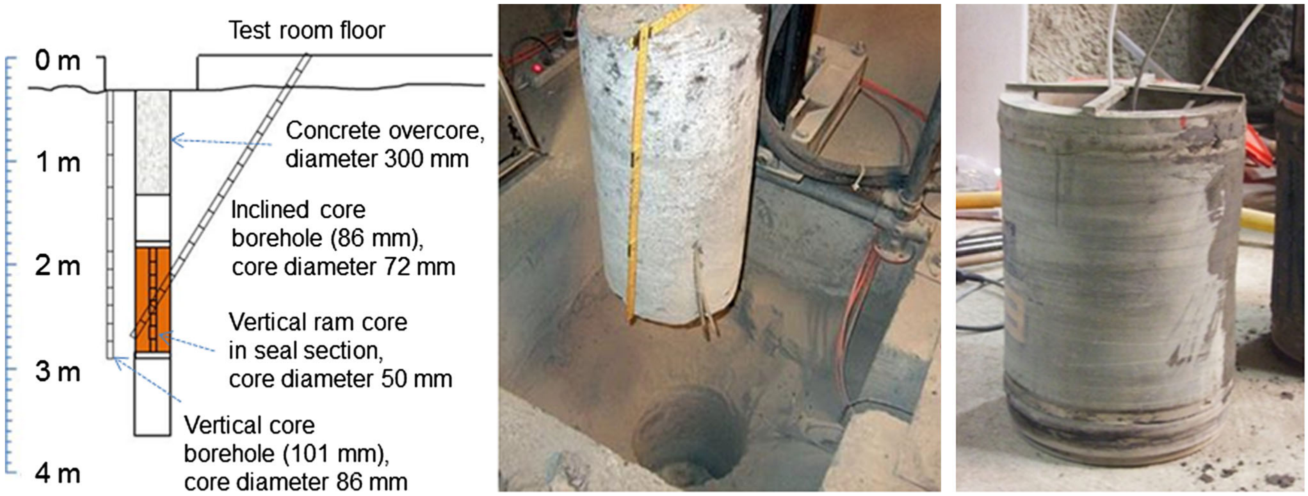


Fig. 19 Sampling overview of borehole SB2 (*left*), retrieved concrete plug (*centre*) and packer (*right*) (Rothfuchs et al. 2012)

All experiments show that for an adequate design and a successful evaluation, reliable model simulations are necessary. Modelling is not a topic of this paper, but detailed information can be found in another paper of this volume (Gens et al. 2017).

In-situ testing of bentonite-based materials is going on: The HE-E is still running in order to follow the slow natural buffer re-saturation, but it is also complemented by Nagra's Full-Scale Emplacement Experiment (FE) which is reported by Mueller et al. (2017). And borehole or shaft seals are planned to be further investigated at the Mont Terri rock laboratory in a new in situ experiment implementing a borehole seal in sandwich architecture, a system which was already tested in mock-up experiments (Emmerich et al. 2012).

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