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ENGINEERING STUDIES
and
DEMONSTRATION of REPOSITORY DESIGNS

A brief presentation of the SB experiment

***(S**elf Sealing **B**arriers of Clay/Sand Mixtures)

Part of Project Module 1 "Buffer Construction Technology"

SIXTH EURATOM FRAMEWORK PROGRAMME for NUCLEAR RESEARCH

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Management of Radioactive Waste

GRS nagra

Introduction

Currently, highly compacted bentonite buffers are studied in the frame of several concepts for the final disposal of high-level waste (HLW). In 2000, GRS started investigations on the suitability of moderately compacted clay/sand mixtures as a sealing material in clay repositories. Such mixtures may represent a reasonable alternative to highly compacted bentonite buffers, especially for the safe closing of repository rooms containing gas generating waste, since they will act as a gas vent thereby avoiding the development of undesired high gas pressures in the disposal cells. The granular material mixtures may be used as buffer and/or as sealing backfill in disposal boreholes or disposal drifts containing either Nuclear Spent Fuel (NSF) or vitrified HLW.

In contrast to highly compacted buffers, moderately compacted clay/sand mixtures exhibit a

- **low gas entry/break-through pressure** in the saturated state while providing a
- **high permeability to gas** in the unsaturated state and a comparably
- **adequate low permeability to water or self-sealing potential against water, respectively** due to swelling of the clay minerals after water uptake from the rock.

The objective of the SB experiment is to test and demonstrate that the sealing properties of clay/sand mixtures determined preliminarily in the laboratory can be technically realized and maintained under repository relevant in-situ conditions. The test programme consists of three steps:

- **laboratory investigations/mock-up tests (GRS-laboratory in Braunschweig)** for selection of suitable seal material mixtures, determination of petrophysical parameters, and testing of material installation techniques
- **design and scoping calculations (GRS Braunschweig)** for in-situ test preparation with a focus on duration of seal saturation under in-situ conditions
- **in-situ tests (Mont Terri Rock Laboratory (MTRL))** for verification of seal performance (mainly hydraulic behaviour) under in-situ conditions

Laboratory Investigations for Selection of Suitable Clay/Sand Mixtures

In the GRS-laboratory in Braunschweig, different clay/sand mixtures with mixing ratios between 35clay/65sand and 70clay/30sand have been investigated with regard to their sealing performance. Figure 1 shows one type of oedometer cell as used by GRS for the determination of swelling pressures.

Figure 1 GRS oedometer cell

The investigations have shown that the requirements given in Table 1 below are best met by a 35clay/65sand and a 50clay/50sand mixture. That is why these mixtures have been selected for further testing under in-situ conditions at the MTRL.

Large-Scale Mock-up at GRS's Geotechnical Laboratory in Braunschweig/Germany

Before going *in situ*, both the installation techniques and the required saturation time for the material mixtures being considered were to be investigated and optimized in large-scale mock-up tests in the above-ground laboratory at Braunschweig. The principle layout of the test tubes used and the test setup are shown in Fig. 2 and Fig. 3.

The mock-up tests have been set up in vertically arranged steel tubes with the same diameter of 0.31 m as the in-situ boreholes. The tube length is 2.5 m and the sealing material is installed in thin layers of

Table 1 Comparison of measured material parameters with pre-determined requirements (averages in parentheses)

Measured parameters at installation conditions					
Mixture	Gas permeability under dry conditions	Initial water permeability at full saturation	Gas break-through pressure	Gas permeability after gas break-through	Swelling pressure
Clay/sand	m^2	m^2	MPa	m^2	MPa
35/65	1.2E-13	3.3E-17 - 9E-18 (5.2E-18)	0.4 - 1.1 (0.75)	1.1E-17 - 1.6E-17 (1.4E-17)	0.2 - 0.4 (0.28)
50/50	7.5E-14	1.1E-18 - 4.3E-18 (2.2E-18)	0.4 - 2.8 (1.83)	5.5E-18 - 6.2E-18 (5.9E-18)	0.3 - 0.5 (0.35)
70/30	1.2E-15	5.5E-19	1	n.d.	0.4-?
Requirements					
	Gas permeability under dry conditions	Initial water permeability at full saturation	Gas break-through pressure	Gas permeability after gas break-through	Swelling pressure
	high	1E-17 - 1E-18	2	high	2

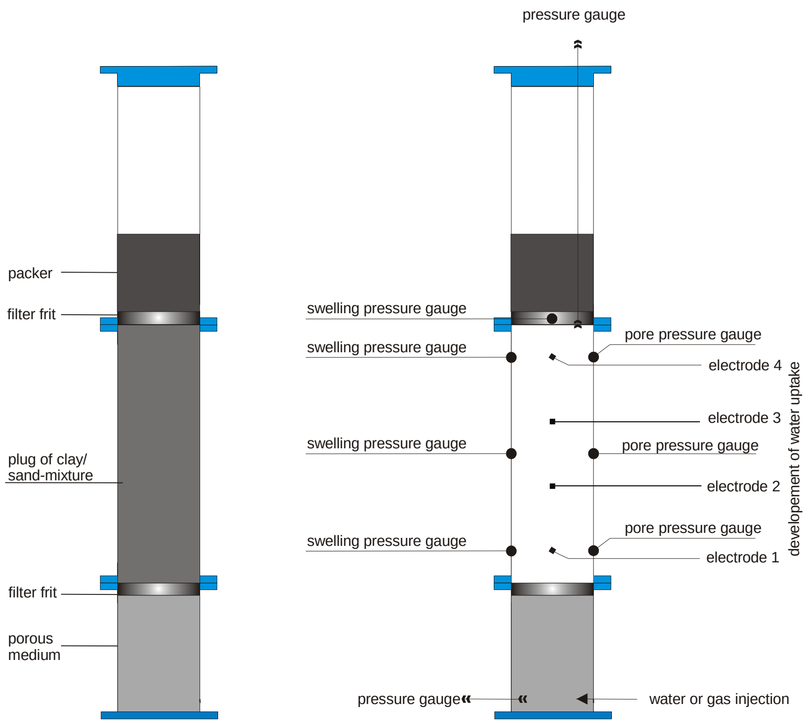


Figure 2 Principle layout of laboratory test tubes with the locations of measuring sensors

Figure 3 Mock-up test in GRS's geotechnical laboratory (left: test set-up, right: packer installation)

about 5 to 10 cm in a similar way as *in situ*. Different techniques (hand stamping, vibrator technique) have been tested and the achievable density has been determined. Additionally, the gas permeability, the time required to achieve saturation, the water permeability, the gas entry/break-through pressures, and the gas permeability after the break-through will be determined in the course of the test in order to provide adequate experimental data and experiences for the design of the in-situ experiments at Mont Terri.

The detailed objectives of the mock-up tests are as follows:

- Development and testing of material mixing methods
- Development and testing of material installation techniques
- Determination of the time needed to reach full seal saturation
- Determination of gas and water permeability as well as gas entry/break-through pressure at dry and saturated conditions
- Test of pre-selected measuring instruments.

The installation density of the mock-up seal element consisting of a 35clay/65sand mixture amounted to 1.94 g/cm^3, right after seal installation. In the dry state a gas permeability of 6.2E-14 m^2 was determined. As can be seen in Fig. 4, after about 18 months of testing, the total pressure in the seal equalized in the lower and middle part of the seal (red and blue lines) at a value of about 1.1 MPa which corresponds to the applied water injection pressure.

Surprisingly, one does not see a similar evolution of the pressure at top of the seal (green line). However, after a testing period of meanwhile more than 36 months, the total pressure at the packer bottom now seems to stabilize at a final value slightly below 3 bars (Fig. 4 right) which would be very close to the swelling pressures determined on the small laboratory samples (compare Table 1) Thus, it is very likely that the seal function at full saturation will fulfil the requirements given in Table 1.

The first water break-through, indicating a situation close to full seal saturationl, was observed in September 2007, after about 29 months of testing. A first assessment of the seal permeability to water yielded a value of about 1E-18 m^2 which is in very good agreement with the data determined at the small samples used in the laboratory. Also

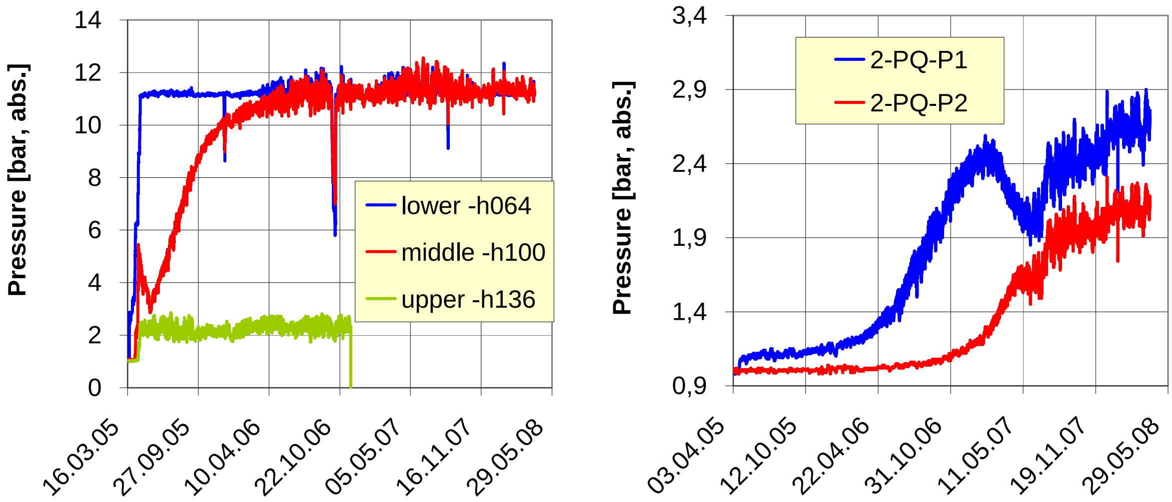


Figure 4 Evolution of total pressure in the mock-up (left: Total pressure along the mock-up, right: Total pressure at packer bottom)

this preliminary result confirms that the required seal function given in Table 1 is fulfilled. The long time until water break-through, however, exceeds the predicted saturation period (compare section "Numerical Simulation" below) significantly. Further research is thus needed to clarify this discrepancy and to enhance the respective process understanding for further model improvement.

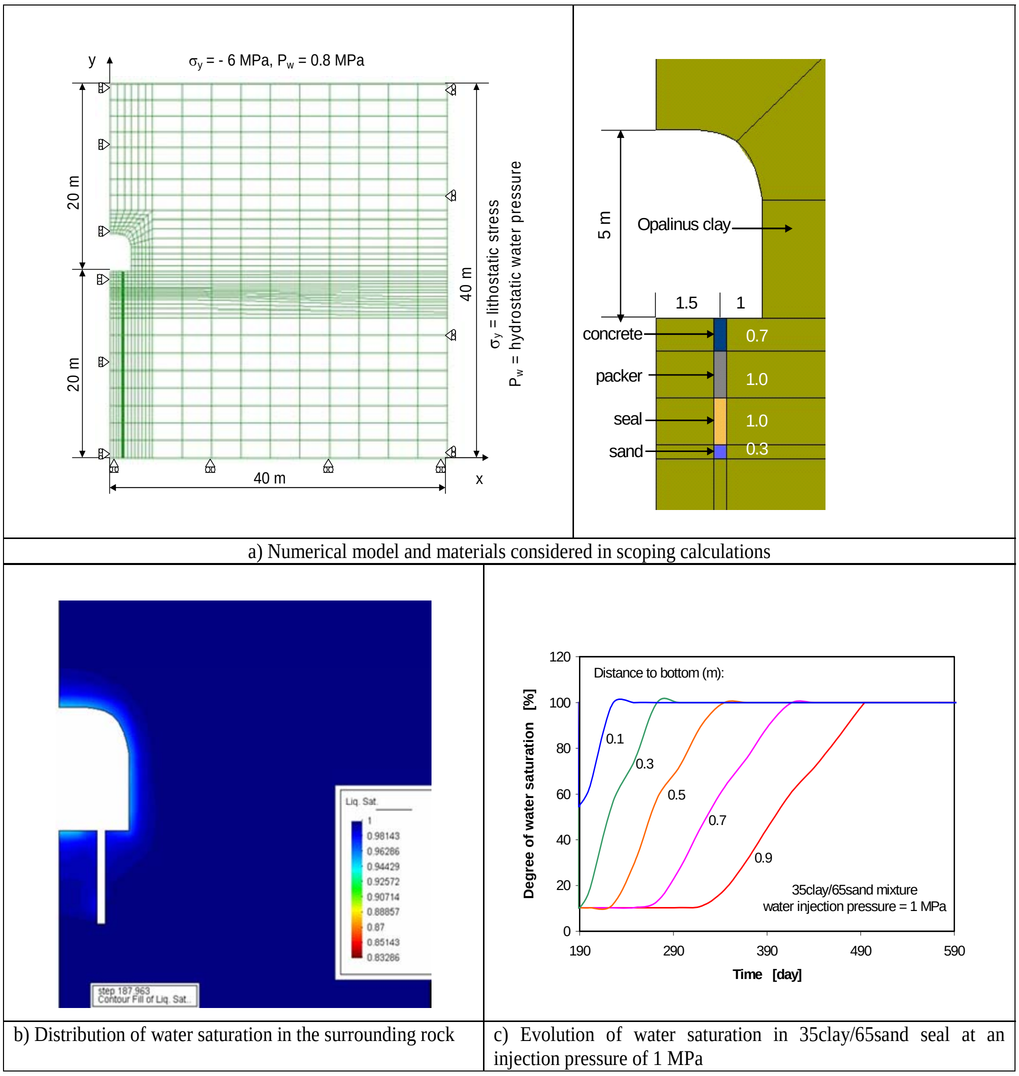
Numerical Simulation

For designing the mock-up and in-situ tests, scoping calculations have been performed by applying the material parameters determined in the laboratory. The calculations focused on the prediction of testing conditions such as injection pressures for water and gas, time needed to reach seal saturation, ranges of measuring parameters (gas and water flux, swelling pressure, total pressure etc.), and the determination of initial and boundary conditions in the in-situ test field prior to the start of testing. In the scoping calculations, the materials installed in the mock-up and in-situ tests were assumed as homogeneous and isotropic.

After the installation of the seal in the borehole, the water injection phase was simulated by applying a water pressure of 0.5 or 1 MPa to the lower porous fluid injection chamber. Figure 5 illustrates the evolution of water saturation at some selected points in the 35clay/65sand seal at an injection pressure of 1 MPa. The seal is saturated from the bottom to the top. The time needed for full saturation at an injection pressure of 1 MPa is about 10 months. Because the permeability of the seal is higher than that of the surrounding clay rock (EDZ was not simulated here), the water flow occurs mainly through the seal.

Mt. Terri Underground Rock Laboratory (MTRL)

For practical reasons and before going into full-scale experiments *in situ*, borehole experiments of reduced scale were planned at the MTRL. A view into the fully instrumented test niche is given in Fig. 6. The SB experiments are performed in vertical boreholes of 0.31 m diameter drilled to a depth of 3 m into the floor of the test niche of 5 m width, 4 m height and 8 m length (Fig. 7). Three boreholes are sealed with 35clay/65sand and 50clay/50sand mixtures, and one borehole for comparison with crushed clay pellets only. The lengths of the seals are 1 m and 0.5 m, respectively. Instruments for measuring different hydro-mechanical parameters have been installed as well.



a) Numerical model and materials considered in scoping calculations

b) Distribution of water saturation in the surrounding rock

c) Evolution of water saturation in 35clay/65sand seal at an injection pressure of 1 MPa

Figure 5 Prediction of initial distribution of water saturation in the rock and evolution of water saturation in a 35clay/65sand seal.

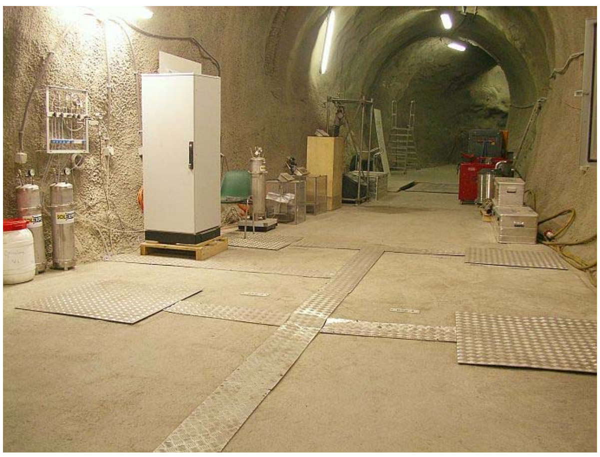


Figure 6 Test Niche at MTRL for the SB experiment

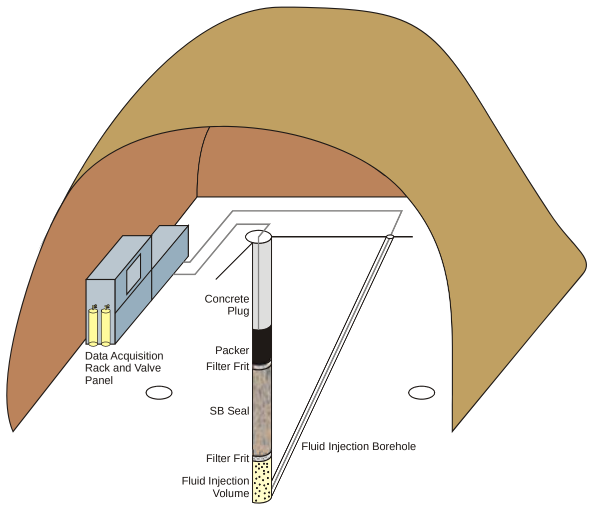


Figure 7 Design of the SB experiment in a test niche at the MTRL

In the lower part of the boreholes (Fig. 7), the injection volume is filled with gravel as porous medium. At the top of the porous medium, a filter frit is placed for ensuring a homogeneous distribution of the injected water over the entire borehole cross section. Above the filter frit, the seal is installed in several layers.

Above the seal, a further filter frit is installed for water and gas collection. The entire borehole is sealed against the ambient atmosphere by a gastight packer. At the bottom of the packer, two swelling pressure sensors are installed. The uppermost part of the test borehole is grouted for keeping the packer in place at the higher swelling pressures developed by the SB seal.

In Figures 8 and 9, the evolution of the total pressures measured in the test boreholes BSB2 and BSB13 is depicted. Borehole BSB13 was filled with pure MX-80 bentonite granulate from Nagra, buffer material from the Module 1 ESDRED bentonite emplacement tests. The injection pressure amounts to approximately 4 bars (abs.). The swelling pressure is one of the relevant parameters for the assessment of the seal performance.

At the seal with the lower clay content of 35% (Fig. 8), the measured swelling pressures amount to 1.5 and 1.9 bars (abs.), respectively. In contrast, the swelling pressure of the pure bentonite granulate develops slowly but continuously (Fig. 9). The measured swelling pressure of 20 bars (abs.) at present is, as expected, significantly higher than those of the clay/sand mixtures.

Figures 4 and 8 indicate that the swelling pressures of the clay/sand mixtures used in the mock-up and in the respective in-situ experiments will be in the same order of magnitude as those determined on the laboratory test samples (compare the value of 0.2 – 0.4 MPa in Table 1). Thus, similar sealing properties as observed on small samples in the laboratory can also be expected in the in-situ experiment.

Also in the in-situ experiment a longer saturation time seems to be needed as the respective water break-through did not take place during the hitherto testing period of actually about 26 months. Testing will thus be continued in the forthcoming months.

The sealing performance of the pure bentonite seal is to be tested for comparison, after full saturation is reached.

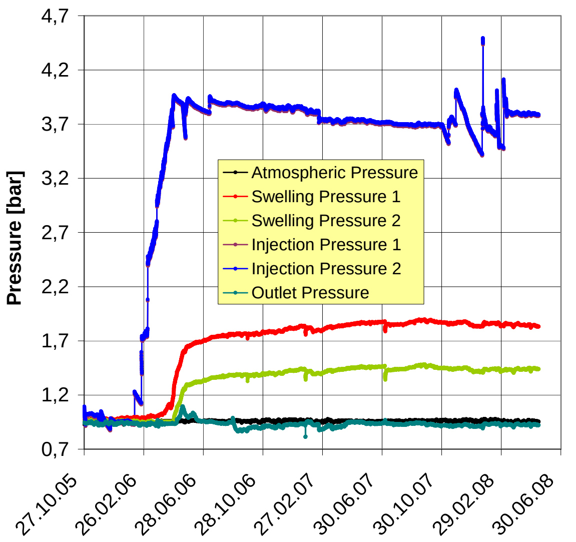


Figure 8 Pressure evolution in test borehole BSB2 sealed with a 35clay/65sand mixture

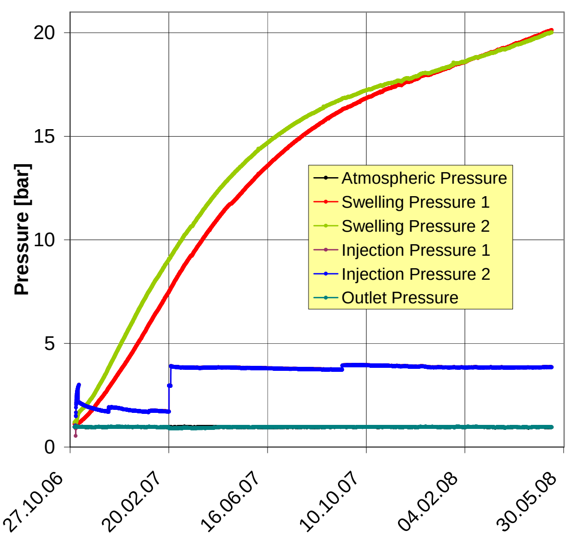


Figure 9 Pressure evolution in test borehole BSB13 sealed with pure bentonite granulate (NAGRA mixture)

Conclusions

The preliminary results of the SB-experiments at the MTRL appear to confirm the advantageous sealing properties of moderately compacted clay/sand mixtures which were previously determined on small samples under ideal conditions in the laboratory. The time needed to reach full saturation of the test seals in both the mock-up and the in-situ experiment, however, exceeds the predictions significantly. Further efforts will be needed to clarify the observed discrepancies, to improve the needed process understanding and to develop further the models in use.

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