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Efficiency of a borehole seal by means of pre-compacted bentonite blocks

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Abstract

The backfilling and sealing of shafts and galleries is an essential part of the design of underground repositories for high-level radioactive waste. Part of the EC funded project RESEAL studied the feasibility of sealing off a borehole in plastic Boom Clay by means of pre-compacted bentonite blocks. Two bentonites, namely the FoCa and Serrata clay, have been used. Based on laboratory tests, the bentonite blocks had an initial dry density of about 1.8 g/cm^3 to obtain a swelling pressure of about 4.4 MPa, corresponding to the in situ lithostatic stress, at full saturation. The set-up was equipped with several sensors to follow-up the behaviour of the seal and the surrounding host rock during hydration. Full saturation was reached after five months and was mainly reached by natural hydration. Swelling pressure was lower than originally foreseen due to the slow reconsolidation of the host rock. Later on, the efficiency of the seal with respect to water, gas and radionuclide migration was tested. The in situ measured permeability of the seals was about 5×10^{-13} m/s. A gas breakthrough experiment did not show any preferential gas migration through the seal. No evidences of a preferential pathway could be detected from ^{125}I tracer test results.

Keywords: Seal; Bentonite; Migration; Diffusion; Radwaste

1. Introduction

Geological disposal of high-level radioactive waste is currently considered a safe solution to ensure the long-term isolation from the biosphere. The backfilling and sealing of shafts and galleries is an essential part of underground repository designs. Any opening created during the repository construction might be a potential preferential pathway for water, gas and radionuclides migration, and has to be effectively sealed afterwards. The demonstration of the feasibility of the sealing on a representative scale is therefore essential. For more than 10 years the applicability of highly compacted bentonite has been investigated for this purpose. The low permeability, high swelling and high sorption capacity of bentonite make it a very effective barrier.

The borehole sealing test is part of the EC funded RESEAL project. RESEAL is 'a large scale in situ demonstration test for repository sealing in an argillaceous host rock'. The project aims at demonstrating the sealing of an experimental shaft and a borehole in the HADES underground research facility (URF) in Mol, Belgium. The HADES URL is situated in the plastic Boom Clay at 220 m below surface. The shaft sealing experiment aims at sealing an experimental shaft with a mixture of highly compacted bentonite pellets and bentonite powder. The shaft sealing experiment is still running. Intermediate results can be found in Volckaert et al. (2000) and Van Geet et al. (2005).

Here, an overview of the borehole sealing experiment, which is now finished, will be given. The borehole sealing

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experiment aimed at sealing a borehole in the plastic Boom Clay Formation by means of pre-compacted blocks of bentonite. The pre-compaction makes it possible to obtain the required dry density of bentonite and hence to get the required permeability of the seal. The pre-compaction technique has been discussed in detail by Volckaert et al. (2000). The experimental set-up used two bentonite materials, namely the French FoCa mixed-layer clay and the Serrata smectite clay. The set-up was focussed on characterising the hydration behaviour of the bentonite blocks, the bentonite – host rock interaction and the radionuclide migration through the seal.

2. Experimental set-up

The experimental set-up consists in a 250 mm diameter and 2.6 m long piezometer installed about 15 m deep into the clay in the HADES URL (Fig. 1). It is divided in two parts, the first part is dedicated to the sealing experiment (~2 m long), and the second to the gas generation experiment (~0.6 m long). The gas generation experiment is not included in the RESEAL project, but has been performed in the frame of the EC PROGRESS project (Rodwell, 2000).

Boom Clay consists of sandwiched silty clay and clayey silt layers of approximately 0.5 m thickness (Vandenberghe, 1978). The sealing experiment is located between 13 and 15 m from the gallery wall in a horizontal well. Because of the slight dip (1%) of Boom Clay strata and the horizontal continuity of lithological layers, fairly good prediction of the performance is possible (NIROND, 2003) since the seal experiment is located in one single lithological layer (layer number 90), composed of silty clay. Hydromechanical tests on both types of layers (silty clay and clayey silt) do not show a significant difference, so that one single set of parameter values can be used for the whole Boom Clay thickness. Some Boom Clay parameters show an anisotropy, e.g. the hydraulic conductivity parallel to bedding is about a factor two higher than perpendicular to bedding. However, when performing hydraulic conductivity measurements with a piezometer in Boom Clay, the horizontal parameters dominate. Consequently, it is justified to use a single set of parameters as described later on. Some mechanical parameters might also exhibit anisotropy, but such parameters are not explicitly represented in this pure hydraulic model.

The RESEAL borehole sealing set-up includes two testing compartments of 55 cm length with a central tube of about 56 mm diameter equipped with filters and "total pressure" sensors. The compartments are filled with pre-compacted blocks of Serrata clay and FoCa clay installed around the central tubes.

The FoCa clay is a sedimentary clay from the Paris Basin, extracted in the Vexin region and supplied by the SFBD Company. The major component (i.e. 80% of the clay fraction) is an interstratified clay of 50% calcium beidellite and 50% kaolinite. It contains also kaolinite, quartz, goethite, hematite, calcite and gypsum (Coulon, 1987; Lajudie et al., 1994). The industrial process consists of drying, grinding and sieving (max. grain size: 2 mm). The Serrata clay is a bentonite coming from the Cortijo de Archidona deposit (Almería, Spain), selected by ENRESA as suitable material for the backfilling and sealing of HLW repositories. The same clay is used for the FEBEX Project in the in situ (Grimsel, Switzerland) and the mock-up (Madrid, Spain) tests (ENRESA, 1998, 2000). The processing at the factory has consisted in disaggregation and gently grinding, drying at 60 °C and sieving (max. grain size: 5 mm). It has a montmorillonite content higher than 90%. The predominant phyllosilicate is in fact a smectite/illite mixed layer, with 10–15% of illite layers. Besides, it contains variable quantities of quartz, plagioclase, K-feldspar, calcite and opal-CT (cristobalite-trydimite).

The "total pressure" measurements are performed with miniature pressure sensors embedded in the set-up. Behind each filter, there is a chamber and each chamber is connected to the main gallery by two microtubes. One tube is connected to a pressure sensor installed in the gallery

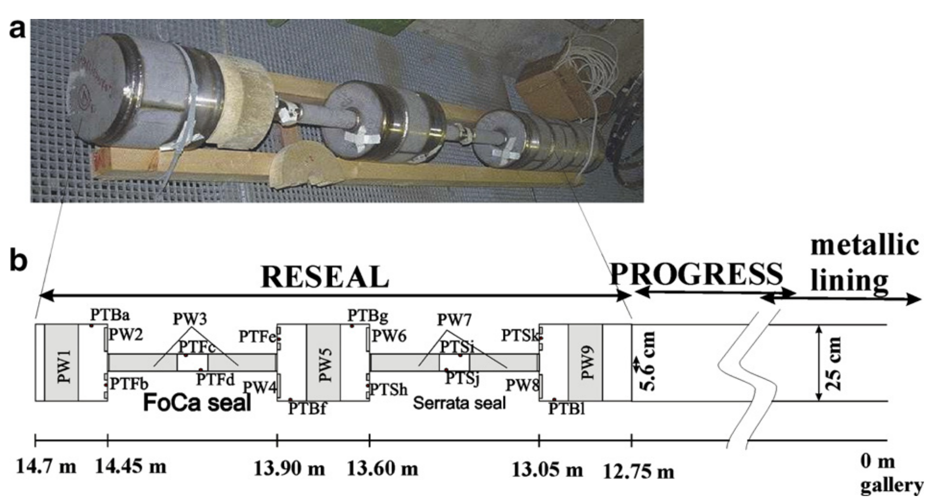

Fig. 1. Photograph (a) and schematic view (b) of the piezometer used in the RESEAL borehole experiment.

and the other tube is planned to be used for water or gas injection.

The lateral faces of the compartments consist of circular filters in which total pressure sensors are included. The different positions of the total pressure sensors give the opportunity to monitor the radial and the longitudinal stress in the seals. Close to the seal compartments, filters and total pressure sensors are installed. These water pressure and total stress measurement points are in contact with the host rock formation after convergence of the clay around the piezometer.

Fig. 1 gives an overview of filter and sensor positions and names. The total stress sensors are identified by PT, followed by B for the sensors in contact with the Boom Clay, F for the sensors in contact with the FoCa clay and S for the sensors in contact with the Serrata clay and finally, a last letter identifies the sensor. A number from 1 to 9 preceded by PW identifies the filters.

3. Experimental programme

During the long period of time that the RESEAL project was running, many tests have been performed on the borehole sealing experiment. Table 1 gives an overview of the chronological evolution of the borehole sealing experiments.

3.1. Installation

The two seals made of half cylindrical elements were fixed together around the central hydration tube of each compartment with fine metallic wires. Fig. 2 illustrates the dimensions of the seal during installation and Table 2 gives the main characteristics of the seals before the installation. The dry density of the blocks of FoCa clay was 1.88 g/cm^3, while for the Serrata clay it was 1.76 g/cm^3. After hydration the joints between the blocks will disappear and when the sealing blocks exactly fill the sealing compartments, the seals will have a reduced dry density of 1.6 g/cm^3 and 1.5 g/cm^3 for Foca and Serrata clay, respectively. These dry densities were chosen to obtain a swelling pressure of 4.4 MPa at full saturation as evolved from laboratory experiments by Volckaert et al. (2000), the pressure corresponding to the lithostatic stress at the depth of the HADES laboratory.

A horizontal borehole of 275 mm diameter and 14.7 m depth was drilled in the Test Drift part of the HADES URF towards the east. The set-up of 2.6 m long was introduced at the end of the borehole and the rest of the borehole was lined with a metallic tube. The difference between the diameter of the set-up and the borehole was foreseen to guarantee an easy installation of the equipment. The installation was done on the December 3rd, 1997. Immediately after the installation, the total pressure sensors were connected to the data acquisition system for following up the convergence of the borehole around the set-up.

Table 1
Chronological overview of the experiments performed on the borehole seal

2 December 1997	Start of drilling
3 December 1997	End of drilling and installation of the sealing
4 December 1997	Start data acquisition for total pressure measurement
8 January 1998	Start data acquisition for water pressure measurement
15 April 1998	Start of the artificial hydration through filters 3 and 7
16 September 1998	End of artificial hydration
15–25 February 1999	Permeability test of the FoCa seal
17–26 March 1999	Permeability test of the Serrata seal
7 April–25 September 1999	Gas breakthrough experiment
6 June 2002	^{125}I tracer injection in filter 3
29 January 2004	End of the migration test

3.2. Hydration

Figs. 3 and 4 show the water pressure and total stress evolution during hydration in the FoCa and Serrata seals, respectively, together with the pressure evolutions at the Boom Clay interface near each seal. Three months after the installation of the piezometer, convergence of the Boom Clay around the piezometer was observed. Once

Table 2
Main characteristics of the seals before installation

	FoCa seal	Serrata seal
Length of the seal	51.8 cm	52.1 cm
Initial volume of the seal	22956 cm^3	23111 cm^3
Weight	48085 g	45666 g
Density	2.09 g/cm^3	1.97 g/cm^3
Grain density	2.65 g/cm^3	2.65 g/cm^3
Initial water content versus dry weight	11.16%	12.42%
Porosity	0.29	0.34
Initial dry density of the seal	1.88 g/cm^3	1.76 g/cm^3

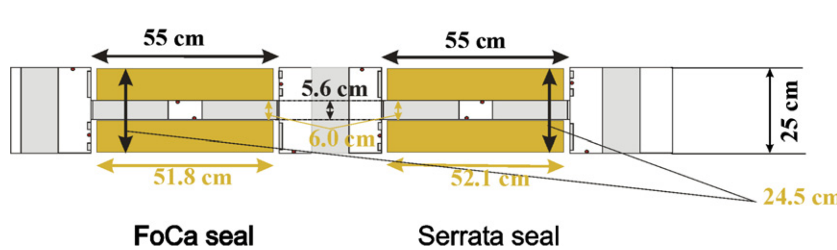

Fig. 2. Schematic view of the RESEAL borehole experiment with an overview of the dimensions of the seals at the moment of installation.

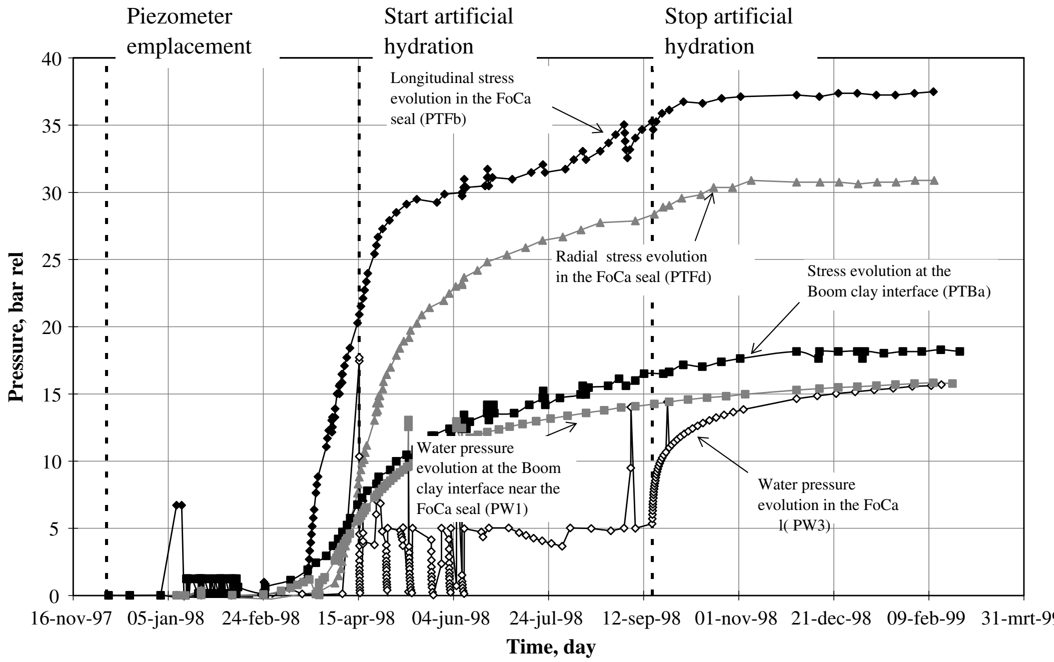

Fig. 3. Water pressure and total stress evolutions in the FoCa seal and at the Boom Clay interface near the seal.

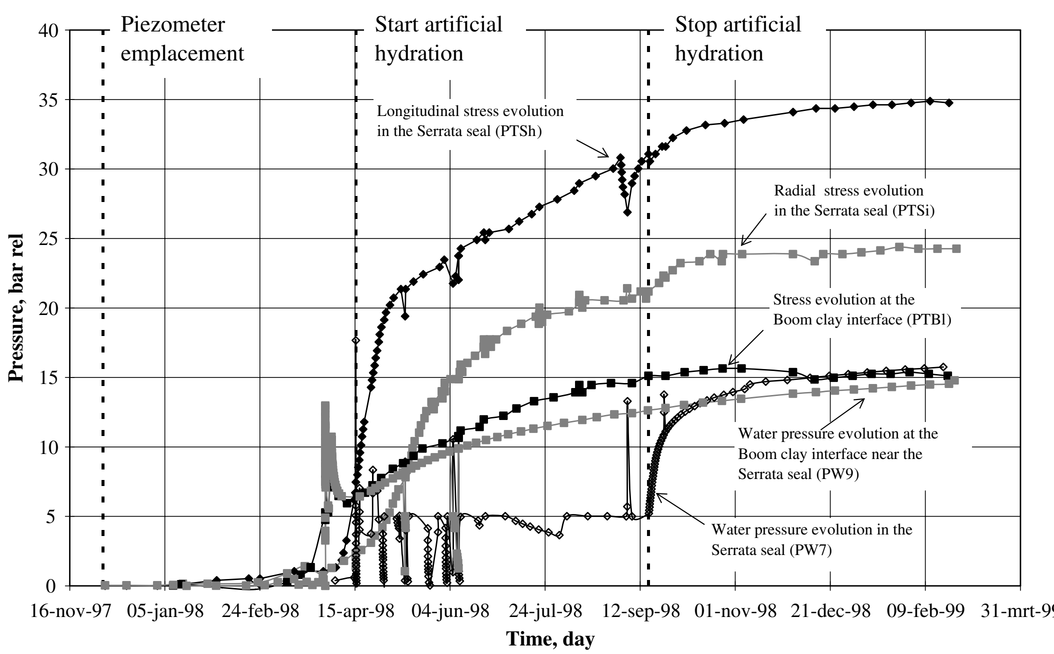

Fig. 4. Water pressure and total stress evolutions in the Serrata seal and at the Boom Clay interface near the seal.

convergence has taken place, a substantial water exchange between host rock and seal starts. The convergence gradually progresses from the rear end of the piezometer towards the gallery, related to the larger disturbance caused by the borehole drilling close to the gallery. This causes the pressure increase to be faster in the FoCa seal, compared to the Serrata seal. For both sealing compartments, the radial stress evolution shows a small time lag compared to the longitudinal stress evolution.

On April 15th 1998, the artificial hydration through the central filters started. Water was injected at 0.5 MPa. The water injection was stopped on September 16th, 1998. 0.5 and 0.7 l of water were injected in the FoCa and Serrata seal, respectively. After the artificial water injection, the pore water pressure slowly continued to increase up to the in situ pore water pressure of 1.5 MPa.

Over the length of the piezometer, a pore water pressure decrease was noticed from the rear end of the piezometer towards the gallery, caused by the natural drainage towards the gallery. However, an anomaly in this trend was found in both seals, but with the largest discrepency at the Serrata clay seal. A chemical analysis of pore water sampled from this Serrata Clay showed an increase in salinity by a factor 10 compared to the salinity of the Boom Clay pore water. This pore water pressure anomaly might be caused by osmosis.

Based on the total pressure and pore water pressure analyses, the swelling pressures of the seals have been calculated. For the FoCa seal, a homogeneous swelling pressure was observed. The longitudinal swelling pressure is 3.80 MPa and the radial swelling pressure was 3.2 MPa. For the Serrata seal the swelling pressure was heterogeneous. The longitudinal swelling pressure ranged between 2.9 and 3.6 MPa and the radial swelling pressure ranged between 2.6 and 2.7 MPa. From the swelling pressures measured in the seal and detailed calibrations of the swelling pressure versus dry density in laboratory experiments (Volckaert et al., 2000), it was possible to calculate the reduced dry density of the seals due to the increase of the seal volume during hydration. A reduced dry density of 1.54 and 1.36 g/cm^3 are obtained for the FoCa and Serrata seal, respectively. From these data, the main characteristics of the seals after saturation have been calculated (Table 3). After saturation and assuming a cylindrical shape of the seal, a diameter of 26.08 and 26.85 cm were obtained for the FoCa and Serrata seal, respectively.

3.3. Permeability test

Permeability measurements have been performed in February and March 1999, after saturation on the FoCa and Serrata seals. The pressure on the filters 3 and 7 has been reduced to the atmospheric pressure to create a water pressure gradient through the seals, i.e. between the host rock and the central filter of both seals. From the following equation (Put et al., 1994; Bastiaens and Mertens, 2005; Bastiaens et al., 2005) the hydraulic conductivity can be calculated:

$$K = \frac{Q}{F \cdot \Delta P}$$

with K, hydraulic conductivity (termed permeability in this paper) (m/s); Q, flow (m^3/s); ΔP, pressure difference between the water pressure in the host rock and the water pressure in the filters; F, filter form factor for circular filter

$$F = \frac{2 \cdot \pi \cdot (l - D)}{\ln \frac{l}{D}}$$

with l, filter length (44 cm in this case); D, filter diameter (5.6 cm in this case).

This estimation was done for a pressure difference (ΔP) of 1.54 MPa for the FoCa seal and 1.49 MPa for the Serrata seal. We obtained a hydraulic conductivity of 4.3×10^{-13} m/s for the FoCa seal and 5.5×10^{-13} m/s for the Serrata seal.

Table 3
Main characteristics of the seals after saturation

	FoCa seal	Serrata seal
Length of the seal	55 cm	55 cm
Diameter of the filter 3 and 7	5.6 cm	5.6 cm
Reduced dry density	1.54 g/cm^3	1.36 g/cm^3
Final volume of the seal	28053 cm^3	29792 cm^3
External diameter of the seal	26.09 cm	26.85 cm
Water content at saturation versus wet weight	27.1%	35.6%

3.4. Gas breakthrough test

To test the gas sealing ability a gas injection was carried out. Gas was injected in the host clay formation from the filter PW1 (Fig. 1) close to the FoCa seal compartment at the end of the borehole. Fig. 5 shows the evolution of the pressures in and around the FoCa during the injection.

The gas pressure was increased step by step. Before gas breakthrough diffusion of dissolved gases occurred, resulting in a rather constant volume of gas injected. The gas breakthrough, which implies gas transport in gaseous phase, occurred at a pressure level of about 3.1 MPa (recorded on PW1), i.e. a pressure equal to the radial total stress measured in the FoCa seal (PTFc) before the start of the gas injection. The breakthrough has been detected on the filter PW5 in contact with the Boom Clay located between the two seals. The breakthrough was confirmed by a sudden increase of the gas flow rate detected on the injection system. The pressure sensors connected to the filters in the FoCa seal, i.e. PW2, PW3 and PW4 showed a very weak reaction to the breakthrough.

3.5. Radionuclide migration test

In order to test the efficiency of the sealing of a borehole and its surrounding EDZ by means of pre-compacted bentonite blocks, a radionuclide migration test has been set-up. This should yield insight in the possibility of transferring laboratory observations towards in situ conditions with regard to the bentonite behaviour. This migration test was limited to the FoCa seal. On June 6th 2002, 3.5 ml of solution with $3.28e^{+8}$ Bq of ^{125}I labelled NaI was introduced. The half life of ^{125}I is 60.14 days.

PW3 (Fig. 1) is used as injection filter of the ^{125}I labelled NaI solution. It should be noted that due to the limited space in the central tube of the piezometer, one single water conduit with a T branch is used to be connected to both parts of PW3. Pore water sampling during the migration test is performed through filters PW1 and PW5. As to avoid any migration of the ^{125}I labelled water into filters PW2 and PW4, a gas cushion at a pressure, a little bit higher than the in situ pore water pressure is applied at those filters to prevent water inflow.

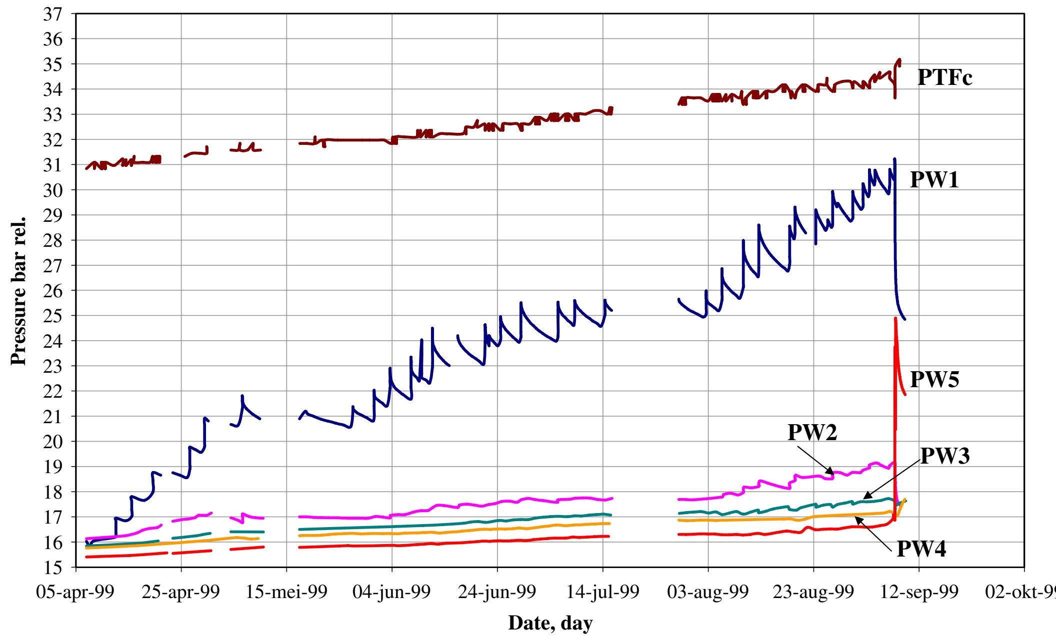

Fig. 5. Evolution of the pressures in and around the FoCa seal during the gas injection.

To perform the migration experiment, a loop of stainless steel tubing of 3.5 ml is filled with Boom Clay pore water containing ^{125}I labelled NaI solution ($3.28e^{+8}$ Bq). One end of this loop is connected to one of the water conduits of PW3. The other end of the loop is connected to the exit of a circulation pump. The inlet of the circulation pump is connected to the other water conduit of PW3. Consequently, a closed system is created. The pump is then used to circulate the water through the filter and the circulation system at a pressure only slightly higher than the in situ pressure at the filter. This creates homogenisation of the tracer and the clay water present in the circulation system. Due to the contact of the filter with the FoCa clay, diffusion of the tracer is enforced with only a small pressure difference. This kind of test is called a diffusive tracer injection.

The sampling from filters PW1 and PW5 is performed periodically with intervals of one month by collecting water during a period of 11–14 days. The dead volume of the water conduits is about 500 ml. A first volume of 500 ml is sampled to rinse the tubing, while a second volume of 500 ml is taken as sample. The first sampling was started on July 29, 2002 and was done in a fractionated way. Each day a sample was withdrawn to follow the flow rate in order to fine-tune further samplings. Sampling was regularly performed for over a period of 600 days in both the PW1 and PW5 filters.

Fig. 6 illustrates the evolution of the ^{125}I concentration for filters PW1 and PW5. It is clear that activity is only measured in the filter nearest to the gallery. In the filter farthest from the gallery, no activity has been measured. This might be caused by an imperfect injection with the used experimental set-up. Using the same water conduits for

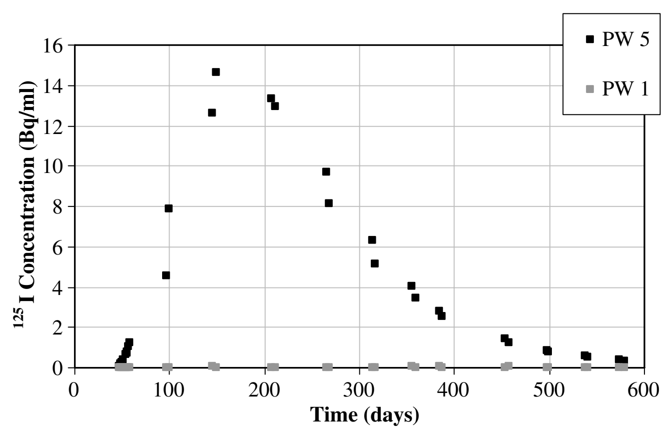

Fig. 6. ^{125}I activity measured in the two filters (PW1 and PW5, see Fig. 1) close to the FoCa seal.

both parts of the injection filter PW3, it is estimated that the labelled water only reached the part of the filter closest to the gallery, where the pressure is lowest. Due to the longer distance to the sampling filter PW1, activity was not measured there.

During the test, pore water pressures of all filters were monitored (Fig. 7). The pressure in filters PW2 and PW4 remained very stable due to the gas cushion. The pressure in the sampling filters PW1 and PW5 showed the expected behaviour: a pressure drop during the sampling and, after sampling, and a rather fast pressure build-up up to nearly the undisturbed in situ pore water pressure. It should be noted that the pressure in the injection filter PW3 showed an unexpected behaviour. It was assumed that the pressure would remain rather constant in this filter during the circulation of the pump. However, careful examination of Fig. 7

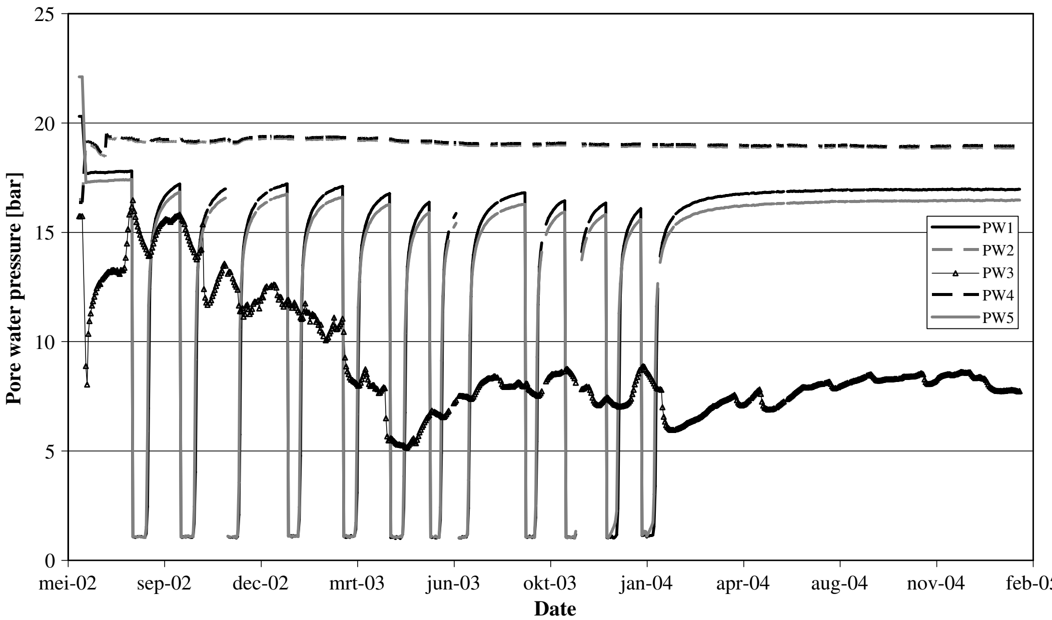

Fig. 7. Pressures measured in filters PW1-5 during the migration experiment.

reveals that the sampling at filters PW1 and PW5 systematically induced a limited pressure drop in injection filter PW3. Moreover, the second sampling was followed by a continuous pressure decrease in PW3, even between sampling events. This was caused by a small leak in the circulation system. The latter could not be fixed during the migration experiment.

4. Discussion

4.1. Hydration

Hydration of the pre-compacted bentonite blocks occurred quite fast (about five months to reach full saturation). The artificially injected volume of water corresponded to about 7% of the total water volume needed for full saturation of the seals. The largest fraction of hydration (more than 90%) thus occurred by natural hydration from the host rock, where the pore water pressure was higher and where the contact surface area was larger, compared to the injection filter. After saturation, the final diameter of the seals was more than 1 cm larger than the 25 cm diameter of the piezometer. This resulted in a lower swelling pressure of the seals than aimed at. This discrepancy is probably related to the quite important disturbance of the host rock by drilling the borehole, causing a slow convergence and reconsolidation.

The hydration of the borehole sealing test, including data obtained after the end of the hydration test, has been calculated by UPC using the CODE-BRIGHT (Olivella, 1995). The data used come from laboratory data and from the in situ permeability tests performed in 1999 on the two fully saturated bentonite seals. A low value for the initial stress inside the Serrata and the FoCa seals has also been considered because of the low reconsolidation of the host clay around the piezometer. Details on the model, equations and parameters used can be found in Volckaert et al. (2000).

A comparison of the results obtained during the modelling and the experiment are shown in Fig. 8 for the Serrata seal. To avoid numerical convergence problems, the simulation has been carried out considering an initial isotropic stress state equal to 0.5 MPa. Saturation is observed close to the time at which PW6 begins to respond. Pore pressure at the time of circuit closure appears to be slightly lower than what was measured. A delay between measurements and simulation results was found for the period April 15th and September 16th. One explanation of the slow response of PW6 may be that it was initially not saturated by being connected to the inner chamber filled with air. The sudden increase of pore water registered at August 9th, 1998 by this sensor could in fact indicate that saturation of the filter was reached. The final calculated swelling pressure remains higher than the measured one. It is, however, difficult to compare the computed and monitored stresses since they evolved from different initial states.

The computed volume of water injected from the central tube was compared with the measured ones. The predicted water intake was nearly zero, while the measured water intake was about 0.7 l.

Results of the final modelling of the FoCa seal are compared with in situ measurements in Fig. 9. Saturation is observed on April 15th, 1998. After this date, computed values of water pressure are higher than the readings at PW2. This fact could be explained in the same way as for sensor PW6, i.e. by desaturation of the filter. In the case of PW2, the sudden increase in the rate of pore water pressure increase is more evident, and the date of saturation of

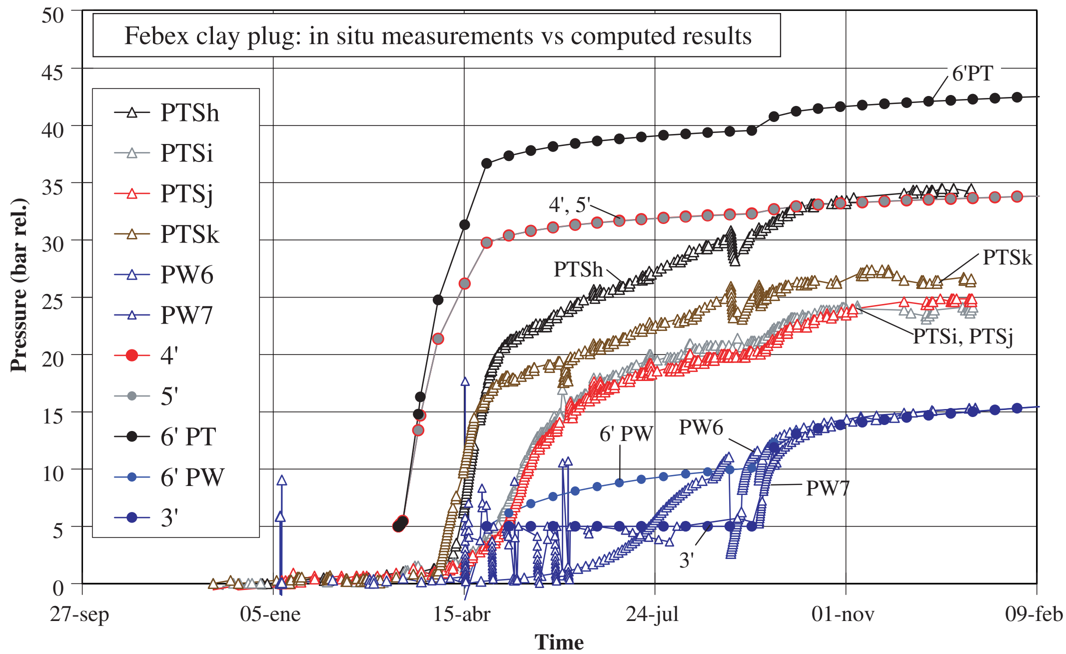

Fig. 8. Comparison between the numerical and the experimental results of the hydration phase of the Serrata clay.

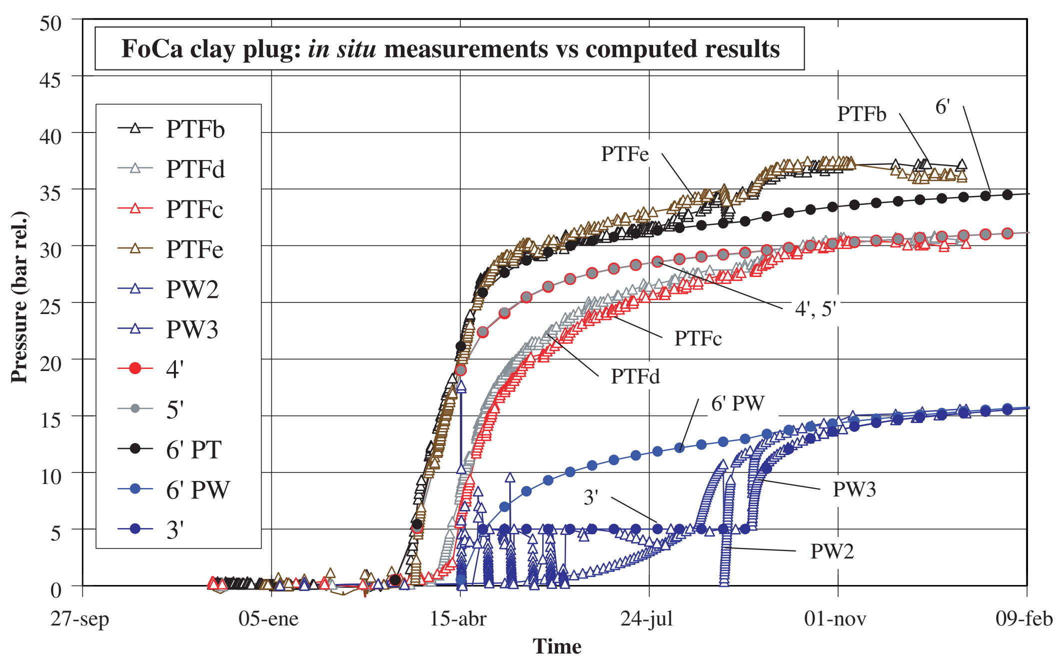

Fig. 9. Comparison between the numerical and the experimental results of the hydration phase of the FoCa clay.

the filter is estimated to have been reached on August 19th, 1998. On the date of circuit closure the water pressure was slightly above the recordings but the total pressure showed good agreement. The computed volume of water injected from the central tube was nearly zero litres, while the measured amount was about 0.5 l of water. As in the Serrata seal, the discrepancy was large. From a general point of view, it seems that the consideration of the average porosity of the brick/joint system leads to overestimating the hydraulic conductivity existing during the whole process. Inflow of water into the bricks governed by the porosity of the blocks appears then to be a factor to be taken into account in the simulation.

The final modelling of the borehole sealing experiment incorporated parameters of laboratory tests performed during the project and in situ permeability tests. The latter indicated a lower average dry density inside the seals due to the presence of joints. The prediction is quite good in terms of stresses by considering the real initial stress state. The rate of hydration was slightly overestimated considering the average dry density, indicating that the density of the bricks plays a role in the hydration kinetics. As a general remark, this exercise provides a useful estimation of most of the parameters involved in the hydro-mechanical response of an engineered barrier.

4.2. Permeability

The obtained values of the hydraulic conductivity are in good agreement with the laboratory values at the corresponding dry density, taking into account the reduced dry density of the seals.

4.3. Gas breakthrough

As the gas pressure was increased to 3.1 MPa in filter PW1, a breakthrough was observed, connecting PW1 to PW5 (Fig. 1). However, no gas inflow was observed at filters PW2, PW3 and PW4, which are located behind the FoCa seal. This suggests that the EDZ along the borehole, or the interface between Boom Clay and seal, is the preferential flow path. Should the bulk of the FoCa itself be a path of least resistance, one would expect PW2, PW3 or PW4 to record gas inflow.

4.4. Radionuclide migration

Through radionuclide transport modelling, it was investigated whether the experimental data could be reproduced with reasonable parameter values. A first model considering only diffusive transport through the FoCa and Boom Clay could not be fitted to the observations. The modelling results shown in Fig. 10 do not match the observations with respect to plume arrival time or long-term plume dissipation. Interestingly, the model results indicate that significant concentration differences might existed between the edge of PW5, which was closer to PW3, the mid-point of PW5 and the distant edge of PW5.

Because of the substantial hydraulic pressure drop that was induced at each sampling from PW5, it is expected that advective transport of the tracer is not negligible. Hence, a coupled flow and transport simulation was performed to model this migration experiment. The hydraulic part of the simulation was calibrated to the measured outflow. The experimental data of the outflow as result of the sampling procedure could be modelled very well using a hydraulic conductivity K of 4.5×10^{-12} m/s. This value of K is equivalent to the horizontal conductivity K_h of the Boom Clay formation (De Cannière et al., 1994; Wemaere et al., 2002) and about a factor 2 larger than the vertical conductivity ($K_v = 2.1 \times 10^{-12}$ m/s). It therefore appears that the smallest resistance, and thus the largest K of the formation determines the flow rate.

Introducing the hydraulic parameters and the measured PW3 and PW5 pressures in this flow and transport model, we obtained the radionuclide breakthrough curve for the PW5 sample filter shown in Fig. 11, using the transport parameter values in Table 4.

The simulation results shown in Fig. 11 exhibit even larger differences between concentrations at different locations within PW5, especially during sampling operations. However, it is clear from comparing Figs. 11 and 10 that the general trend of the measured concentrations is better reproduced when advection is taken into account.

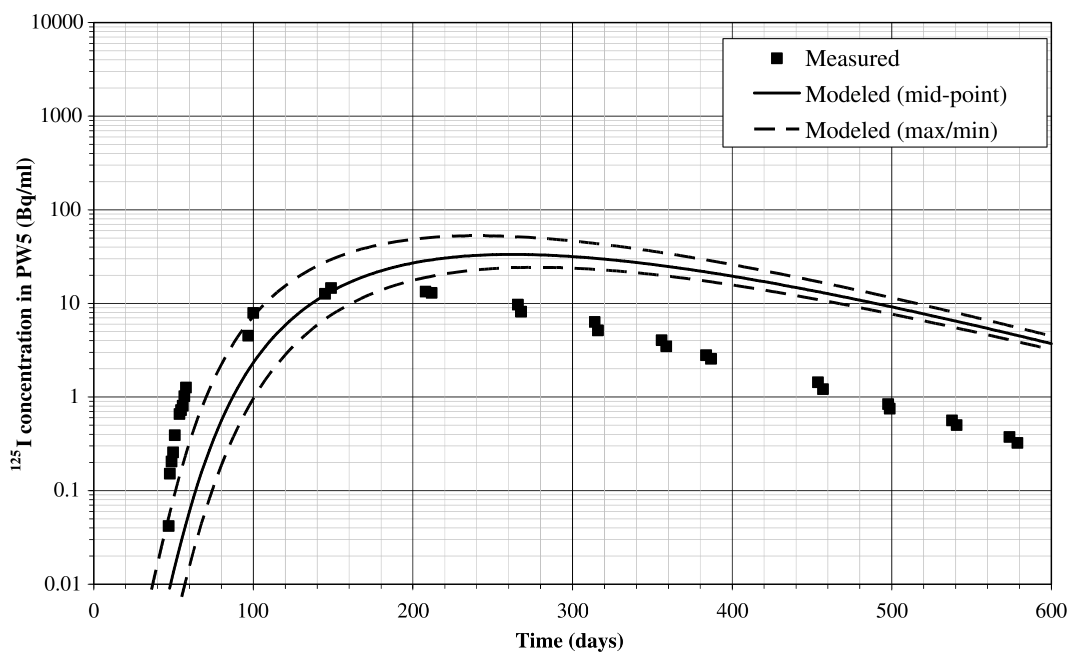

Fig. 10. Comparison of observed ^{125}I concentrations from filter PW5 with predictions from a diffusive transport model.

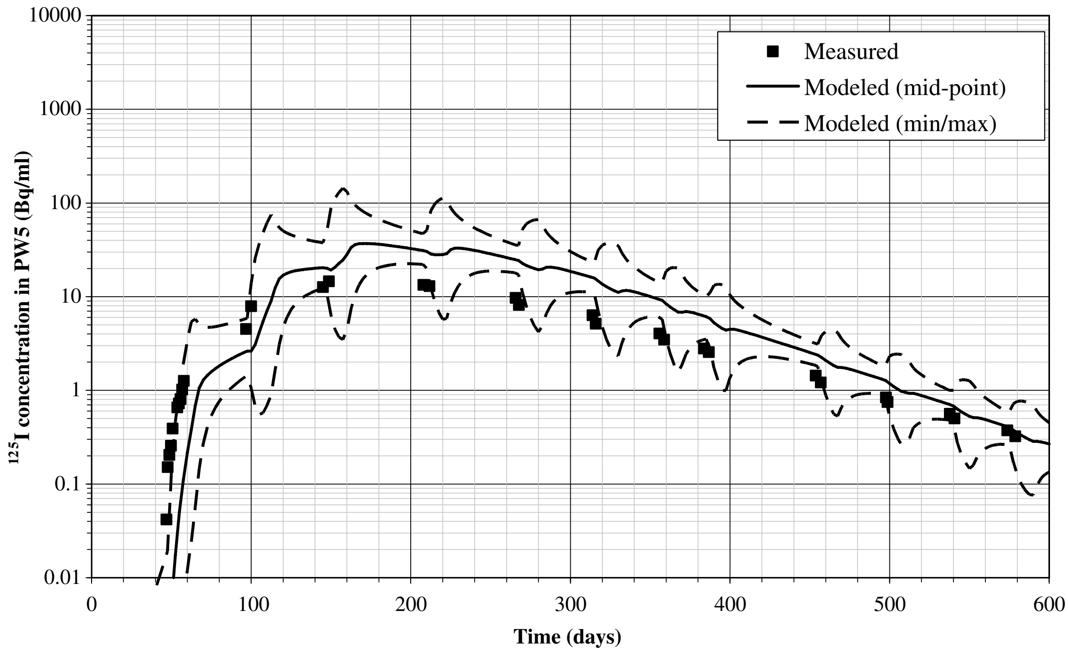

Fig. 11. Comparison of observed ^{125}I concentrations from filter PW5 with predictions from a flow and advection–diffusion transport model.

Table 4
Transport parameter values for advection–diffusion model (results shown in Fig. 11)

Diffusion accessible porosity of Boom Clay	η_a	0.12
Pore diffusion coefficient of Boom Clay	D_p	2×10^{-10} m^2/s
Diffusion accessible porosity of FoCa seal	η_a	0.06
Pore diffusion coefficient of FoCa seal	D_p	2×10^{-10} m^2/s

Due to the high concentration gradient along the contact surface between PW5 and the Boom Clay, the concentration at the mid-point of PW5 might be a poor estimate of the concentration in the sampled fluid. Hence, the average concentrations at the times of sampling have been calculated by dividing the total convective flux of ^{125}I through the PW5 filter by the corresponding water outflow. These

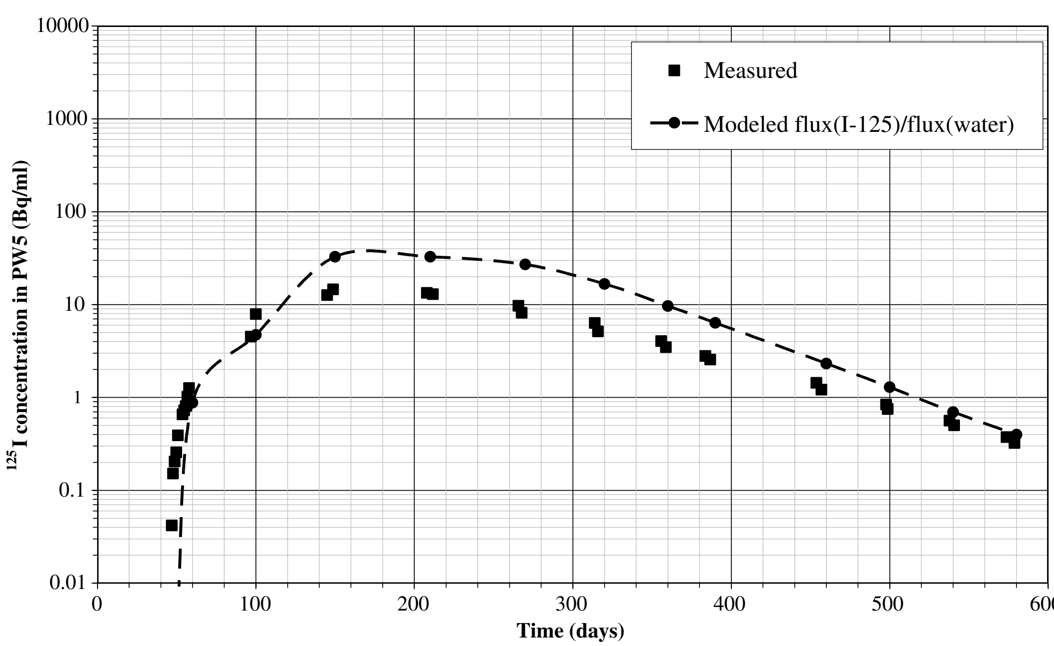

Fig. 12. Comparison of observed ^{125}I concentrations from filter PW5 with flux-based estimates of the average concentrations from the flow and transport model.

computed average concentrations are compared to the observations in Fig. 12. Both the plume arrival and its long-term dissipation are satisfactorily captured by the model. However, the peak concentration is overestimated by a factor of about 2.

A better description of the system, including measured pressure evolutions in PW1 and taking into account the hydraulic role of the second segment of PW3 in the model could possibly lead to better modelling results. It is also worth noting that at this point only best estimates of the radionuclide transport parameters have been used in the advection–diffusion model, i.e. there has been no attempt yet to adjust these parameters to better fit the observed results. In any case, Fig. 12 seems to indicate that the observed concentrations can be reproduced adequately without resorting to preferential pathways such as fractures or poorly sealed interfaces.

5. Conclusions

The backfilling and sealing of shafts and galleries is an essential part of underground repository designs. On a small scale, the sealing of a borehole can provide valuable information on the feasibility and effectiveness of such a sealing technique. During the RESEAL project, it has been demonstrated that sealing a borehole in the plastic Boom Clay by means of pre-compacted blocks of bentonite is technically feasible. The pre-compaction technique gives any specific dry density for achieving required physical characteristics of the seals, which were easily placed on site. The hydration of the seals occurred reasonably fast and hydration occurred mainly by water uptake from the host rock. Other large scale experiments with pre-compacted bentonite blocks illustrated very slow hydration (Villar et al., 2005) but the limited thickness of the seals and the presence of joints in the discussed borehole sealing experiment led to quick saturation. The obtained swelling pressures were lower than foreseen, but this is believed to be related to boring induced disturbance of the host rock and not to changes in physical properties as derived in the laboratory. The hydraulic conductivity measured in situ agreed very well with the predicted values based on laboratory measurements. The gas breakthrough experiment showed that no preferential gas flow through the seal occurred but that it is not possible to determine whether gas flow occurred along the seal/host rock contact, through the EDZ of the host rock, or through the host rock. Concerning the radionuclide migration through the seal, comparison of observed concentrations with modelling results did not yield evidence of the presence of preferential pathways within or around the seal. This does not mean that poorly sealed interfaces and fractures do not exist, but if such features are present, they do not seem to play a significant role in the tracer transport process. It seems that the sampling procedure makes advection quite significant in transport experiment.

Finally, concerning sealing boreholes in plastic clay of Boom Clay type we generally conclude that:

- pre-compacted bentonite blocks can be used and that sealing is technically feasible,
- the required physical parameters (dry density at saturation and swelling pressures) can be obtained by choosing a suitable initial dry density,
- the efficiency of the seal with respect to water and gas migration can be fairly well predicted,
- no evidence of preferential pathways could be detected from tracer test results.

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