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On the hydration of unsaturated barriers for high-level nuclear waste disposal

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ABSTRACT: The paper addresses the topic of the effects of hydration and temperature on the final state of an engineered barrier composed of compacted bentonite. In particular the distributions of water content and dry density are examined. Those issues are explored with reference to a long-duration field test that reproduces at full scale the behaviour of an unsaturated compacted bentonite barrier subjected to hydration and thermal effects. The state of the barrier is discussed at two different stages using data from two separate dismantling operations. It is observed that the state of the barrier is not homogenous even after reaching saturation. It is shown that coupled THM analyses are able to predict satisfactorily the state and evolution of the barrier throughout.

1 INTRODUCTION

Most designs for deep geological disposal of high-level radioactive waste are based on the multi-barrier approach. The long-term minimization of radionuclide release is the result of the combined effect of a series of barriers that are placed between the nuclear waste and the biosphere: waste canister, engineered barrier and geological barrier. A good understanding of the behaviour of each one of these components is essential to achieve a robust and reliable design of the underground repository.

In many concepts, the engineered barrier surrounding the canister is made up of unsaturated bentonite. The suction of the unsaturated bentonite will draw water from the surrounding host rock that eventually will saturate the barrier. As high-level nuclear waste is heat emitting, the barrier will simultaneously be subjected to thermal effects. So the final state of the barrier at the end of this transient phase will be the outcome of a complex set of coupled phenomena. Unsaturated bentonite (sometimes mixed with other materials) is also used for the sealing of access tunnels and shafts. The issues associated with their hydration are similar except that thermal effects are absent. Seals are not considered in this paper.

The safety functions of the engineered barrier are assumed to be in place when target values of swelling pressure and hydraulic conductivity are achieved. For a particular bentonite and hydration water composition, both properties depend mainly on the dry density (or porosity) of the material (Figure 1). The

required dry density is attained by either the placement of compacted bentonite blocks or the use of high-density bentonite pellets.

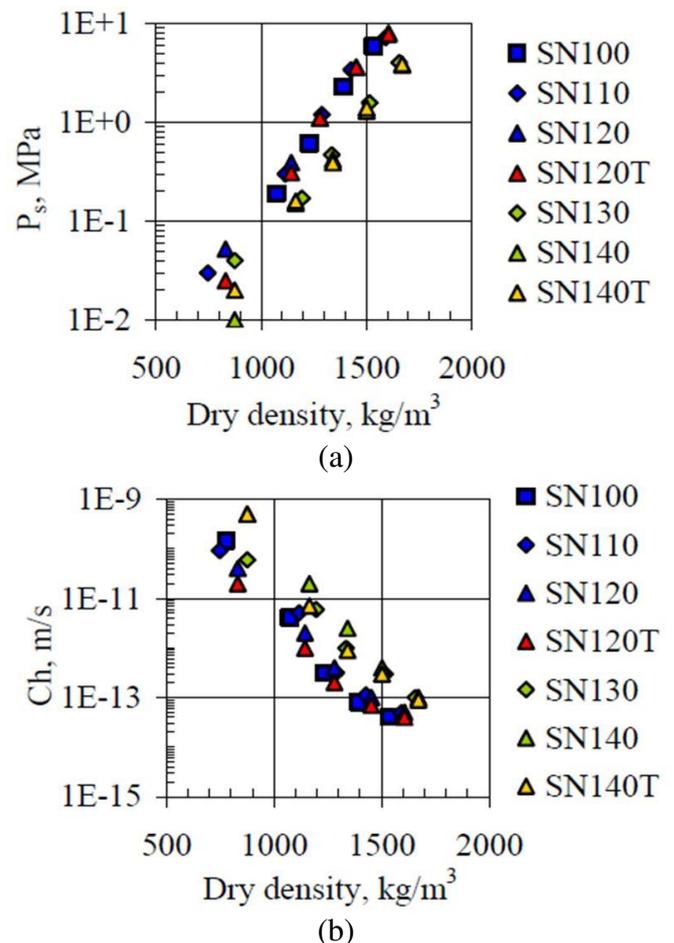


Figure 1. Dependence of (a) swelling pressure, P_s , and (b) hydraulic conductivity, Ch , on the dry density for MX-80 bentonite (Karlund et al., 2007).

Because the host rock and the canister are very stiff, the engineered barrier is an enclosed system where any overall volume change is bound to be very small. Therefore, the average dry density of the barrier will stay basically constant throughout. However, average dry density does not fully characterize the hydromechanical behaviour of the bentonite but its distribution across the barrier is equally significant. Even in the case of an initially homogenous installation (which is seldom the case), the barrier may become heterogeneous as a consequence of the hydration and thermal processes occurring during its transient phase. It is therefore of the utmost importance to be able to understand and predict the final state of the barrier at the end of the transient phase.

Opportunely, there has been in recent times that a number of field tests on engineered barriers that have been dismantled so that the state of the barrier at the end of the test can be observed directly. These dismantling operations are probably the only way to obtain reliable information on the distributions of water content and, especially, dry density in the barrier.

The paper describes first the main characteristic of one such large-scale field test that has been recently dismantled, with particular attention to the distributions of water content and dry density observed in the barrier. After the description of the test and the main observations, the numerical modelling undertaken to simulate the hydro-thermo-mechanical (THM) behaviour of the barrier is presented. Special attention is given to the prediction of the state of the barrier at the two dismantling stages.

2 DESCRIPTION OF THE FIELD TEST

The test selected (Febex in-situ test) was carried out in the Grimsel Test Site, an underground research laboratory located in the Swiss Alps. This experiment has two unusual features that make it very suitable for the purpose of investigating the state of the barrier: (i) it is a very long-term test (more than 18 years) so that nearly full saturation of the barrier can be achieved under natural conditions, and (ii) the tests were also partially dismantled after five years so there is information on the state of the barrier at two different stages of the test.

The test was installed in a 2.28 m diameter circular tunnel that was especially bored for this purpose. The host rock is good quality Central Aare granite. In the final 17.4 m of the tunnel, two heaters (4.54 m long and 0.90 m diameter) were installed to apply the thermal loading required for the test. The space between the rock and the heaters as well as any other free space was filled with blocks of compacted bentonite (Figure 2). The average values of water content and dry density of the blocks were 14.4% and

1.69 g/cm³ respectively. Because of the presence of joints and gaps, the overall average dry density of the emplaced barrier was 1.60 g/cm³. The test zone was sealed by a concrete plug.

The test was heavily instrumented with a total of 632 sensors installed in the barrier and in the rock. The basic variables measured were temperature, relative humidity and stresses in the bentonite and temperatures, pore pressures and stresses in the rock. The general layout of the test is presented in Figure 3a.

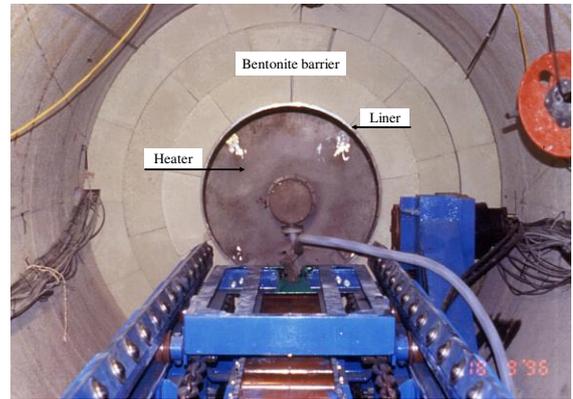


Figure 2. Cross section of the engineered barrier of the test showing one of the heaters and the blocks of compacted bentonite.

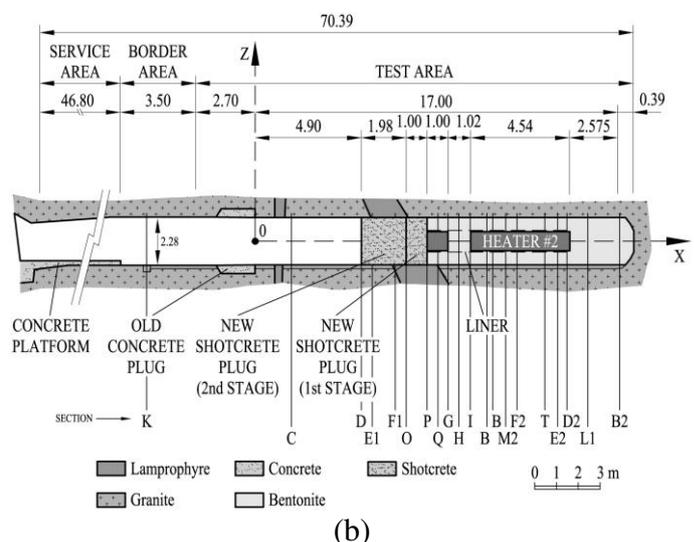
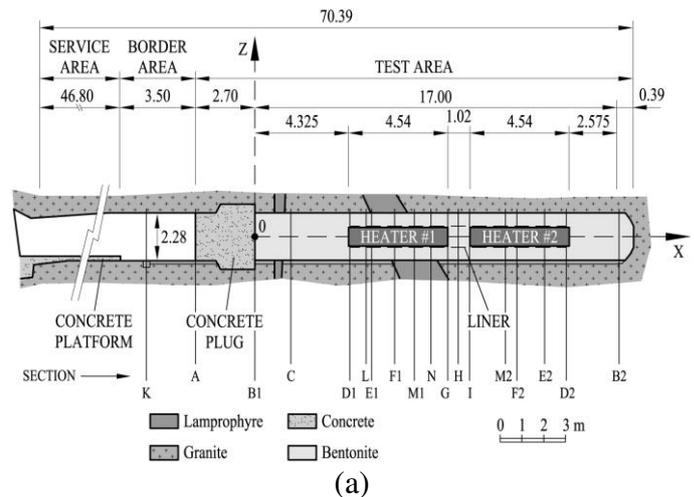


Figure 3. Layout of the test. (a) Initial and (b) after first dismantling.

The test was performed under temperature control maintaining a temperature of 100 °C in the contact between the canister and the bentonite. The barrier was thus subjected to simultaneous hydration from the rock and heating. Hydration and heating interact in a coupled manner involving also other phenomena such as evaporation/condensation of the water, vapour migration and swelling stress development.

3 OBSERVATIONS OF THE STATE OF THE BARRIER

After five years of heating, the heater closer to the concrete plug was switched off and the barrier was partially dismantled removing the switched-off heater and half of the length of the bentonite barrier (Bárcena et al., 2003). The layout of the experiment after the partial dismantling is depicted in Figure 3(b) whereas Figure 4 shows the visual state of the barrier as observed in the first dismantling. During the dismantling a comprehensive sampling and testing operation was carried out (Villar et al., 2005). Of interest here was the extraction of numerous samples in specified sections that allowed the construction of detailed pictures of the state of the barrier in terms of water content, dry density and degree of saturation. The tests to determine these parameters were performed on site, immediately after sample extraction. It was noted that the observations exhibited an approximate radial symmetry indicating a rather uniform hydration and thermal effects around the canister.



Figure 4. State of the barrier in the first dismantling. The location of the samples extracted from this section can be noted.

Figure 5 shows the observations of dry density, water content and degree of saturation obtained in a section across the centre of the heater. It can be noticed (Figure 5(a)) that the zone close to the rock has reduced its dry density due to swelling caused by hydration from the rock whereas the bentonite close to the heater has contracted. The distribution of water

content (Figure 5(b)) also shows the effect of bentonite hydration close to the rock whereas the zone near the heater has in fact dried initially but, afterwards, hydration also starts reaching this area bringing the water content close to the initial value. It can also be noted (Figure 5(c)) that, after five years, the barrier is still far from saturation except in the area near the rock.

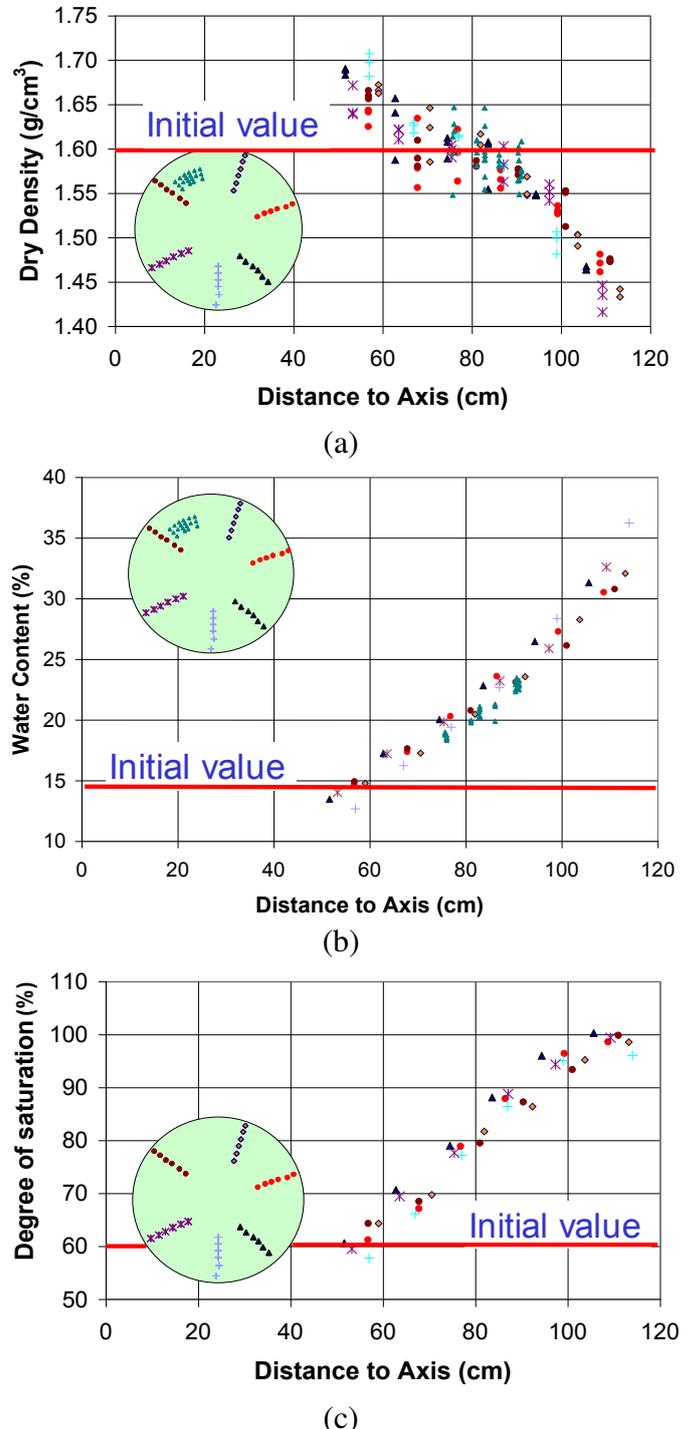


Figure 5. Distributions observed in the first dismantling of (a) dry density, (b) water content and (c) degree of saturation in a section across the centre of the heater (Daucousse & Lloret, 2003).

During dismantling, the second heater was maintained operational throughout at a 100 °C temperature. The remaining test area was closed again with a shotcrete plug and the experiment was kept going for

a further 13.5 years making a total of 18.5 years since the start of heating. Finally, the second heater was switched off and the remaining bentonite was removed (García-Siñeriz et al., 2016). A comprehensive sampling and testing programme similar to that of the first dismantling was performed again. Figure 6 shows visually the state of the barrier in the final dismantling



Figure 6. State of the barrier in the final dismantling. The location of the samples extracted from this section can be noted.

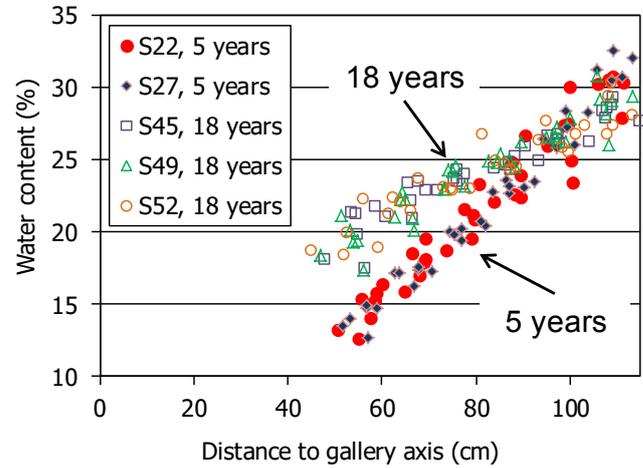
The dry density and water content determinations indicated that the barrier was either saturated or very close to saturation throughout. This is the result of the long testing time that has allowed hydration to proceed to practically completion. It is interesting to compare the changes between the two dismantling stages (Villar, 2017). Figure 7(a) shows that, as should be expected, the water content has increased in the inner part of the barrier due to the progress of hydration. Dry density distributions are plotted in Figure 7(b). It can be noted that practically no change is recorded between the two dismantling stages. This is a very important observation – it shows that the distribution set up by the initial stages of hydration and thermal effects becomes frozen and the barrier remains heterogeneous even when it becomes saturated. This behavioural irreversibility is a key feature to be taken into consideration.

4 MODELLING

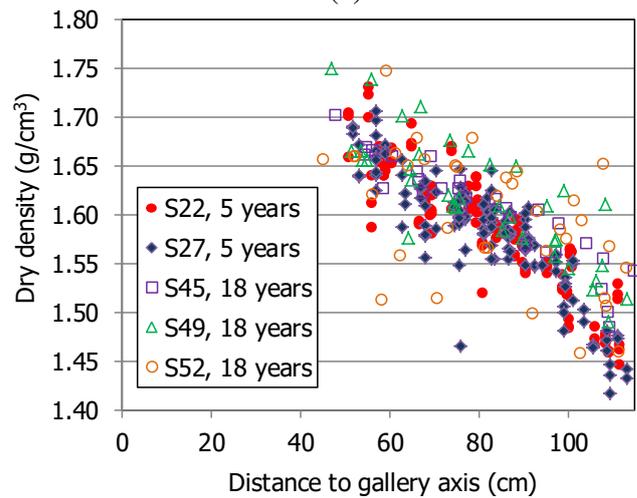
The test was concurrently modelled numerically using a coupled THM formulation capable of incorporating the various phenomena expected to occur in the barrier including vapour transport, swelling pressure development and variations of permeability with dry density. The analyses were performed using the computer code CODE_BRIGHT. A detailed description is given in Gens et al. (2009).

Although it is obviously necessary that the thermo-hydraulic (TH) formulation should be able to represent appropriately the progress of the test, the

evolution and distribution of the dry density in the barrier (the main goal of this paper) is strongly dependent on the mechanical constitutive law adopted in the analysis. In the modelling reported here, the Barcelona Basic Model, BBM (Alonso et al., 1990) was used. To take into account the specific swelling behaviour of the bentonite, the elastic component of the model was modified as described in Gens et al. (2009).



(a)



(b)

Figure 7. Distributions of (a) water content and (b) dry density, in sections in the heating area. First (5 years) and final (18 years) dismantling (Villar, 2017)

The first dismantling was simulated using the phases and times indicated in Figure 8. The comparisons between the predictions of the numerical model and the dismantling operation in a section across the centre of the heater are presented in Figure 9. Considering that the results of the numerical analysis constitute genuine predictions obtained before the observations were known, the correspondence with the measurements is noteworthy. The distribution pattern is well reproduced and the quantitative agreement is also close with perhaps a slight underestimation in the progress of hydration.

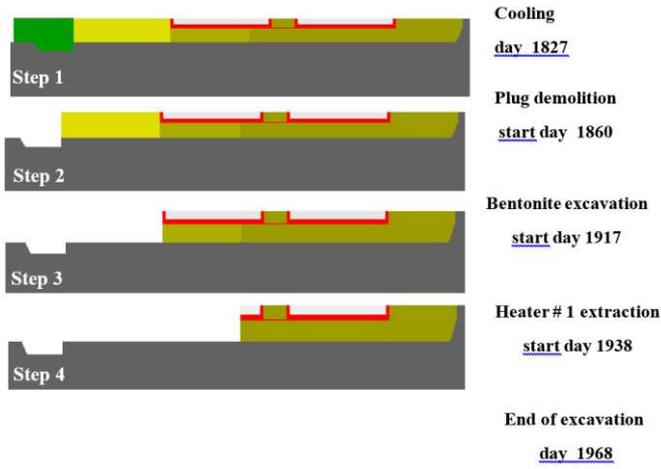


Figure 8. Phases and times used in the simulation of the first dismantling.

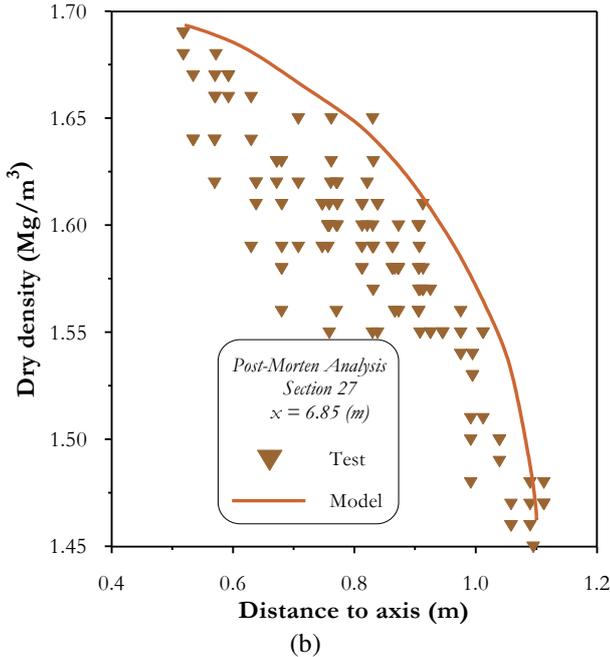
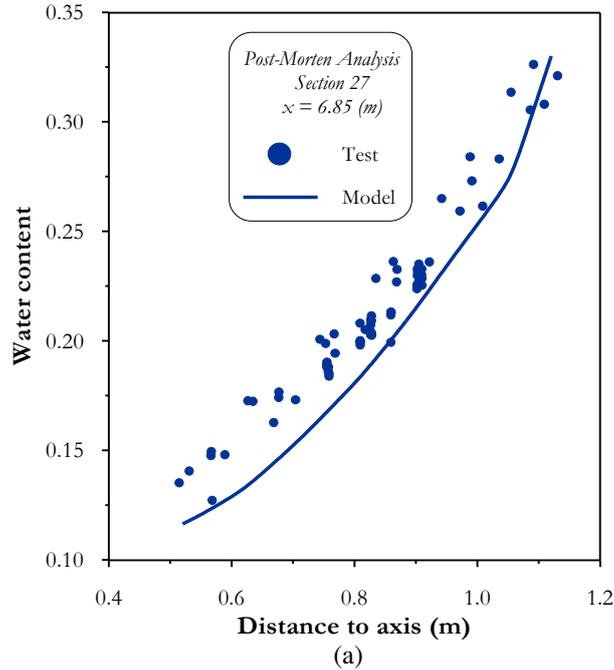


Figure 9. Comparison between the predictions of the numerical analysis and observations in a section across the centre of the heater in the first dismantling: (a) water content and (b) dry density.

The final dismantling was also modelled in a similar way using the same mechanical constitutive law (BBM) with the same parameters. Figure 10 shows the phases and times corresponding to this final dismantling.

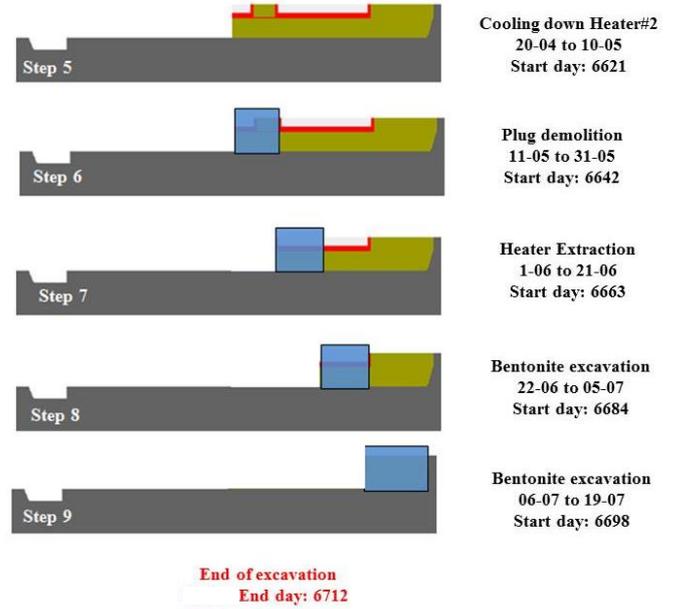


Figure 10. Phases and times used in the simulation of the first dismantling.

To illustrate the sensitivity of hydration with respect to the retention curve, the results of two analyses are reported. A modified Van Genuchten expression has been used:

$$S_l = \left[1 + \left(\frac{s}{P_o} \right)^{\frac{1}{1-\lambda_0}} \right]^{-\lambda_0} f_d, \text{ where } f_d = \left(1 - \frac{s}{P_d} \right)^{\lambda_d} \quad (1)$$

with $\lambda_0 = 0.18$, $P_d = 1100$ MPa and $\lambda_d = 1.10$. The two analyses presented correspond to values of P_o of 7 and 20 MPa. As Figure 11 shows, the difference between the two retention curves is apparently small and both are consistent with the experimental data.

The comparisons between model predictions and observations are presented in Figure 12. Again, the analyses were performed before the results of the dismantling were known. It can be noted that the progress of hydration is very sensitive to the details of the retention curve; this is a quite common result in this type of problem. The analysis with $P_o = 20$ MPa again slightly underestimates the degree of hydration. In contrast, the predicted dry density is quite insensitive to this parameter, confirming that the dry density distribution is little affected by the later stages of hydration. Indeed, it is very significant that, even using this rather simple mechanical model, the analysis is able to predict the irreversibility of dry density changes all the way to barrier saturation.

5 CONCLUSIONS

The dismantling of a large-scale long-duration field test on two separate occasions has allowed the direct observation of the state of a bentonite barrier at two stages of the hydration process: an intermediate one in which the barrier was still far from saturation and a final one when the barrier was practically fully saturated. It has been noted that the final state of the barrier is heterogeneous, the dry density distribution set up during the initial stages of hydration appears to become permanent and the barrier does not revert to a homogenous state even on reaching saturation.

The coupled THM analyses performed have proved capable of predicting quite satisfactorily the state of the barrier at the two dismantling stages. However, the mechanical constitutive law adopted is a simple one and does not account for the full complexity of the mechanical behaviour of the bentonite during hydration and thermal loading. Numerical analyses are currently ongoing to perform additional simulations using more advanced constitutive equations.

6 ACKNOWLEDGEMENTS

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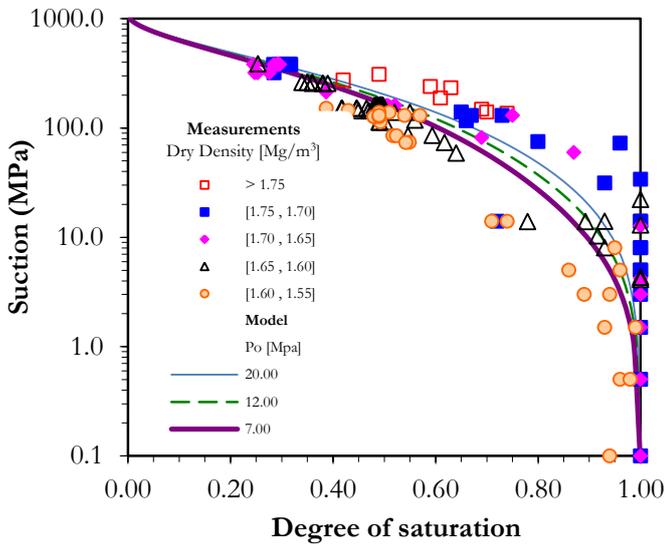
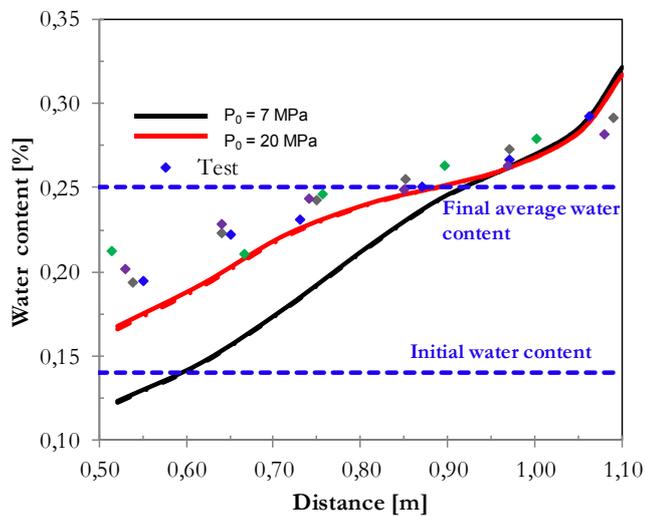
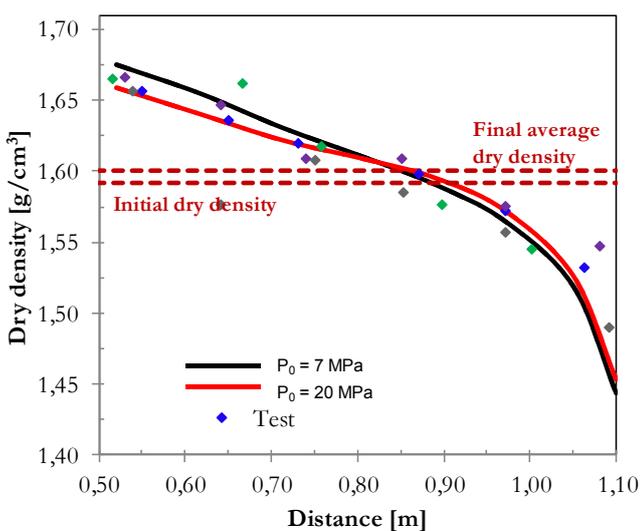


Figure 11. Retention curves used in the analyses.



(a)



(b)

Figure 12. Comparison between the predictions of the numerical analysis and observations in the final dismantling: (a) water content and (b) dry density.