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A comparative study on the hydro-mechanical behavior of compacted bentonite/sand plug based on laboratory and field infiltration tests

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ABSTRACT

SEALEX is a research project aiming at identifying the key factors that affect the long-term performance of bentonite-based sealing systems with an initial technological void. In this context, a series of in situ experiments have been performed in field conditions. Meanwhile, a small-scale test (1/10) was carried out in controlled conditions in the laboratory, aiming at providing useful information for analyzing the in situ tests in terms of saturation time and sealing effectiveness. In this paper, the results of the small-scale test are presented along with the results from the first in situ test (PT-N1). It was observed that during the saturation process, the evolution of the injected water volume followed a hyperbolic relationship with time in both the laboratory and field conditions. In the laboratory conditions, a decrease in axial swelling pressure occurred due to filling of the technological void. By contrast, this decrease has not been observed in the field conditions. Comparison of the injected water and the axial swelling pressure between the two different scales enabled the definition of a same time upscaling ratio of 2.5 (in situ experiment/small-scale test). Accordingly, the saturation duration of the in situ experiment was estimated to be equal to two years. For the small-scale test, a swelling strain evolution rate of 0.588 mm/day was identified in the case of infiltration from two sides of the sample. This is useful when predicting the evolution of swelling strain in the case of failure of the sealing plug. After filling of an additional 20% void, a swelling pressure of 0.18 MPa was obtained, indicating the favorable sealing capacity of the material after filling the technological void.

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1. Introduction

In the design of deep geological repository for high level long lived radioactive wastes, compacted bentonite-based materials are often considered as buffer/sealing materials. These materials are expected to exhibit a swelling pressure high enough to fulfill their buffer/sealing functions.

Numerous laboratory studies have been conducted to assess the performance of buffer/sealing materials (e.g. Delage et al., 1998; Lloret et al., 2003; Romero et al., 2005; Lloret and Villar, 2007). Various experiments were also performed in the underground research laboratories (URL) (TSX at Manitoba, Canada; FEBEX at Grimsel, Switzerland; RESEAL at Mol, Belgium; KEY at Bure, France, etc.). Recently, IRSN (Institut de Radioprotection et de Sûreté Nucléaire, France) has launched the SEALEX project aiming at identifying and quantifying the key factors related to the long-term performance of bentonite-based sealing systems taking into account an initial technological void. This project consists of a series of in situ experiments in the Tournemire URL, and a small-scale test (1/10) in the laboratory.

The in situ experimental program was purposefully built allowing systematical exploration of the effects of technical specifications, design, construction, defect, etc., by changing a single parameter each time. As a reference case (see Barnichon and Deleruyelle, 2009; Barnichon et al., 2012 for more details), the first test PT-N1 with a clay core made up of pre-compacted monolithic disks of MX80 bentonite/sand mixture (70/30 in dry mass) has been conducted in the URL of Tournemire. Due to the low permeability of this material, saturation is expected to be reached in several years (see Barnichon et al., 2012). During the saturation process, the injected water volume, total pressure, pore water pressure and relative humidity changes have been monitored at several positions within the plug. After the saturation stage, hydraulic tests will be performed to determine the overall hydraulic properties (permeability, occurrence of leakage) of the sealing system. In addition to this reference case, three other tests are designed to quantify the impact of the technical specification and design of the sealing plug by changing the intra-core geometry (jointed instead of monolithic disks), core composition (MX80/sand ratio) and core conditions (compacted in field instead of pre-compacted). Moreover, to investigate the effect of altered conditions, an additional test is designed

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to simulate an incidental decrease of swelling pressure caused by failure of the confining structure.

Based on the design of the in situ experiments, a laboratory small-scale test (1/10) was performed, focusing on the recovery capacity of the bentonite-based seal with technological voids. The material identical to that used in test PT-N1 was used (MX80 bentonite/sand mixture). A confining cell of stainless steel was used to simulate the constant-volume boundary conditions. After the initial saturation process as in the PT-N1 in situ experiment, the seal evolution upon a confinement failure was simulated by allowing a given amount of free swell. This free swell was followed by a last stage of wetting under constant volume conditions. To assess the sealing capacity, the injected water volume, axial swelling pressure and swelling strain were monitored in different stages. It was expected to obtain useful information from the laboratory small-scale test for analyzing the field tests in terms of saturation time and sealing effectiveness.

In this paper, the results of the small-scale test are presented along with the results from the in situ test (PT-N1). An upscaling ratio was obtained by comparing the injected water volume and the axial swelling pressure evolution between the laboratory and field conditions. The time needed to reach the stabilization of axial swelling pressure for the in situ test (PT-N1) as well as the evolution of swelling strain and swelling pressure in the case of failure of the confining structure were estimated accordingly.

2. Materials and methods

2.1. Materials

The soil studied is a compacted MX80/sand mixture with a proportion of 70/30 in dry mass. The bentonite is from Wyoming, USA, with a high content of montmorillonite (80%). It has a liquid limit of 575%, a plastic limit of 53% and a unit mass of 2.77 Mg/m^3. The cation exchange capacity (CEC) is 76 meq/100 g (83% of Na^+). The quartz sand used in the mixture comes from Eure and Loire (France) with a unit mass of 2.65 Mg/m^3. It was sieved at 2 mm prior to being mixed with the bentonite.

The water used has the same chemical composition as the pore water of the Callovo-Oxfordian claystone from the ANDRA URL in Bure (France), namely synthetic water (Wang et al., 2012, 2013). It was obtained by mixing the corresponding chemical compounds (see Table 1) with distilled water using a magnetic stirrer until full dissolution.

2.2. SEALEX in situ test (PT-N1)

As mentioned above, the in situ experiment (PT-N1) has been conducted in the Tournemire URL excavated in Toarcian claystone. A horizontal borehole (0.60 m in diameter) was drilled for this purpose. Fig. 1 shows the layout of the experiment. A seal made up of compacted MX80/sand mixture was sandwiched between two porous plates, allowing water inflow from two water reservoirs (i.e. upstream and downstream). The 14.33% annular technological void (volume of void/volume of borehole) was defined by adopting a smaller initial diameter (0.555 m) of the pre-compacted seal as compared to the borehole diameter (0.60 m). The upstream plate is in direct contact with the host-rock while the downstream one is retained by a confining system ensuring a constant-volume condition. A packer-like device was used to prevent water leakage from the interface between the confining plug and host-rock.

The clay seal in test PT-N1 is made up of 8 monolithic pre-compacted disks (0.555 m in diameter and 0.15 m thick) of MX80/sand mixture with an initial dry density of 1.97 Mg/m^3 (Figure 2). The disks were arranged in vertical slices giving rise to the geometry of seal as shown in Fig. 2. The bricks were obtained through uniaxial compaction of the mixture at its initial water content of 11%. The initial dry density (1.97 Mg/m^3) of the bricks was selected based on the consideration of the 14.33% technological void and the need to have a final dry density of 1.67 Mg/m^3 after saturation of the plug and filling of the initial technological voids.

Three types of sensors were installed within the compacted blocks to monitor the swelling pressure, pore pressure and relative humidity. For clarity, only the distribution of sensors for swelling pressure measurement is shown in this paper (Figure 3a). Three total pressure sensors were installed on the surface of the column at section 0.60 m (from the downstream saturation system, L-01, L-02, L-03) to measure the radial swelling pressure; two total pressure sensors were installed at section 0 and 1.20 m to measure the axial swelling pressure (A-01, A-02). For each sensor, a hole as shown in Fig. 3b was prepared at their pre-assigned positions before the assemblage of blocks, keeping the hole to a minimum size. Wireless sensors ($d = 32$ mm) were used to limit preferential flow along cables and a wireless transmitter was installed at each measurement section. Data were recorded automatically by a data acquisition system.

Regarding the test operational phases, a volume of water of 49 l was first injected, which corresponded to the volume of the technological void adopted. This process ended in one hour. Afterwards, the water supply was stopped because the side packer was not properly inflated; it restarted after 20 days under a water pressure of 0.1 MPa. During the saturation process, the swelling pressure, pore pressure, water content or water saturation within the plug were monitored. The injected water volumes at both upstream and downstream chambers were also measured. When the saturation process is completed, hydraulic tests will be performed to determine the overall hydraulic properties (permeability, occurrence of leakage) of the corresponding sealing systems.

2.3. Laboratory small-scale test

The experimental devices used for the laboratory small-scale test (1/10) are shown in Fig. 4. A stainless steel cell of 60 mm in inner diameter and 200 mm long was used. As in the in situ test, an annular technological void was defined by adopting a smaller initial diameter (55.5 mm) for the pre-compacted sample as compared to the diameter of the hydration cell (60 mm). Note however that the hydration cell was placed in the vertical direction (see Figure 4) and it was then different from the in situ test which is performed in a horizontal borehole (see Figures 1 and 2). Water supply was conducted through the water inlets in the bottom base which was connected to burettes. This allowed measurement of the total amount of water taken up by the sample. A piston of 60 mm diameter was used to simulate the confining structure. On the bottom of the piston, there was drainage with two inlets (upside inlet in Figure 4) and a porous stone of 50 mm diameter, allowing water/air flow. A mechanical press was used to restrain the axial deformation and a force transducer was used to monitor the axial swelling pressure. A displacement transducer fixed on the piston allowed monitoring of the axial displacement to an accuracy of 1 μm. The axial pressure and axial displacement were recorded automatically to a data logger, while the inlet water volume was measured manually by determining the water level in the burettes.

Table 1
Chemical composition of the synthetic water.

Compound	$NaHCO_3$	Na_2SO_4	NaCl	KCl	$CaCl_2.2H_2O$	$MgCl_2.6H_2O$	$SrCl_2.6H_2O$
Mass (g) per liter of solution	0.28	2.216	0.615	0.075	1.082	1.356	0.053

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