

# A comparative study on the hydro-mechanical behaviour 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 27 affect the long-term performance of bentonite-based sealing systems with an initial 28 29 technological void. In this context, a series of in-situ experiments have been being performed in field conditions. Meanwhile, a small scale test (1/10) was carried out in 30 controlled conditions in the laboratory, aiming at providing useful information for 31 32 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 33 34 first in-situ test (PT-N1). It was observed that during the saturation process, the 35 evolution of the injected water volume followed a hyperbolic relationship with time in 36 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, 37 38 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 39 definition of a same time up-scaling ratio of 2.5 (in situ experiment /small scale test). 40 41 Accordingly, the saturation duration of the in situ experiment was estimated to be 42 equal to two years. For the small-scale test, a swelling strain evolution rate of 0.588 43 mm/day was identified in the case of infiltration from two sides of the sample. This is 44 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 45 was obtained, indicating the favorable sealing capacity of the material after filling the 46 47 technological void.

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Keywords: small-scale test; in-situ experiment; bentonite/sand mixture; technological

49 void; swelling pressure; swelling stain.

#### 50 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 fulfil their buffer/sealing functions.

Numerous laboratory studies have been conducted to assess the performance of 55 buffer/sealing materials (e.g. Delage et al., 1998; Lloret et al., 2003; Romero et al., 56 2005; Lloret & Villar, 2007). Various experiments were also performed in the 57 underground research laboratories (URL) (TSX at Manitoba, Canada; FEBEX at 58 Grimsel, Switzerland; RESEAL at Mol, Belgium; KEY at Bure, France, etc.). 59 Recently, IRSN (Institut de Radioprotection et de Sûreté Nucléaire, France) has 60 61 launched the SEALEX project aiming at identifying and quantifying the key factors 62 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 63 experiments in the Tournemire URL, and a small-scale test (1/10) in the laboratory. 64

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 et al. 2009, 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) 70 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., 71 72 2012). During the saturation process, the injected water volume, total pressure, pore water pressure and relative humidity changes have been monitored at several 73 74 positions within the plug. After the saturation stage, hydraulic tests will be performed 75 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 76 quantify the impact of the technical specification and design of the sealing plug by 77 78 changing the intra-core geometry (jointed in stead of monolithic disks), core composition (MX80/sand ratio) and core conditions (compacted in field in stead of 79 pre-compacted). Moreover, to investigate the effect of altered conditions, an 80 81 additional test is designed to simulate an incidental decrease of swelling pressure caused by failure of the confining structure. 82

Based on the design of the in-situ experiments, a laboratory small-scale test (1/10) 83 84 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 85 86 bentonite/sand mixture). A confining cell of stainless steel was used to simulate the 87 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 88 simulated by allowing a given amount of free swell. This free swell was followed by a 89 90 last stage of wetting under constant volume conditions. To assess the sealing capacity, 91 the injected water volume, axial swelling pressure and swelling strain were monitored 92 in different stages. It was expected to obtain useful information from the laboratory
93 small-scale test for analysing the field tests in terms of saturation time and sealing
94 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 up-scaling 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.

## 102 2 MATERIALS AND METHODS

#### 103 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<sup>3</sup>. The cation exchange capacity (CEC) is 76 meq/100g (83 % of Na<sup>+</sup>). The quartz sand used in the mixture comes from Eure and Loire (France) with a unit mass of 2.65 Mg/m<sup>3</sup>. It was sieved at 2 mm prior to being mixed with the bentonite.

110 The water used has the same chemical composition as the pore water of the 111 Callovo-oxfordian claystone from the ANDRA URL in Bure (France), namely 112 synthetic water (Wang et al., 2012a, 2012b). It was obtained by mixing the 113 corresponding chemical compounds (see Table 1) with distilled water using a114 magnetic stirrer until full dissolution.

115 **2.2 SEALEX in-situ test (PT-N1)** 

As mentioned above, the in-situ experiment (PT-N1) has been conducted in the 116 Tournemire Underground Research Laboratory excavated in Toarcian claystone. A 117 horizontal borehole (0.60 m in diameter) was drilled for this purpose. Figure 1 shows 118 the layout of the experiment. A seal made up of compacted MX80/sand mixture was 119 sandwiched between two porous plates, allowing water inflow from two water 120 121 reservoirs (i.e. upstream and downstream). The 14.33% annular technological void 122 (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 123 124 (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 125 condition. A packer-like device was used to prevent water leakage from the interface 126 127 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<sup>3</sup> (Figure 2). The disks were arranged in vertical slices giving rise to the geometry of seal as shown in Figure 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<sup>3</sup>) 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<sup>3</sup> after 135 saturation of the plug and filling of the initial technological voids.

Three types of sensors were installed within the compacted blocks to monitor the 136 137 swelling pressure, pore pressure and relative humidity. For clarity, only the distribution of sensors for swelling pressure measurement is shown in this paper 138 (Figure 3a). Three total pressure sensors were installed on the surface of the column at 139 140 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 141 1.20 m to measure the axial swelling pressure (A-01, A-02). For each sensor, a hole as 142 143 shown in Figure 3b was prepared at their pre-assigned positions before the 144 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 145 146 installed at each measurement section. Data were recorded automatically by a data acquisition system. 147

Regarding the test operational phases, a volume of water of 49 L was first injected, 148 149 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 150 was not properly inflated; it restarted after 20 days under a water pressure of 0.1 MPa. 151 During the saturation process, the swelling pressure, pore pressure, water content or 152 water saturation within the plug were monitored. The injected water volumes at both 153 upstream and downstream chambers were also measured. When the saturation process 154 155 is completed, hydraulic tests will be performed to determine the overall hydraulic properties (permeability, occurrence of leakage) of the corresponding sealing systems. 156

### 157 **2.3 Laboratory small-scale test**

The experimental devices used for the laboratory small-scale test (1/10) are shown in 158 Figure 4. A stainless steel cell of 60 mm in inner diameter and 200 mm long was used. 159 As in the in-situ test, an annular technological void was defined by adopting a smaller 160 161 initial diameter (55.5 mm) for the pre-compacted sample as compared to the diameter 162 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 163 performed in a horizontal borehole (see Figure 1 and Figure 2). Water supply was 164 165 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 166 sample. A piston of 60 mm diameter was used to simulate the confining structure. On 167 168 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 169 was used to restrain the axial deformation and a force transducer was used to monitor 170 171 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 172 173 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. Note 174 that in this small-scale test, the radial swelling pressure was not measured. 175

A monolithic cylindrical sample (55.5 mm in diameter, 120 mm high) was used in the test. It was statically compacted in a mould to the same dry density as in the in-situ test (1.97  $Mg/m^3$ ). In order to ensure the homogeneity of the specimen, the

compaction was carried out in two layers. The surface of the first compacted layer 179 was carefully scarified before the second layer was added to ensure a good junction 180 between them. Figure 5a shows the pre-compacted specimen with the hydration cell. 181 After compaction, the specimen (55.5 mm in diameter) was placed at the center of the 182 183 cell (60 mm in inner diameter), leaving an annular void (2.25 mm) between the 184 specimen and cell wall (Figure 5b). An initial axial stress of 0.1 MPa was applied on 185 the specimen before hydration in order to ensure good contacts between the load cell 186 and the piston, between the piston and the sample, between the sample and the cell 187 bottom, as well as satisfactory load measurement. Then, the upside inlets (see Figure 4) were sealed and vacuum was applied to evacuate all air in the voids (technological 188 void mainly). The synthetic water was finally injected from the bottom. 189

190 As described in Figure 6, hydration was carried out in three stages. First, the axial 191 deformation was restrained and water was injected to the sample; during this stage (Stage 1. initial saturation phase), the evolution of the vertical swelling pressure was 192 193 monitored. Once the hydration ended, the confining pressure in the axial direction was removed by unloading, allowing a free swell of 20% (Stage 2. recovery of the void 194 195 phase). To reduce the test duration in this stage, two-side infiltration was applied by 196 injecting water from both the bottom and the top, while recording changes in axial 197 swelling strain over time. This stage aimed at simulating the case of a saturation defect or a failure of confining structure that may occur during the long-term lifespan 198 199 of the disposal system. The free swell of 20% represents the sealing capacity required after filling the technological void. When the axial swelling strain reached the desired 200

value of 20%, the piston was automatically blocked thanks to a reserved distance of
24 mm (corresponding to 20% swelling strain) between the piston and the load cell
(Figure 7); the evolution of swelling pressure was monitored again (Stage 3.
confinement phase).

## 205 **3 EXPERIMENTAL RESULTS**

#### 206 **3.1 In situ test (PT-N1)**

Figure 8 shows the evolution of injected water volume over time. As mentioned above, 207 a volume of 49 L was first injected to fill the technological void and the injection was 208 stopped for 20 days due to a technical problem related to the packer. After resuming 209 the injection, it was observed that the increase rate of water volume was followed by 210 an asymptotic curve with a decreasing rate. After 367 days, the total injected water 211 volume was 71.39 L (Figure 8). Examination of the curve shows that the shape of 212 213 water volume versus time (after rejection) can be described by a hyperbolic function. 214 Figure 9 presents the time/water volume (day/L) versus time. A good linear relationship is obtained, confirming that the water volume-time curve is of a 215 hyperbolic shape. Thereby, the following equation can be adopted for this 216 relationship: 217

218 
$$\frac{t}{V} = a + bt$$
 Eq.1

where *t* is time, *V* is injected water volume, *a* and *b* are the intercept and the slope of
the straight line, respectively (Figure 9).

221 According to this hyperbolic relationship, the maximum water volume corresponds to

*1/b* (Eq.2), equal to 72.46 L. This is to be compared with the total volume of voids
including the technological void and the soil porosity: 69.1 L.

224 
$$V_{max} = \lim_{t \to \infty} V(t) = \lim_{t \to \infty} \left(\frac{1}{a/t + b}\right) = \frac{1}{b}$$
 Eq.2

225 During hydration, both the axial and radial swelling pressures were recorded by the total pressure sensors (see Figure 3) and the results are shown in Figure 10. The data 226 by the sensor located at 1.20 m section for the axial swelling pressure measurement 227 228 were unfortunately not available; only the axial swelling pressure values at 0 m 229 section are presented. This pressure increased at an almost constant rate and reached 1.63 MPa after 367 days. For the radial swelling pressure, the evolution rates were 230 231 very different for the three sensors (see Figure 3); the pressure values reached were 232 1.78 MPa, 0.56 MPa and 1.05 MPa for sensors L-01, L-02 and L-03, respectively. This indicates the heterogeneous radial swelling under the in-situ conditions. 233

#### 234 **3.2 Small-scale test**

235 Figure 11 shows the measured water inflow over time. Once the water supply was connected to the bottom inlet, water volume increased rapidly and reached 49 mL in a 236 237 few minutes. This value corresponded exactly to the volume of technological void 238 (49 mL). Afterwards, water volume increased gradually to reach a maximum value of 70.6 mL. No more water could infiltrate after about 200 days. The total volume of 239 void (including the technological void  $V_{tech}$  and the void inside the soil  $V_{v-s}$ ) that 240 241 could be filled with water was estimated at 69.1 mL. The result shows that a little more water was injected with respect to the estimated one (70.6 mL against 69.1 mL), 242

but the difference is quite small.

For further analyzing the evolution of water volume, the time/water volume (day/mL) is plotted versus time in Figure 12. As in the case of in-situ test, a straight line is obtained justifying a hyperbolic relationship between the water volume and the elapsed time (Eq.1). The value of 1/b corresponds to the maximum volume of water: 1/b = 71.43 mL, which is very close to the measured water volume (70.6 mL).

Figure 13 and Figure 14 depict the evolution of swelling pressure in the first stage (i.e. 249 initial saturation phase). Once water was injected into the specimen, the axial swelling 250 251 pressure increased very quickly (Figure 14). After about 2 days, the swelling pressure reached a first stability stage (1.30 MPa) and it restarted to increase on the 4<sup>th</sup> day. 252 When the swelling pressure reached 1.45 MPa after about 12 days, a significant 253 254 decrease of swelling pressure occurred and a minimum value of 0.70 MPa was reached. Afterwards, the swelling pressure increased again after about 33 days (Figure 255 13), but at a slower rate. In addition, the evolution curve shows fluctuating pattern. 256 257 The swelling pressure reached a mean value of 1.80 MPa after 300 days and then fluctuated in the range of 1.75-1.95 MPa. 258

The axial deformation during the swelling pressure development was also recorded, and shown in Figure 13. It followed the same trend as the swelling pressure. Note however that the variation of displacement was smaller than 0.2 mm. It represents 0.16% of the specimen height (120 mm), suggesting a satisfactory control of axial displacement in this stage.

According to the data obtained in the first stage (Figure 13), no obvious swelling 264 pressure increase occurred during a period of 50 days from day 300 to day 350. Thus, 265 266 it was decided to start the second stage. For this purpose, the confining pressure was removed on day 350, allowing the free swell. Changes in axial swelling strain were 267 recorded and presented in Figure 15. The uplifting of load cell led to an instantaneous 268 rebound of 1.1% (1.4 mm / 120 mm). Afterwards, the axial swelling strain increased 269 almost linearly at a rate of 0.145 mm/day. Following this rate, 20% of swelling strain 270 was expected to be reached after 157 days. In order to reduce the test duration, two 271 272 sides infiltration was applied on day 364. This resulted in an increase of the swelling strain rate to 0.588 mm/day, which is four times faster than that with one-side 273 infiltration. The expected value of 20% (24 mm) was reached on day 400. The piston 274 was then re-blocked automatically to start Stage 3. Note that the measured axial swell 275 was 24.4 mm. 276

The evolution of swelling pressure was then measured again and the results are presented in Figure 16. Small fluctuation was observed and this fluctuation can be attributed to the daily temperature variations. As expected, the evolution curve follows a hyperbolic curve with a decreasing rate over time. It reached stabilization on day 520 with a final swelling pressure of 0.18 MPa.

## 282 4 COMPARISON AND DISCUSSION

It was observed that more water infiltrated into the soil than that calculated by considering the technological void and the soil porosity in both the in situ test

(71.39 L) and laboratory small-scale test (70.60 mL). Even though the water volume 285 has been not yet reached stabilization in the in-situ conditions, the discrepancy is 286 287 found to be larger than in the small-scale test. This can be related to the natural conditions of the in-situ test, where some water intake by the host-rock did occur. 288 289 With a well controlled condition in the small-scale test, the larger infiltrated water obtained may be related to the low water density (1.00 Mg/m<sup>3</sup>) considered in the 290 determination of soil void ratio. Indeed, for high plasticity materials as the MX80 291 bentonite, the water density can be much higher than 1.00 Mg/m<sup>3</sup> (Marcial 2003, 292 Villar and Lloret 2004, Lloret and Villar 2007, Jacinto et al. 2012). This is in 293 agreement with the observation from the KBS-3H mock-up test (Börgesson et al. 294 2005). 295

296 Regarding the evolution of water volume, a hyperbolic relationship between the injected water volume and elapsed time was obtained in both tests. Accordingly, the 297 maximum water volume was estimated at 72.46 L and 71.43 mL for the in-situ and 298 299 small-scale tests, respectively. To compare the evolution curve at different scales, the water volume was normalized by using these two values. The normalized water 300 301 volume is equal to the ratio of water volume at time  $t(V_t)$  to the maximum water 302 volume that can be injected (72.46 L and 71.43 mL for the in-situ and small-scale test, respectively). In terms of time scale, an up-scaling ratio of 2.5 (in situ test/small scale 303 test) was found from the normalized water volume shown in Figure 17, where very 304 similar evolution curves (normalized water volume versus normalized time) were 305 obtained for the two tests (in situ and small scale tests). 306

This up-scaling ratio is much smaller than that estimated based on the consolidation 307 theory by considering the experiment scale and hydration conditions: according to the 308 309 infiltration length, the hydration rate of the in-situ test should be 100 times lower than in the small-scale test (1/10). As the two-side infiltration applied in the in-situ test 310 increased the hydration rate by 4 times, the up-scaling ratio should be equal to 25 311 312 (in-situ test / small scale test), still ten time larger than the rate identified from the measurements. In fact, under the field conditions, water may fill some voids between 313 314 the pre-compacted disks during the first minutes (0.15 m thick, see Figure 2). This 315 infiltration length of 0.15 m leads to an up-scaling ratio to 0.56. The up-scaling ratio of 2.5 observed is possibly related to the combined effect of these two phenomena. 316

317 Using this up-scaling ratio, the axial swelling pressure evolution curve obtained from 318 the in-situ test (Figure 10) was normalized and presented in Figure 18, together with 319 the axial swelling pressure measured in the first stage of the small-scale test. Except for the first 33 days (see Figure 13) where significant decrease of swelling pressure 320 321 occurred in the small-scale test, the normalized curve of swelling pressure for the in-situ test join the curve of the small-scale test, confirming the up-scaling ratio of 2.5. 322 323 Based on the results of small-scale test, this ratio allows the time needed to reach the 324 stabilization of swelling pressure in the in-situ test to be estimated. It can be observed in the small-scale test that the swelling pressure reached the stability after about 300 325 days. Thus, 155 days more is needed to reach the maximum swelling pressure at the 326 327 normalized time scale for the in-situ test. Accordingly, it can be estimated that the maximum swelling pressure in the in-situ test should be reached after 388 days, 328

329 corresponding to 754 days starting from the time of water injection.

330 As regards the kinetics of the axial swelling pressure in the first 33 days of small-scale 331 test, stabilization was attained after about 2 days at 1.30 MPa and restarted to increase from day 4 (Figure 14). Wang et al. (2012b) observed similar phenomenon in swelling 332 pressure tests on smaller samples (35 mm in diameter, 10 mm in height) with the same 333 percentage of technological void. This is related to changes in microstructure of soil. 334 With the progress of hydration, the effect of microstructure changes is reduced, 335 resulting in the re-increase in swelling pressure (Cho et al., 2000; Baille et al., 2010). 336 337 When the swelling pressure reached 1.45 MPa on day 12, a significant decrease of 338 swelling pressure occurred, reaching a minimum value of 0.70 MPa. This decrease can be attributed to the filling of the technological void. Afterwards, the swelling 339 340 pressure increased again from day 33. However, the evolution curve showed fluctuation due to the re-organization of soil microstructure under the effect of 341 technological void. 342

343 On the contrary, the axial swelling pressure measured in the in-situ test increased constantly without any fluctuation. This can be related to a coupled effect of large 344 scale and pressure sensor location. Indeed, in the small-scale test, the axial swelling 345 pressure was measured on the whole cross section and any changes in axial pressure 346 could be monitored. However, in the in situ test, the total pressure sensor was installed 347 348 in the centre of the cross section (Figure 3) and the axial swelling pressure herein 349 corresponded to the local one. Therefore, the axial swelling pressure changes occurred in the zone of technological void could not be detected by this sensor. 350

351 After the axial swelling pressure of small-scale test reached stabilization, removing the axial confining restriction led to a very small rebound of 1.1% (1.4 mm/ 120 mm). 352 353 This observation provides valuable information for the confinement removal phase of the in-situ test. During the free swelling process (Stage 2), a swelling strain evolution 354 rate (swelling strain/time) of 0.588 mm/day was observed under two-side infiltration 355 conditions. Combined with the up-scaling ratio, this result (0.588 mm/day) allows 356 prediction of the swelling strain evolution in the in-situ test when simulating an 357 incidental decrease of the swelling pressure caused by a failure of the concrete 358 359 confining structure.

360 As the piston was re-blocked automatically in the small-scale test (Stage 3), swelling 361 pressure developed again. This indicates the favorable sealing capacity after filling of 362 the technological void. If a saturation defect or a confining structure failure occurs in the field, a 20% additional void could be sealed. A final swelling pressure of 363 0.18 MPa was attained, which is in accordance with the swelling pressures measured 364 in the laboratory on smaller samples (Wang et al., 2012b): after the 20% free swell 365 (24.5 mm), the dry density decreased to a final value of  $1.39 \text{ Mg/m}^3$ ; this corresponds 366 367 to a swelling pressure of 0.23 MPa.

## 368 **5 CONCLUSION**

In the context of SEALEX project, a laboratory small-scale test (1/10) was carried out
to investigate the recovery capacity of bentonite-based plug with technological void.
By comparison with the first results from the in-situ test PT-N1, the phenomena

identified in the laboratory were used for interpreting and estimating the results fromthe in-situ test.

During the saturation process, a hyperbolic relationship between the injected water volume and elapsed time was obtained in both laboratory and field tests. However, a little more water was injected as compared to the water volume estimated by considering the total porosity. Larger discrepancy was found for the in-situ test due to the effect of natural conditions.

379 Decrease of axial swelling pressure was observed in the small-scale test due to the 380 filling of technological void. In contrast, the axial swelling pressure measured 381 increased continually in the in-situ test. This could be attributed to the effects of both 382 the scale and the locations of pressure sensors.

Comparison of the injected water volume and the axial swelling pressure between the two different scales gave the same up-scaling ratio of 2.5 (in-situ scale / laboratory scale). Using this up-scaling ratio, the time needed to reach the swelling pressure stabilization in the in-situ test was estimated at 754 days.

After removal of the axial confining restriction, a swelling strain evolution rate (swelling strain/time) of 0.588 mm/day was observed in the case of two-side infiltration. Combined with the up-scaling ratio, this rate allowed prediction of the swelling strain evolution in case of a confining structure failure. A swelling pressure of 0.18 MPa was obtained after filling an additional void of 20%, indicating the favorable sealing capacity after filling the technological void.

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	Compound	NaHCO <sub>3</sub>	$Na_2SO_4$	NaCl	KC1	$CaCl_2.2H_2O$	MgCl <sub>2</sub> .6H <sub>2</sub> O	SrCl <sub>2</sub> .6H <sub>2</sub> O
	Mass (g) per Litter	0.28	2.216	0.615	0.075	1.082	1.356	0.053
_	of solution							
463								
464								
465								
466								

462 Table 1. Chemical composition of the synthetic water.





470 Figure 1. Layout of the SEALEX in-situ experiment (after Barnichon and Deleruyelle, 2009).



- 472 Figure 2. Geometry of the clay plug and the pre-compacted blocks.



(a) Distribution of the total pressure sensors







481

Figure 4. Experimental devices.





486

Loadce

Piston







Figure 7. Lifting of load cell for free swell.



493

494

Figure 8. Injected water volume versus time.





Figure 9. Time/water volume versus elapsed time after water rejection.





Figure 11. Water volume injected into the specimen.





Figure 13. Evolution of axial swelling pressure and displacement in the first stage.









(a) Evolution of axial swelling strain during the first 15 days after unloading.





510

## (b) Evolution of axial swelling strain



Figure 15. Evolution of axial swelling strain during Stage 2.



512

Figure 16. Evolution of axial swelling pressure during Stage 3.





Figure 17. Normalized water volume versus normalized time.

