DOPAS Work Package 4
Deliverable D4.2: "Report on Bentonite Saturation Test (REM)"

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PS: D4.2 publicity is “PP”. The report will be available during the project duration on request. This report will also be available on the DOPAS web site after the DOPAS project has ended.

Executive Summary

The Full-Scale **D**emonstration **of Plugs and S**eals (DOPAS) Project is a European Commission (EC) programme of work jointly funded by the Euratom Seventh Framework Programme and European nuclear waste management organisations (WMOs). A set of full-scale experiments, laboratory tests, and performance assessment studies of plugs and seals for geological repositories are being carried out in the course of the Project.

The DOPAS Project focuses on tunnel, drift, vault and shaft plugs and seals for crystalline, clay and salt host rocks (formations considered for deep geological repository programmes).

The project is coordinated by POSIVA Oy, Finland. Work Package 4 (WP4) of the DOPAS Project concentrates on the activities subsequent to WP3 field experiments (design and construction of seals and plugs), i.e. on the appraisal of the plugs and seals functions. WP4 is coordinated by RWM, United Kingdom.

This report is Deliverable D4.2 of DOPAS WP4, and describes the "Bentonite saturation Test (REM)" carried out by Andra at a metric scale, with the same bentonitic material (pellets and powder admixture) as that employed in the construction of the FSS swelling core (construction experiment carried out in Saint-Dizier, within the frame of WP3activities). This saturation test is instrumental in comforting the knowledge and in the modelling of the bentonite seal behaviour (i.e. its saturation phenomenology), since the characterization work of the bentonitic material was anteriorly carried out at a pluricentimetric scale only (in "ordinary" oedometers): in summary, following the saturation course at a metric scale is more representative of real phenomena happening in a decametric core than doing so at a centimetric scale.

This document D4.2 presents the links between the FSS construction and the saturation experiment. The experimental set-up and the way its phenomenological functioning will be monitored throughout 10 to 30 years are detailed (doing so at the FSS core decametric scale would take… thousands of years!). The very first experimental outcomes provided by REM are indicated.

Note1: As mentioned above, the REM experiment is engaged as a complement to the preliminary characterization works carried out in WP3, at a much smaller geometrical scale and on a much shorter time scale (Cf. DOPAS WP3 Deliverable D3.5 "Lab test report on the performance of the clayish material for FSS").

Note2: The description and design justification of the Cigéo seal concepts are motivated in the DOPAS WP5 Deliverable D5.2 "*Report on Andra's PA Methodology for Sealing Systems*", while the Repository phenomenology and its interacting with seals are exposed in DOPAS WP5 Deliverable D5.3 "*Andra's Understanding of Processes involved in Time and Space*".

List of Acronyms

HRL: Äspö hard rock laboratory

CEA : Commissariat à l'énergie atomique (French Atomic Commission)

Cigéo: Centre Industriel de Stockage Géologique (Industrial Repository in France)

DAC: Demande d'autorisation de construction (Cigéo License application file - 2016)

DOMPLU: Dome Plug

DOPAS: Full-scale Demonstration of Plugs and Seals

DOS: Dossier d'options de sûreté (Safety Option Dossier)

EBS: Engineered barrier system

EC: European Commission

EDZ: Excavation damaged zone

ELSA: Entwicklung von Schachtverschlusskonzepten (development of shaft closure concepts)

EPSP: Experimental Pressure and Sealing Plug

ETe: Espace Technologique (Technological show-room, located near the Bure URL, where the REM experiment is installed)

FSS: Full-scale Seal (experiment)

HLW: High-level waste

IL-LLW: Intermediate-level long live waste

KBS: KärnBränsleSäkerhet (Nuclear Fuel Safety; the "3" in KBS-3 denotes the 3rd version, the "V" in KBS-3V denotes the vertical deposition mode and the "H" in KSB-3H refers to the horizontal deposition mode)

LECA: Lightweight expanded clay/concrete aggregate

LECBA: Laboratoire d'étude du comportement des bétons et des argiles (CEA Laboratory for concrete and clay material characterization)

NSC: Noyau de Scellement (Sealing experiment implemented in Andra's Bure URL underground works)

POPLU: POSIVA Plug Experiment to demonstrate deposition tunnel end plug

REM: Resaturation à l'échelle métrique du matériau bentonitique de FSS (Metric Resaturation Test)

SAGD: Système d'acquisition des données (Data acquisition system)

SET: Saignée à l'ETe (Hydraulic cut-off experiment carried out in Andra's Technical show-room)

URCF: Underground rock characterisation facility

URL: Underground research laboratory

VAHA: Vaatimusten hallintajärjestelmä (POSIVA's requirement management system)

VSG: Vorläufige Sicherheitsanalyse Gorleben (Preliminary Safety Analysis for Gorleben)

WMO: Waste management organisation

WP: Work package

List of DOPAS Project Partners

The fourteen (14) partners in the DOPAS Project are listed below. In the remainder of this report each partner (if cited) is referred to as indicated:

POSIVA	Posiva Oy	Finland
ANDRA	Agence nationale pour la gestion des déchets radioactifs	France
DBE TEC	DBE Technology GmbH	Germany
GRS	Gesellschaft für Anlagen- und Reaktorsicherheit	Germany
NAGRA	Die Nationale Genossenschaft für die Lagerung Radioaktiver Abfälle	Switzerland
RWM	Radioactive Waste Management Limited	UK
SÚRAO	Správa Úložišť Radioaktivních Odpadu (Radioactive Waste Repository Authority – RAWRA)	Czech Republic
SKB	Svensk Kärnbränslehantering AB	Sweden
CTU	Czech Technical University	Czech Republic
NRG	Nuclear Research and Consultancy Group	Netherlands
GSL	Galson Sciences Limited	UK
BTECH	B+ Tech Oy	Finland
VTT	Teknologian tutkimuskeskus VTT Oy (VTT Technical Research Centre of Finland Ltd)	Finland
UJV	Ustav Jaderneho Vyzkumu (Nuclear Research Institute)	Czech Republic

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1. FSS experiment and link to REM

1.1 General

The Full-Scale **D**emonstration **of Plugs and S**eals (DOPAS) Project is a European Commission (EC) programme of work jointly funded by the Euratom Seventh Framework Programme and European nuclear waste management organisations (WMOs). A set of full-scale experiments, laboratory tests, and performance assessment studies of plugs and seals for geological repositories are being carried out in the course of the Project.

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1.2 Link between REM and FSS

In the design phase of the CIGEO Deep Geological Repository project, Andra plans to progressively build horizontal drift seals to re-establish site integrity and safety on closure. Various technical solutions have been considered, involving a swelling clay core inserted between two concrete support structures (aka “containment walls”). In order to check the industrial feasibility of this facility, a Full-Scale Seal (FSS) technological demonstrator was built in Saint-Dizier within the frame of the European DOPAS project. This demonstrator tested industrial construction equipment by using existing and specifically developed technologies to set up and perform a full scale sealing operation. The seal core was made from a material formed of an admixture of bentonite pellets and crushed pellets (aka “powder”). The core support structures (also called “containment walls”) are made of low PH concrete, with self-compacting concrete for the “upstream wall” and shotcrete for the “downstream wall”.

Given the size of the construction facility, a phenomenological test could not be envisaged. In fact, the saturation of a **decametric**-sized core would take hundreds or thousands of years and would generate very high levels of mechanical stress on the drift model structure (concrete liner) due to bentonite swelling. A series of experiments are therefore being implemented in addition to the FSS construction demonstration in order to test the phenomenological aspects and the seal hydro-mechanical behaviour under real operating conditions.

The REM saturation experiment is thus complementary to the FSS construction experiment and will demonstrate the feasibility of resaturating the bentonite admixture used in FSS and analyse the pellets/powder mixture behaviour during resaturation at a **metric** scale that is difficult to achieve with standard laboratory equipment (**decimetric** scale cells at most).

The experiment set-up has in fact two parts:

- The construction and operation of a metric-scale model, with a start-up as of September 2014, located at the ETe (Andra's technical show-room), near the Bure URL. Saturation is carried-out with formation water (from the Argillites);
- The performance of "in-laboratory" hydro-mechanical tests (centimetric and decimetric scale cells), which are still being finalised at the time of writing. Saturation is then also carried-out with cementitious water (leachates coming either from OPC concrete or from low pH concrete) to check how the bentonite mixture swelling pressure is affected by an alkaline plume.

2. Introduction

This experiment is part of the European DOPAS project (Full-Scale Demonstration of Plugs and Seals) WP4. The REM experiment was designed jointly by Andra and the CEA (LECBA). Installation was performed by LECBA representatives in the presence of Andra contributors. Data monitoring and analysis was and is still performed by Andra contributors under the expertise of LECBA representatives.

2.1 REM experiment objectives

The REM experiment specifications (D.SP.AMFS.13.0033) define the experiment objectives as follows:

- Change the scale from the preliminary tests of the FSS experiment (carried out at centimetric scale in a surface laboratory), which defined the admixture of pellets and crushed bentonite (grain size and proportion). This test must be carried out at metric scale at least in order to be representative of the Full-Scale Seal test;
- Verify the possibility of resaturating the bentonite mixture at this scale;
- Study the phenomenology and kinetics involved in achieving saturation;
- Check that the hydraulic behaviour involved in achieving saturation is generally uniform at this scale;
- Once fully saturated, check that the hydraulic characteristics (gas entry pressure, water and gas permeability) and mechanical characteristics (swelling pressure) are compliant with Andra sealing specifications and are generally uniform at the test scale.

These objectives have been specifically assigned to this test and are complementary to the objectives of other seal-related tests carried out by Andra (in particular NSC and SET), and especially FSS at Saint-Dizier.

In CIGEO, the core will be partially hydrated via the concrete lining on the drifts and the concrete plugs, and directly via the claystone in the contact zones. Although low pH concrete will be used in the sealing zones, the impact of higher pH water bearing different ions to the on-site water will be checked and quantified using laboratory experiments at a representative scale.

2.2 Document contents

This report presents the REM experiment installation phase and initial measurements. It covers all operations carried out during the installation phase and presents the initial results since the launch of hydration. The results of laboratory tests are also presented and analysed.

This report contains:

- The experiment concept and experimental strategy;
- The various measurement systems used;
- Their installation procedures;
- The location of the equipment installed;
- The initial measurements obtained at the time of writing;
- The results of laboratory tests.

3. Description of the REM experimental set-up

In order to get as close as possible to *in situ* conditions, several criteria were defined for experiment design. The pellet-powder admixture emplacement should be representative of the technique used in FSS (use of screw type conveyors to transport materials), particularly in terms of compacting rates. To ensure comparable properties (permeability, swelling pressure) between the REM model and the FSS demonstrator, equivalent dry density must be similar in both systems. Equivalent dry density primarily depends on the compacting rate, residual void level and initial water content. The technique for pellet / powder admixture emplacement, although manual, should draw on the technique used in FSS. The reduced dimensions of REM prevent the use of the filling tool used in FSS.

The experimental strategy used in the REM experiment is as follows:

- Monitoring of water saturation;
- Monitoring of injected water volumes;
- Monitoring of removed air volume;
- Measurement of pore and total pressure;
- Occasional permeability measurements (water and gas);
- Measurement of swelling pressure;
- Measurement of gas entry pressure.

It is also necessary to know the system's initial hydraulic state and the exact volume available for bentonite emplacement (excluding the volume of sensors and other instruments).

Measurements must give a three-dimensional view of the hydraulic and mechanical behaviour within the test, throughout the entire resaturation phase. They must also determine when saturation is achieved from a hydraulic and mechanical standpoint (swelling pressure). In smaller scale tests, stress balance is achieved before pore pressure balance.

3.1 Vessel

The dimensions of the vessel have primarily been determined for the initial swelling pressure target (7 MPa). In a metric-scale object, there is a high load on the walls of 700 metric tonnes per m^2. Because hydration of the granular mixture is one-dimensional, the vessel installed is inspired by the large-diameter swelling cells used at LECBA (CEA). In order to facilitate filling and avoid creating "arching" effects that prevent the material from reaching uniform density, sensors had to be spread out with intervals of at least the size of the pellets, and for the experiment as a whole, the vessel diameter had to be at least equal to its height (slenderness ratio of 1/1 to minimise edge effects).

The vessel was manufactured by Fives Stein in Bar-le-Duc (Eastern France). The vessel is cylindrical with a 1 m internal diameter and an inside height of 1 m. The thrust of the saturated swelling material on the cylinder surfaces (surface area = 0.79 m^2) could thus reach 553 tonnes.

The vessel comprises a 40 mm thick confinement cylinder, with 2 lids fitted with sintered stainless steel porous discs in the bottom part and air vents in the top part (Figure 3-2).

The lids are fitted with an O-ring to ensure leak tightness and are held onto the cylinder by four high-resistance steel tie rods with a 72 mm diameter. The load is absorbed and distributed by two retaining frames arranged in a square formation on each surface. At an internal pressure of 7 MPa, the tie rod elongation is around 1.5 to 2 mm.

All surfaces in contact with the bentonite and hydration water are made of stainless steel.

The diagram in Figure 3-1 includes the different vessel components, such as the porous discs in the lids and the instruments positioned around the confinement cylinder in a radial direction.

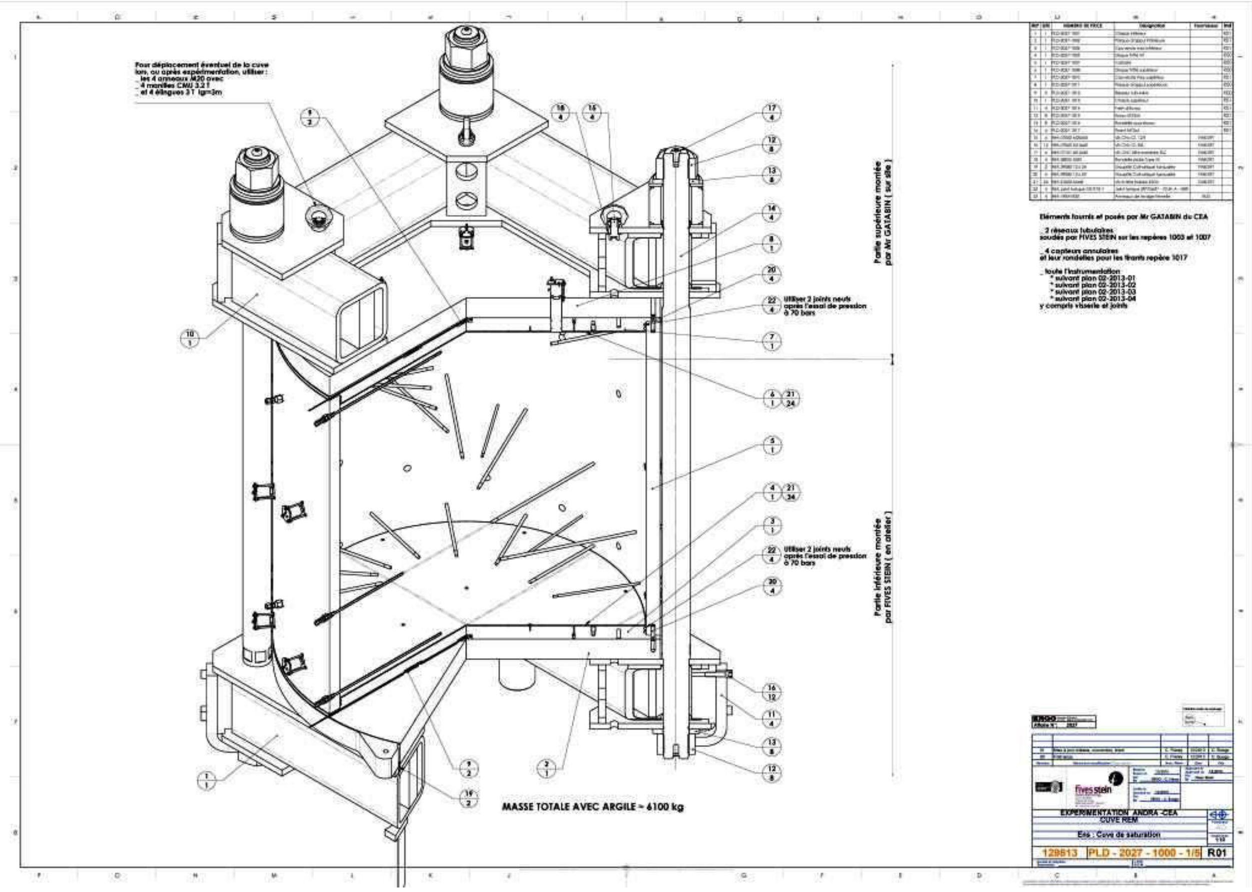


Figure 3-1 Vessel cutaway diagram, from FIVES STEIN Manufacturing

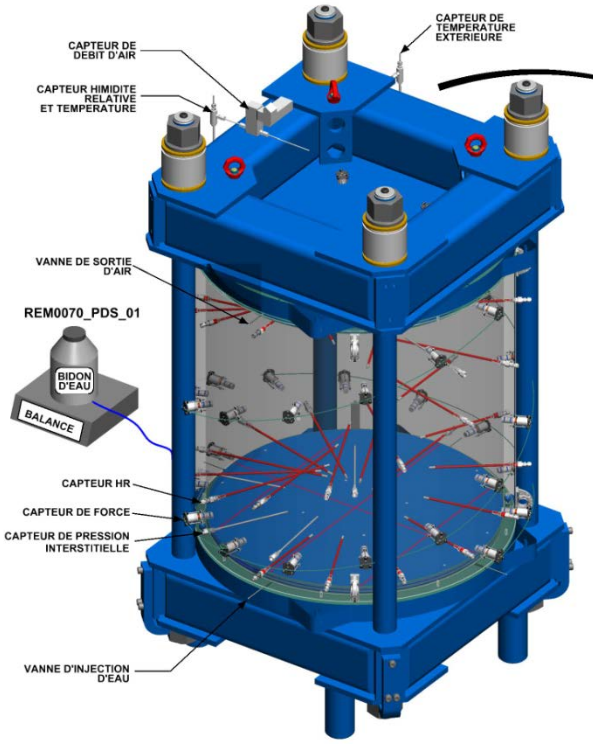


Figure 3-2 Schematic representation of the REM model

3.2 Experiment conceptual approach

The REM experiment is a “1D” saturation test of a confined swelling clay material at “constant volume”.

The vessel environment comprises the vessel hydration or injection circuit and the air outflow circuit. The injection system must supply water to the sample inside surface and regulate and/or quantify the volume of water provided.

The hydration water (host formation water) is taken from the “Bure site borehole FTP1101”. This borehole was drilled in October 2010 along the underground “GMR drift” wall. It is sub-horizontal and 100 m long with a 10 cm diameter. Since April 2012, water has been collected from the borehole and its composition is monitored by sampling and laboratory analysis.

The injection pressure is slightly higher than atmospheric pressure, typically 1 to 2 metres head of water (10 to 20 kPa).

In practice, *in situ* water flows are very low (host rock permeability of the order of 10^{-13} m/s) and will not therefore modify the structure of the pellet/powder mixture by carrying away the smallest particles (no erosion phenomena are anticipated). In order to get as close as possible to these very low flow conditions and given the usual flowrates observed in the Bure site underground laboratory experiments, it had to be possible for the injection rate to be very low, at least for the first weeks/months.

At first, the hydration rate was set at 50 ml per day, which is representative of the water supplied from a desaturated rock mass close to a seal. This rate is the flowrate reported at the vessel surface, which was measured *in situ* in “Bure site boreholes PAC1002 and POX1201” (Vinsot et al., 2011) at the underground laboratory. Finally, once the pressure has risen, the hydration system will be directly connected to the feed tank for gravitational supply driven by the suction of the sample, **a scenario corresponding to a saturated rock mass supplying continuous water in sufficient quantities**.

In disposal conditions, resaturation will be primarily radial and centripetal for a drift diameter of the order of 10.8 m. In this type of test, it is difficult to reproduce radial hydration. However, in order to understand resaturation dynamics, water will be injected at low flowrate or at constant pressure on a single surface to help understand how the resaturation processes operate. In particular, a zone in contact with water will hydrate quickly and swell, thus compressing areas that still have the initial water content. In this set-up, it is important to avoid the risk of “easy flows” caused by contact between the vessel and the bentonite pellet mixture. Resaturation from the bottom of the vessel has therefore been selected.

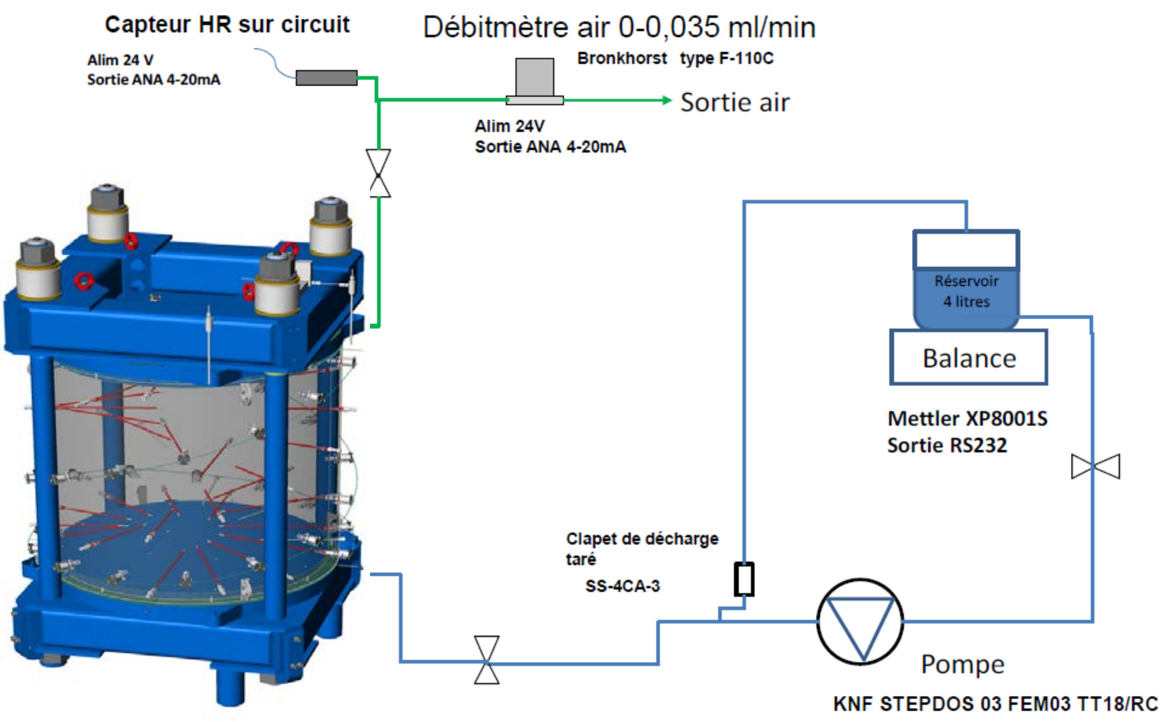


Figure 3-3 Schematic circuit diagram of the REM vessel and its environment

The output circuit collects air ejected from the vessel. A very precise flowmeter must measure the flowrate and a Relative Humidity (RH) measurement sensor is placed on a branch of the circuit. Figure 3-3 above is a diagram of the vessel with its 2 systems.

3.3 Vessel instruments

As previously mentioned, the instruments were provided and installed by LECBA/CEA (Gatabin and Guillot, 2004).

The permeability of the bentonite pellet mixture at target saturation in the FSS experiment must be lower than10^{-11} m/s and the duration of saturation for a metric-scale sample is very long, several decades (current calculations estimate the saturation time at approximately 10 to 30 years; correlations with smaller-scale tests give results as high as 60 years). The instruments must precisely measure changes to the sample's hydrological and mechanical state (swelling pressure, pore pressure) and quickly give indications for the DAC (Andra's construction license application scheduled in 2016). These considerations influenced the choice of sensors and their location in the vessel. The sensors must be sufficiently unobtrusive to measure the inside surface as closely as possible and sufficiently robust to function for as long as possible.

Three types of sensors have been installed "on and in" the vessel. These sensors provide five different types of measurements: total radial and axial pressure, pore pressure, relative humidity and temperature. "Off-the-shelf" sensors were adapted by CEA specifically for this configuration. All measurements are transmitted to the outside of the vessel. With the exception of the force washers, all sensors can be easily replaced, tested or changed if required, without modifying test operation.

The radial sensors are distributed at various heights in a spiral formed around the confinement cylinder, perpendicular to the hydration flow (Table 3-1, Figure 3-4).

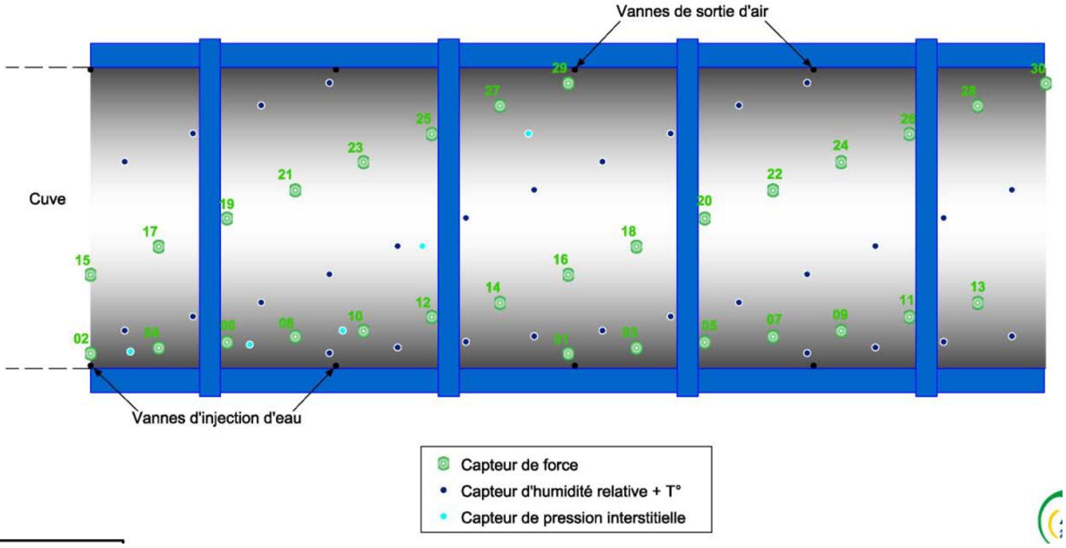


Figure 3-4 *Sensors on the REM experiment vessel*

Table 3-1 *Number of sensors and theoretical position of the sensor centerline according to inside height (z) on the confinement cylinder*

Z-axis position (mm)	**Total radial pressure**	**Relative Humidity + Temperature**	**Pore pressure**
0	Upper surface of bottom lid, including the porous disc		
20	2	2	-
25	-	-	1
40	2	2	-
50	-	-	1
60	2	2	-
80	2	2	-
100	2	2	1
150	2	2	-
200	2	2	-
300	2	2	-
400	2	2	1
500	2	2	-
600	2	2	-
700	2	2	-
800	2	2	1
900	2	2	-
980	2	2	-
TOTAL	**30**	**30**	**5**

3.3.1 Total pressure measurements

Total pressure (or swelling pressure because the pore pressure must not exceed atmospheric pressure during the resaturation phase) is measured using load cells. The test configuration and duration led to the choice of these reliable sensors, which offer the least drift in results over time. These are beam-type strain gauge sensors manufactured and distributed by MEAS France. This type of sensor remains reliable for several decades.

3.3.1.1 Measuring total radial pressure

The vessel confinement cylinder contains 30 total radial pressure measurement points. Measurements are taken with a load cell, secured to the vessel wall by three tie rods, via a bronze piston that slides inside the wall. The piston transfers the material's swelling force to the load cell using a thrust piece (ball joint). The piston is 40 mm long with a 20 mm diameter and two O-rings to ensure leak tightness (Figure 3-5). The bearing surface is 3.142 cm^2.

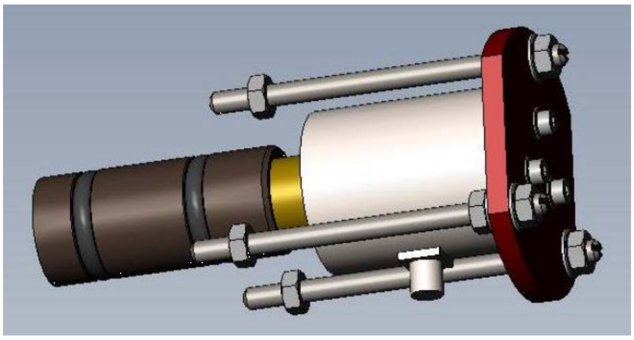


Figure 3-5 Schematic representation of a radial load cell and its transmitting piston

The model chosen was the 20 kN capacity FN2420, in part for its compact design.

Each load cell was paired with a thrust piece and a piston, and calibrated using a special pressurization unit. The unit thickness simulates the vessel wall. It is linked to a pressurization circuit operated by a manual pump, fitted with a "Class A" precision pressure gauge. The load cell is electrically connected to a high-precision "process calibrator", which generates the sensor excitation voltage and measures the output signal (Figure 3-6).

A datasheet was drawn up for each load cell, in accordance with the Andra procedure.

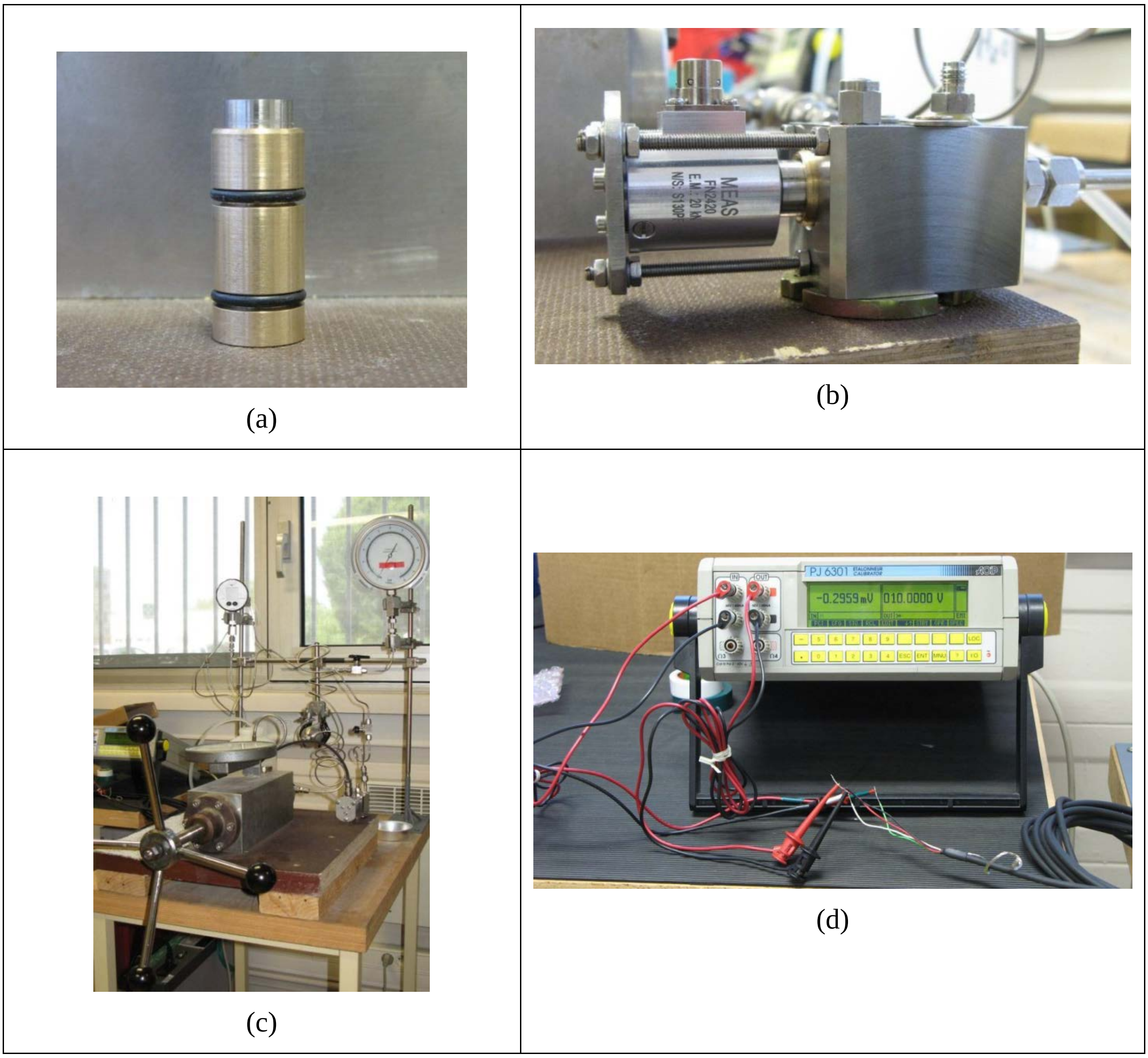


Figure 3-6 *20 mm diameter piston (a), and load cell calibration system: (b) test chamber, (c) calibration pump and pressure gauges, (d) standard calibrator: load cell power supply and signal measurement*

3.3.1.2 Measuring total axial pressure

Two types of load cells are used to measure total axial pressure:

- load cells + pistons:

Four sensors are located in the top lid to measure the total axial pressure. The same load cells are used as for radial measurement (FN 2420 20 KN) and they are fitted with 30 mm diameter and 116 mm long bronze pistons (Figure 3-7). The pistons slide in and out of a hole drilled into the top lid, including the porous disc. Leak tightness is ensured by two greased O-rings. The axial load cells are attached using the same principle as for the radial cells. Although these load cells measure the swelling pressure across a larger surface area of 7.069 cm^2, measurements are only occasional.

These load cells were calibrated in the same way as the radial load cells and paired with their 30 mm diameter pistons.

- force washers:

For overall and quick measurements of the swelling pressure, four force washers are inserted between the top retaining frame and the locknuts. Each of them is designed to measure the average stress applied to the vessel surface due to material swelling.

The dimensions of these force washers required special manufacture by MEAS France. Their size and mass is substantial (Figure 3-8).

The force washers were calibrated using the LECBA 200 tonne press and their support washers.

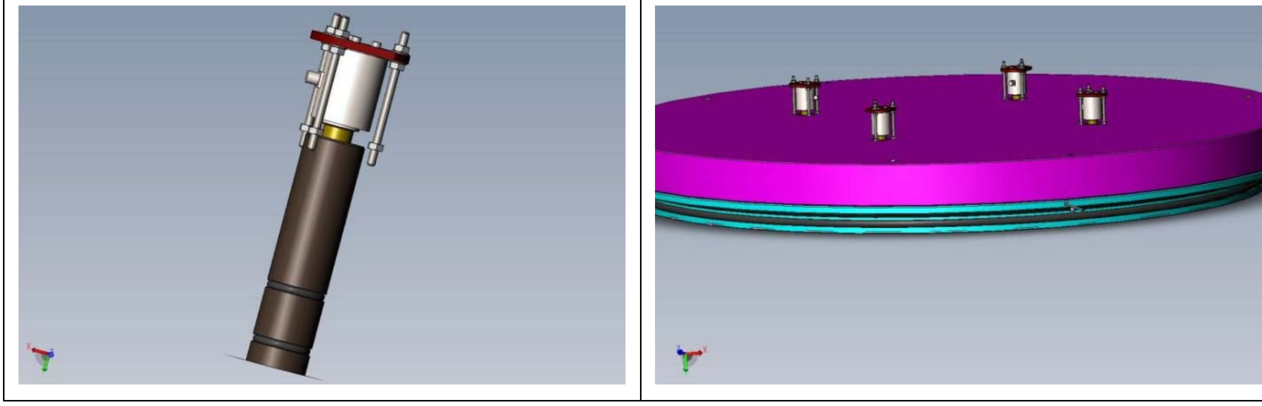


Figure 3-7 *Diagram of total axial pressure measurement load cells and installation in the top lid*

Figure 3-8 *Force washer (left) with its support washers and under the press during calibration (right)*

3.3.2 Core saturation measurements

Saturation is indirectly measured using sensors to measure relative humidity and the associated temperature. Relative humidity is converted to saturation via the water retention curve for the material.

The experiment uses miniature capacitive probes supplied by ROTRONIC France. Any hydrological variation in the clay material leads to a variation in relative humidity, which is detected by the sensor.

The probes are inserted into an extension tube fitted with end filters (Figure 3-9). The air contained in the filter and tube quickly balances with the material (a few minutes are enough for good stability) and this balance is measured by the sensor, which is fitted with a sensitive hygroscopic element.

The tube is screwed into the vessel wall perpendicular to the hydration flow, such as to ensure leak tightness.

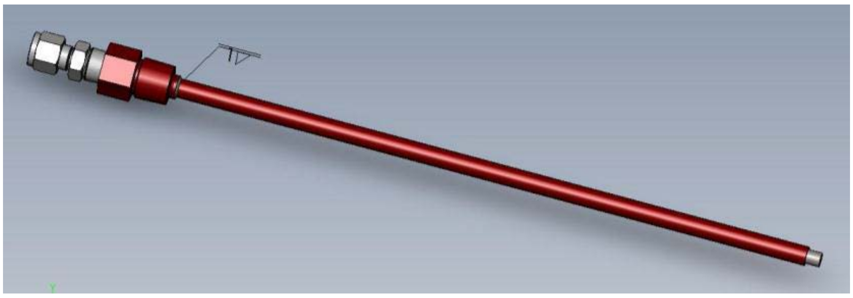


Figure 3-9 Extension tube for RH sensor - The probe is inserted into the tube, up to the filter

The system used means that these sensors could be replaced with psychrometers and then pore water pressure sensors at saturation or when they indicate 100% RH.

The sensors measure the relative humidity across a 100 mm radius, 250 mm from the centre of the vessel.

Each sensor (HC2-C05) is 2.0 m long with a 5 mm diameter and is connected to its own signal conditioning unit. Although the sensors were factory calibrated, they were all verified at LECBA using the 3-point saturated saline solution method: 12% (LiCl), 33% ($MgCl_2$) and 85% (KCl) at 23°C (Figure 3-10).

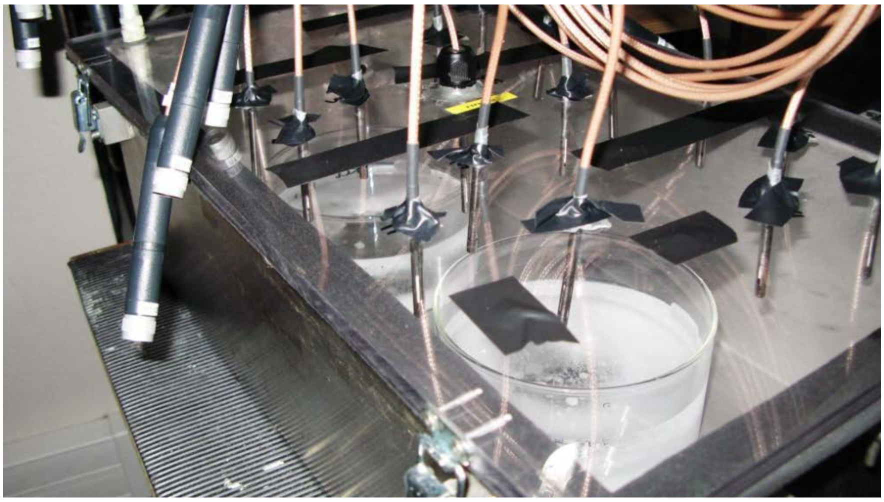


Figure 3-10 Verification of Rotronic RH sensors after being paired with their signal conditioners

After this verification phase, the probes were inserted into the tubes, the sensitive element was placed in contact with the porous tip, and then the tubes were sealed to make them leak tight (Figure 3-11).

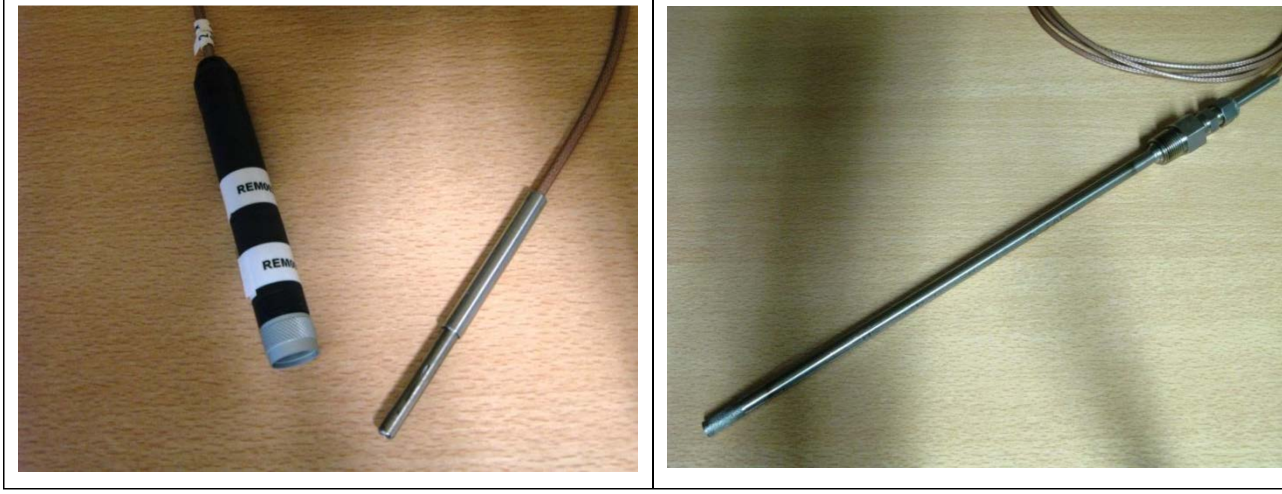


Figure 3-11 *RH sensors: before and after insertion in the extension tube for use in the REM vessel.*

3.3.3 Pore pressure measurements

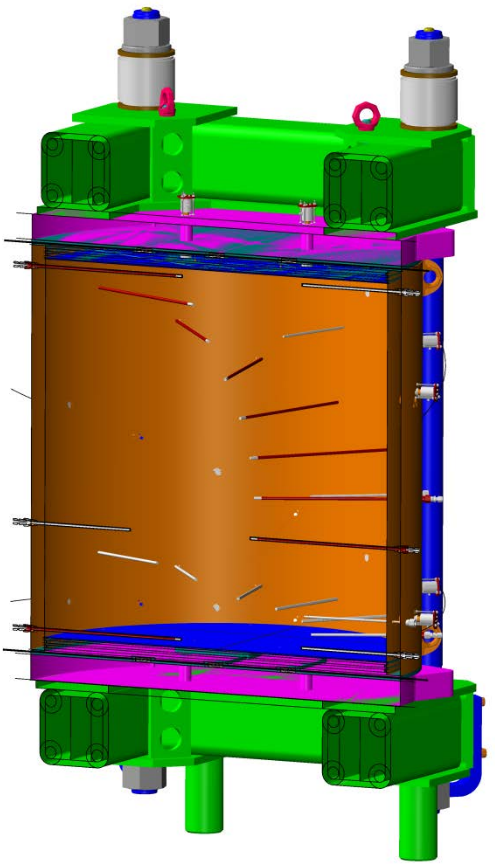
The vessel contains 5 sensors for measuring pore pressure (REM_PRE_01 to 05). The experiment uses Schaevitz sensors (P1502/4) similar to atmospheric pressure sensors (vented gauge), with a membrane fitted with highly reliable gauges. Their small measuring range of 0-350 mbar relative and the quality of their manufacture gives them excellent resolution of under 1 mbar. At first, they measure variation in air pressure in the porosity between pellets using an extension tube with low dead volume, fitted with a porous sintered stainless steel cylinder at the tip (Figure 3-12). The extension tube is screwed onto the vessel wall.

Figure 3-12 *Pore pressure sensor fitted onto its extension tube*

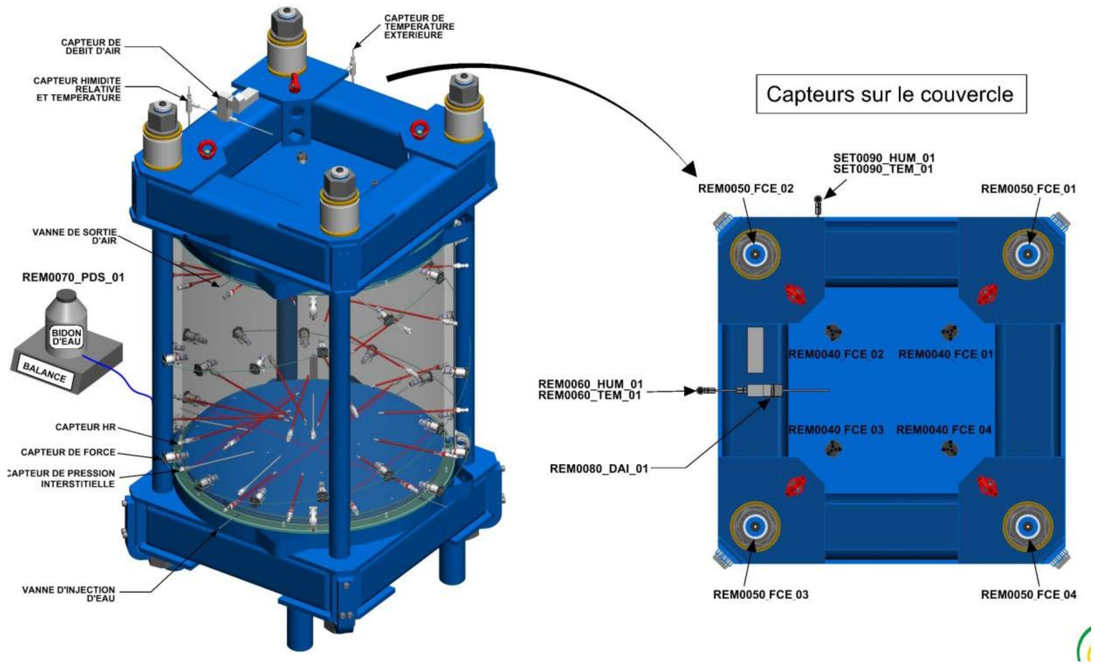
The five sensors underwent electrical checks.

After saturation, they will be able to measure low water pressure. These pore pressure sensors measure the pressure over a 250 mm radius from the centre of the vessel.

Figure 3-13 shows the position of all sensors as installed “on/in” the vessel.



(a)



(b)

Figure 3-13 *3D schematic representation of all sensors installed in the REM vessel (a) internal view (b) external view*

3.4 Water injection system

The site water injection system has been made as simple as possible as it must operate without continuous monitoring over several years (Figure 3). It comprises a 4-litre polyethylene tank fitted with a tap in the bottom part. In order to precisely measure water uptake by the bentonite core over time, the tank is placed on top of a set of METTLER scales (model XS8001S: 0.1 g precision and 8100 g capacity).The scales have a digital display and communicate with the SAGD (Andra's Data Acquisition System) using an RS-232 connection.

As the initial hydration method involves the constant flow of 50 ml per day, a metering pump with adjustable flowrate is inserted between the tank and vessel. This injection method corresponds to the water inflow from a desaturated rock surface and is designed, in principle, to operate for a few weeks from test launch, until the flowrate accepted by the bentonite core is lower than 50 ml per day and the system pressure rises.

In order to protect the pump from overpressure, a pressure relief valve set to 1.5 bars is placed on a branch of the circuit with a return to the tank. Two choices are then possible: i) maintain flowrate using the pump until the flowrate drops below 50 ml per day, ii) switch to direct supply by bypassing the pump after a specified operation duration. From this point onwards, the scales and tank must be raised to create a sufficient pressure head.

The pipes have an external diameter of 1/8'' and are made from stainless steel 316 or PTFE. The four symmetric inlets to supply the vessel will be fitted with quarter-turn ball valves. Given the low initial supply rate, connection to the vessel via one 1/8" supply tube is sufficient.

3.5 Air outlet circuit

The vessel's air outlet circuit is symmetrical to the input circuit. A porous disc collects the air via the core's upper surface. A circuit built into the top lid drains this air into 4 outlet tubes fitted with valves, all of which is connected to a 1/8" stainless steel nozzle (Figure 3-3). A relative humidity sensor identical to the sensors installed in the vessel is fitted in-line on this nozzle and monitored by a flowmeter to measure the output airflow and compare it with the input flow. The experiment uses a BRONKHORST mass flowmeter (F-110C), calibrated for air at 1 bar. It operates across the range of 0.014 ml per minute to 0.7 ml per minute, i.e. between 20 ml per day and 1000 ml per day.

It uses a 24 Volt DC electricity supply with a 0-5 volt output signal.

3.6 Temperature & humidity in the technical environment

A sensor measuring humidity and temperature was installed close to the vessel (SET0090_HUM_01/TEM_01).

3.7 Conclusions

The REM experiment includes a total of 109 sensors. The name and location of these sensors are given in the following section (Chapter 4).

4. Experiment installation

4.1 Vessel receipt

4.1.1 Packing

The vessel was delivered to the technical area on 27 May 2014 (DCSTACSR140161B) on a flatbed lorry in 2 packages. The first package (Figure 4-1) related to the factory-mounted bottom part of the vessel. This part of the vessel included the lower frame, legs and the 4 tie rods installed, and the bottom lid placed on the frame to support the confinement cylinder. A rubber plate was in place to protect the rim of the confinement cylinder during transport. A plywood panel was used to space the tie rods apart and rested against the top part of the cylinder. This panel was held in place by four M 72 nuts via four spacers.

This assembly constitutes the receptacle for the swelling clay material. It was unloaded from the lorry using a bridge crane, with M16 lifting rings screwed onto the bottom panel for this reason. The first package had a mass of 3,100 kg. FIVES STEIN provided ad hoc slings and shackles.

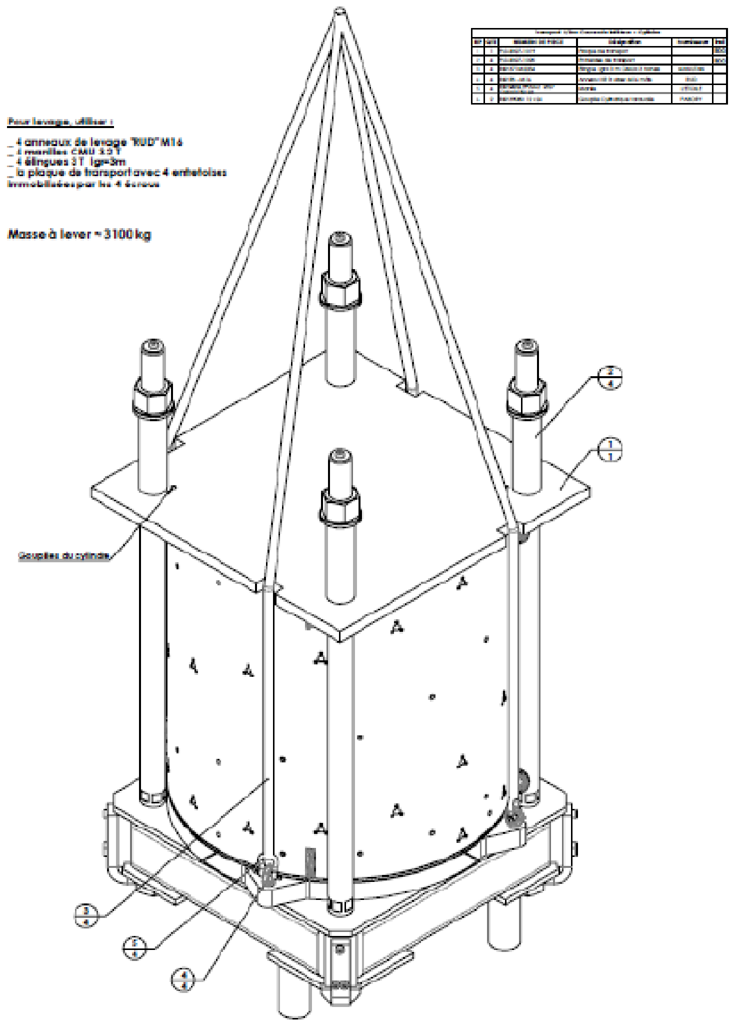


Figure 4-1 REM vessel package no. 1 (extract from FIVES STEIN 1000-2/5 drawing)

The second package (Figure 4-2) contained the top frame placed on the transport pallet, which supported the top lid's two discs. The stainless steel panel including the porous disc and air collection nozzle was on top of this, and the steel force absorption panel was underneath.

It was unloaded using the same tools as for package no. 1. This second package had a mass of 1,550 kg.

During the instrument installation phase, this pallet was kept wrapped up and in an accessible location until operations had finished.

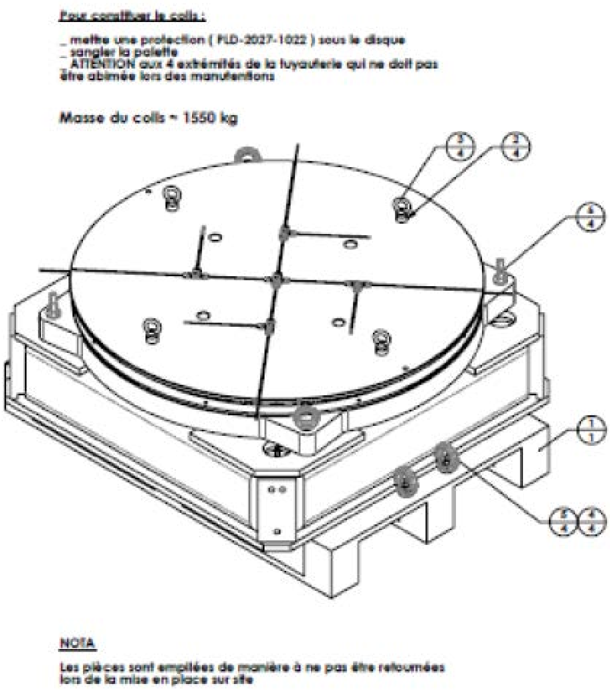


Figure 4-2 *REM vessel package no. 2 (extract from FIVES STEIN 1000-2/5 drawing)*

4.1.2 Location

The location of the REM model in the ETe (Andra's Technological show room near the Bure site) is indicated by a blue square in Figure 4-3.

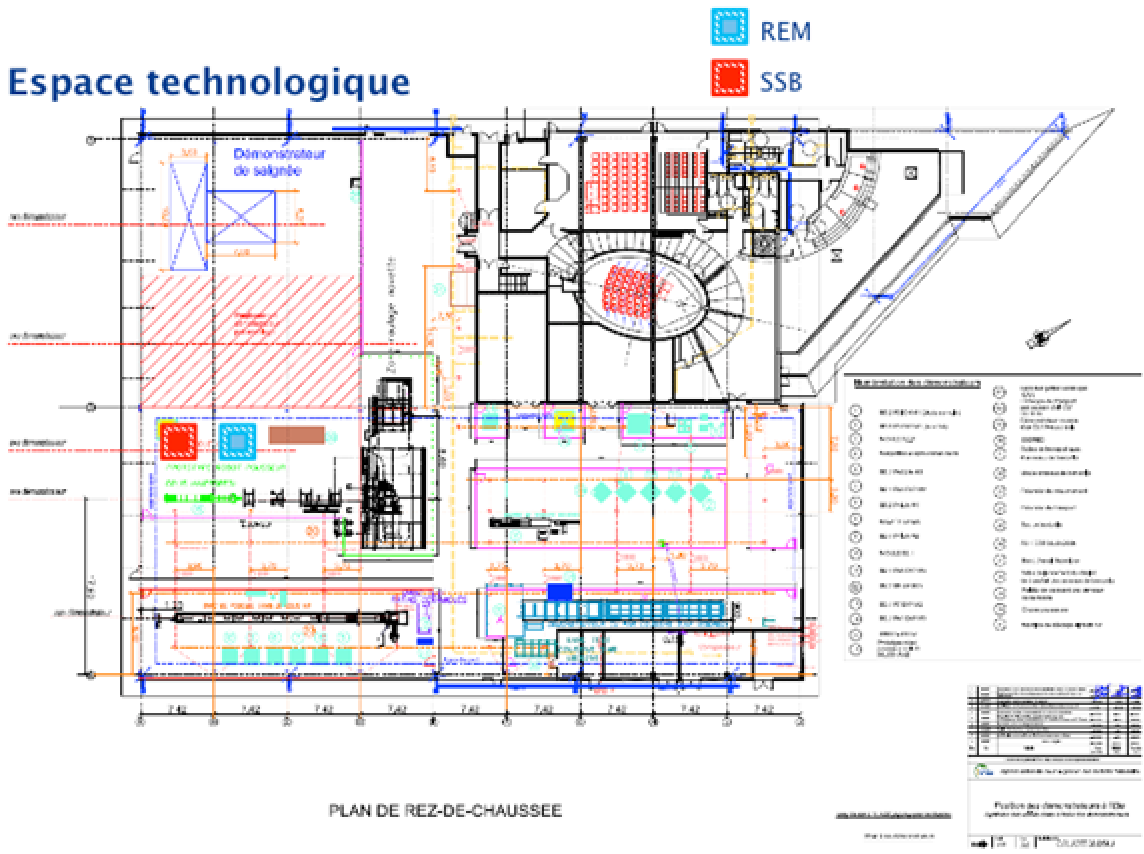


Figure 4-3 Diagram showing the location of the REM model in the ETe (blue square)

The vessel is fitted with four factory-assembled metal legs and rests on the test room's concrete slab floor. However, in order to electrically insulate the floor, four special heavy-machinery rubber plates provided by LECBA were placed under the four legs.

The bare vessel has a footprint of approximately 1.2 m^2. In addition, there is an equipment manoeuvring and test assembly zone, shown in blue in Figure 4-3.
It will be possible to move the vessel after closing the top lid using lifting rings provided for this purpose (plan 1000-1/5).

The total vessel mass once the bentonite has been saturated can be broken down as follows:

- Vessel mass: 4 700 kg;
- Mass of bentonite at apparent density of 1.56 g/cm^3: 1 225 kg;
- Mass of bentonite at apparent density of 1.62 g/cm^3: 1 272 kg;
- Water mass to reach saturation: 350 kg.

The total mass of the vessel and its saturated bentonite core is estimated at between 6 274 kg and 6 322 kg depending on the density of the bentonite used.

4.1.3 Vessel delivery

The vessel was unloaded without incident. It was transported to its final location using a bridge crane controlled by an Andra CMHM/MEI operator.

The following table presents all operations in chronological order.

 Arrival of the lorry in the technological area	 Unloading of package no. 2
 Transport of package no. 2	

Transport of package no. 1

Installation of the vessel in its definitive location

4.2 Supply of bentonite

The bentonite core has a filling volume of 785 litres, which represents approximately 1 300 kg of material, comprising 900 kg of pellets and 400 kg of crushed bentonite (powder). These materials were taken from the FSS test manufactured stock.

The material was delivered to the technological area by LAVIOSA MPC (member of the FSS Consortium of companies). The pellets and crushed bentonite were contained in 25 kg leak tight buckets (60 buckets) and unloaded by CEA/LECBA. The buckets were stored along the back siding before use.

4.3 Vessel filling and instrument installation

The test was installed by filling the vessel during the third week of September 2014, which was finished late morning on 25 September 2014 when the final sensor was connected to the SAGD measurement system.

Following final communication tests with the data acquisition unit, the test started at 3:05PM when the water supply pump was started and the injection and air outlet circuit valves were opened.

All operations were carried out by LECBA (CEA) under Andra supervision.

4.3.1 Preparation

The vessel was delivered in a very clean state. A provisional plywood lid protected the inside from any risk of dust entering. The sintered stainless steel disc on the bottom lid was protected by a plastic foam sheet.

The inside and outside were nevertheless carefully cleaned using a degreaser to eliminate any residual organic products as far as possible. Special attention was paid to the holes for sensors and their internal threads (Figure 4-4).

Figure 4-4 Careful cleaning of the vessel by CEA before sensor installation

Once cleaning had been finished, height markings were created inside the vessel to give visual guides for bentonite filling.

Cardinal markings outside the vessel helped place the vessel inside the technological area to facilitate the installation and numbering of sensors. North is towards the building entrance and West towards the SET model.

4.3.2 Installation of the radial sensors

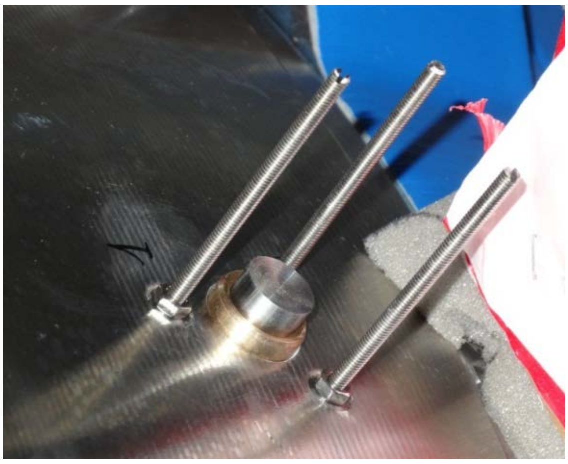
The radial sensors were installed in 100 mm tiers, alternating with the pellet and crushed bentonite filling, except for the radial load cells which were all installed before bentonite filling.

4.3.2.1 Installation of load cells

The load cell and piston assemblies were installed as follows:

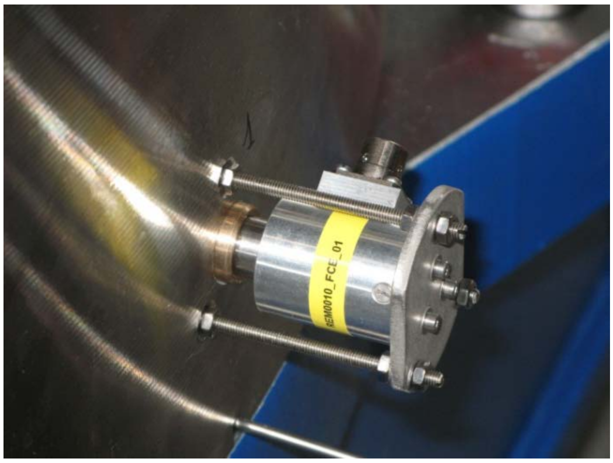
- Inspection of the hole and presentation of the piston with its O-rings and thrust piece, Figure 4-5a, lubrication;
- Installation of the piston, Figure 4-5b;
- Three threaded rods screwed in place and locked against the vessel, Figure 4-5b;
- Flange and sensor assembly fitted on the threaded rods, sensor aligned on the thrust piece, Figure 4-5c;
- Retaining flange and locknut screwed on, Figure 4-5d.

(a)



(b)

(c)



(d)

Figure 4-5 *Installation of radial load cells 4a: load cell + flange and piston assembly; 4b: piston and threaded rods installed; 4c: load cell positioned; 4d: sensor installed*

Figure 4-6 shows the installation of radial load cells before progressive vessel filling with the bentonite admixture.

Figure 4-6 Installation of radial load cells

Figure 4-7 shows the piston surfaces that in contact with the bentonite inside the vessel. In the picture, the bronze pistons are clearly visible in contrast to the stainless steel wall.

Note1: the piston and load cell assemblies directly measure the radial swelling pressure in bars.

Note 2: the height is marked here in cm.

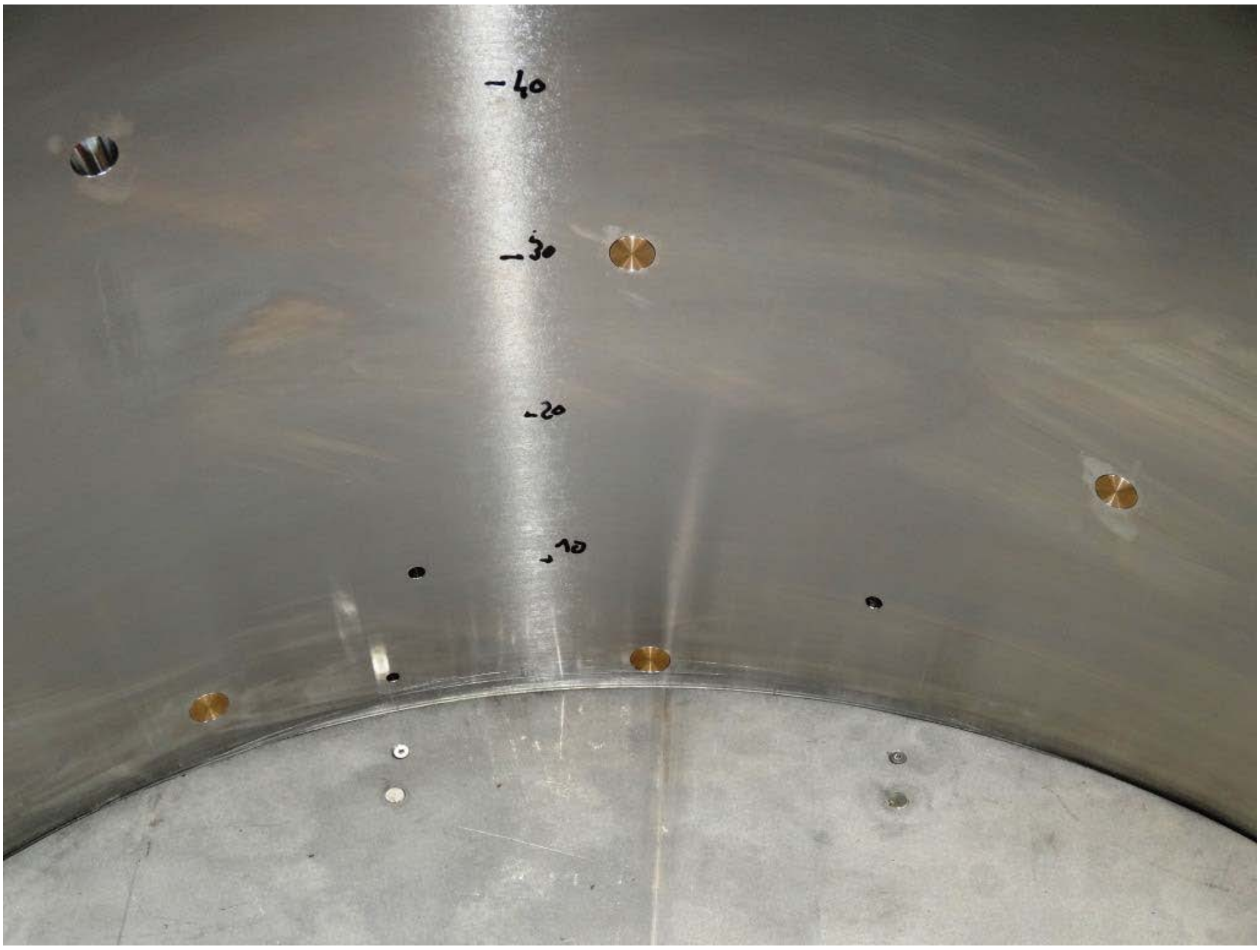


Figure 4-7 Ends of the radial load cell pistons

The location of the load cells on the vessel was designed according to two opposing 180° spirals and the vessel is split into four sectors: odd numbers start in the northern sector and even numbers start in the southern sector (Table 4-1 and Figure 4-8).

The height is given with respect to the hydration plane (top surface of the inside sintered disc).

Table 4-1 Position of radial load cells on the vessel

Height (mm)	Load cell	Sector
20	REM0010_FCE_01	NORTH
	REM0010_FCE_02	SOUTH
40	REM0010_FCE_03	NORTH
	REM0010_FCE_04	SOUTH
60	REM0010_FCE_05	WEST
	REM0010_FCE_06	EAST
80	REM0010_FCE_07	WEST
	REM0010_FCE_08	EAST
100	REM0010_FCE_09	WEST
	REM0010_FCE_10	EAST
150	REM0010_FCE_11	WEST
	REM0010_FCE_12	EAST
200	REM0010_FCE_13	SOUTH
	REM0010_FCE_14	NORTH
300	REM0010_FCE_15	SOUTH
	REM0010_FCE_16	NORTH
400	REM0010_FCE_17	SOUTH
	REM0010_FCE_18	NORTH
500	REM0010_FCE_19	EAST
	REM0010_FCE_20	WEST
600	REM0010_FCE_21	EAST
	REM0010_FCE_22	WEST
700	REM0010_FCE_23	EAST
	REM0010_FCE_24	WEST
800	REM0010_FCE_25	EAST
	REM0010_FCE_26	WEST
900	REM0010_FCE_27	NORTH
	REM0010_FCE_28	SOUTH
980	REM0010_FCE_29	NORTH
	REM0010_FCE_30	SOUTH

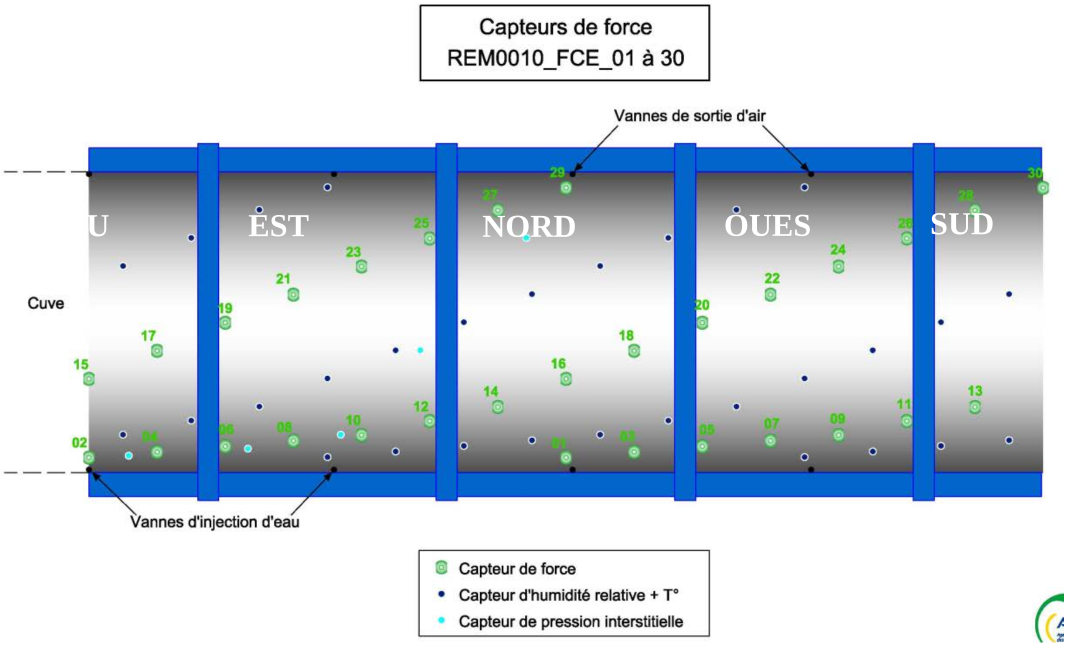


Figure 4-8 Diagram showing the position of radial load cells on the vessel

4.3.2.2 Installation of humidity / temperature and pore pressure sensors

The combined Relative Humidity / Temperature (HUM & TEM) sensors and pore pressure (PRE) sensors were installed very easily without incident, since all these sensors had already been mounted into their extension tube in the laboratory (see Section 3.3).

The tubes were therefore directly screwed onto the vessel walls with a bit of sealing compound on the thread Figure 4-9.

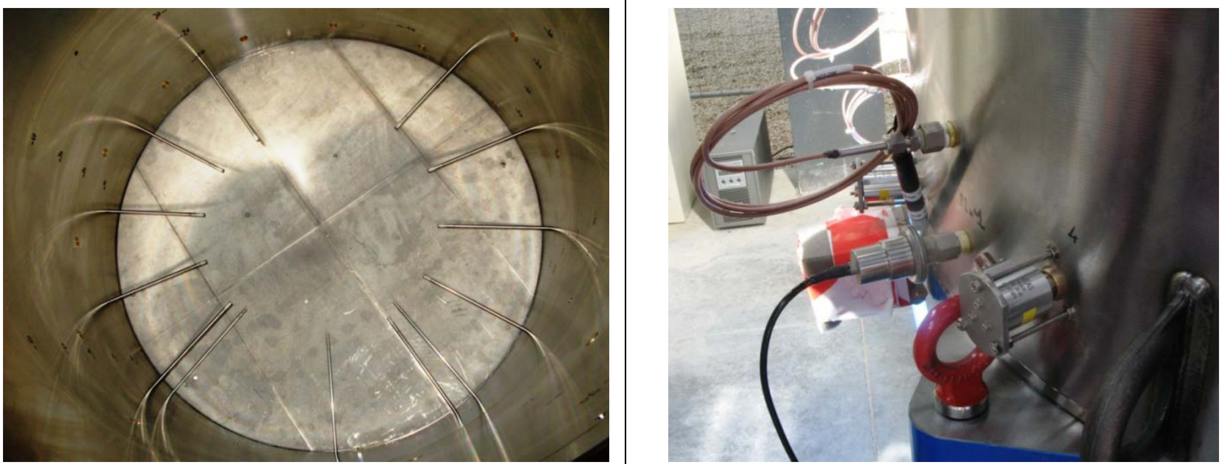
At first, only the first 13 sensors were installed between the height of 20 mm and 100 mm. Each sensor was checked after installation. The other sensors were installed gradually as the pellet and crushed bentonite layers were filled.

Figure 4-10 shows the inside of the vessel with the first 10 humidity sensors and the three types of sensors installed.

The positions of these sensors in the vessel are given in Table 4-2 and Table 4-3, and shown in diagrams in Figure 4-11 and Figure 4-12.

(a) (b)

Figure 4-9 *Humidity and temperature sensor: (a) inside and (b) outside view*



(b)

(a)

Figure 4-10 *(a) Vessel interior with the first 10 HUM/TEM and PRE sensors installed (b) View of the vessel exterior, illustrated the three types of sensors installed*

Table 4-2 Position of humidity and temperature sensors on the vessel

Height (mm)	Sensor		Sector
20	REM0020_HUM_01	REM0020_TEM_01	WEST
	REM0020_HUM_02	REM0020_TEM_02	EAST
40	REM0020_HUM_03	REM0020_TEM_03	WEST
	REM0020_HUM_04	REM0020_TEM_04	EAST
60	REM0020_HUM_05	REM0020_TEM_05	SOUTH
	REM0020_HUM_06	REM0020_TEM_06	NORTH
80	REM0020_HUM_07	REM0020_TEM_07	SOUTH
	REM0020_HUM_08	REM0020_TEM_08	NORTH
100	REM0020_HUM_09	REM0020_TEM_09	SOUTH
	REM0020_HUM_10	REM0020_TEM_10	NORTH
150	REM0020_HUM_11	REM0020_TEM_11	SOUTH
	REM0020_HUM_12	REM0020_TEM_12	NORTH
200	REM0020_HUM_13	REM0020_TEM_13	EAST
	REM0020_HUM_14	REM0020_TEM_14	WEST
300	REM0020_HUM_15	REM0020_TEM_15	EAST
	REM0020_HUM_16	REM0020_TEM_16	WEST
400	REM0020_HUM_17	REM0020_TEM_17	EAST
	REM0020_HUM_18	REM0020_TEM_18	WEST
500	REM0020_HUM_19	REM0020_TEM_19	NORTH
	REM0020_HUM_20	REM0020_TEM_20	SOUTH
600	REM0020_HUM_21	REM0020_TEM_21	NORTH
	REM0020_HUM_22	REM0020_TEM_22	SOUTH
700	REM0020_HUM_23	REM0020_TEM_23	NORTH
	REM0020_HUM_24	REM0020_TEM_24	SOUTH
800	REM0020_HUM_25	REM0020_TEM_25	NORTH
	REM0020_HUM_26	REM0020_TEM_26	SOUTH
900	REM0020_HUM_27	REM0020_TEM_27	WEST
	REM0020_HUM_28	REM0020_TEM_28	EAST
980	REM0020_HUM_29	REM0020_TEM_29	WEST
	REM0020_HUM_30	REM0020_TEM_30	EAST

Table 4-3 Position of pore pressure sensors on the vessel

Height (mm)	**Sensor**	**Sector**
25	REM0030_PRE_01	SOUTH
50	REM0030_PRE_02	EAST
100	REM0030_PRE_03	EAST
400	REM0030_PRE_04	EAST
800	REM0030_PRE_05	NORTH

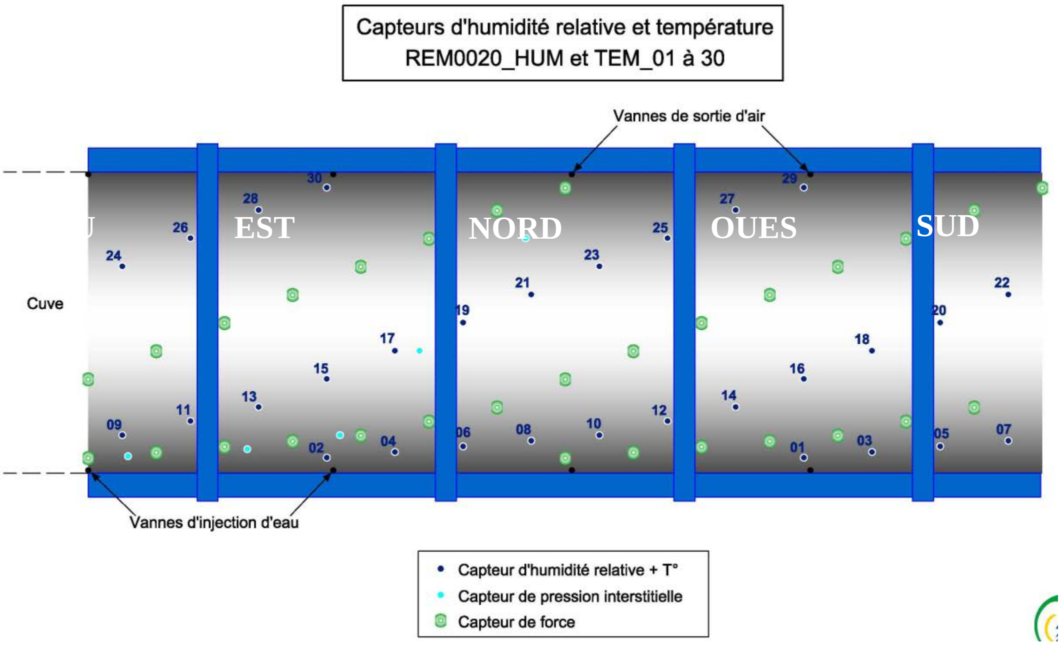


Figure 4-11 Diagram showing the position of humidity and temperature sensors on the vessel

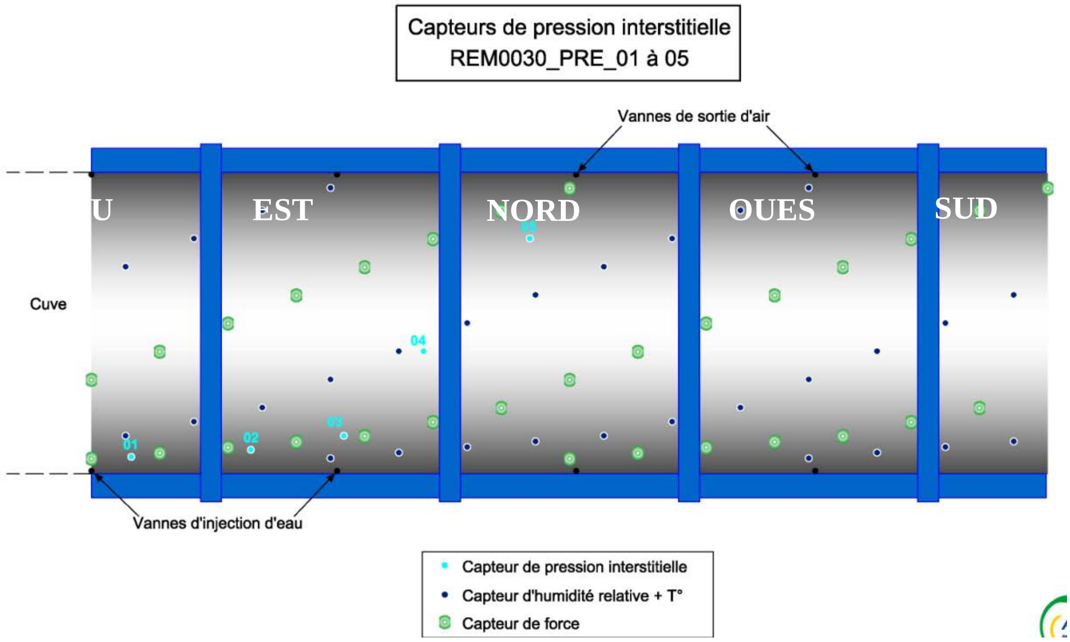
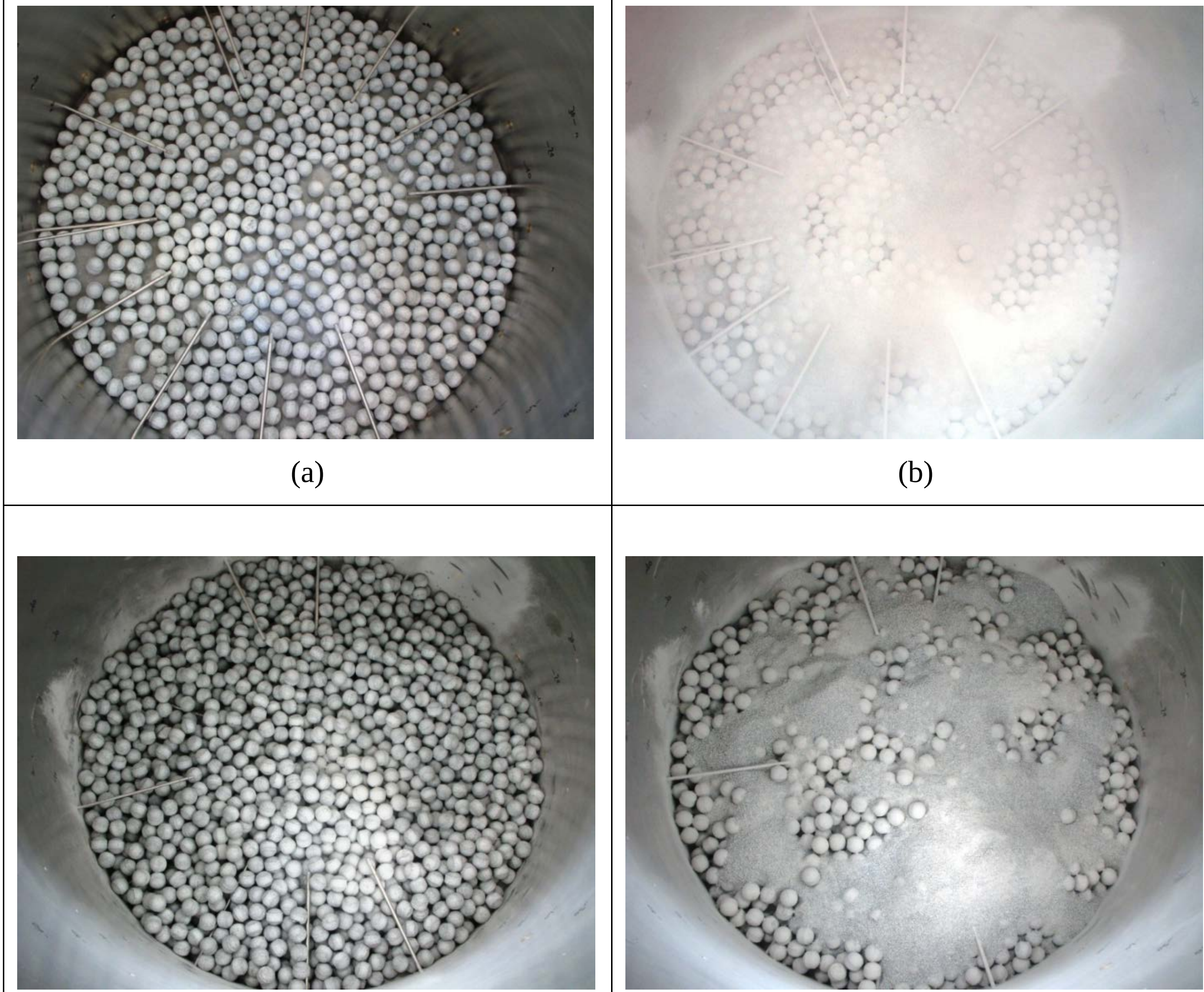


Figure 4-12 Diagram showing the position of pore pressure sensors on the vessel

4.3.2.3 Bentonite emplacement

After installing the first layer of sensors (13 sensors at a 100 mm height), the bentonitic materials were poured out of buckets weighing around 20 kg, until reaching this 100 mm height, alternating between pellets and crushed bentonite (powder) in the mass proportions of 70% / 30% (Figure 4-13). The end goal was to achieve final dry density of 1.50 g/cm^3 while guaranteeing uniform filling throughout the volume of the vessel. This method meant that the emplaced density in each layer could be easily assessed in order to make adjustments with the following layer, if required.



(a) (b) (c) (d)

Figure 4-13 Installation of the first 100 mm of the pellet / crushed pellet mixture: a) 1st layer of pellets; b) 1st layer of crushed pellets added; c) third layer of pellets ; d) third layer of crushed pellets added

Some voids are required locally to avoid exceeding this target density. The difficulty lies in: i) the fact that these zones represent a small volume of a few dozen cm^3 maximum, ii) distributing these areas in a uniform way across the diameter and height as filling continues.

This was the only possible way to fill the vessel in order to achieve the target emplacement density. The many handling tests carried out under the FSS project [2] showed that if the admixture is prepared in advance, crushed bentonite segregation means that the density obtained is regularly around 1.35 g/cm^3.

The pellets used come from Octabin no. 1198 and the crushed bentonite from big bag no. C65, taken from the stocks manufactured for FSS by LAVIOSA MPC.

This operation was repeated by 100 mm layers, alternating with the installation of humidity sensors (HUM/TEM) and pore pressure sensors (PRE). Each bucket of material was precisely weighed (Figure 4-14). The masses introduced and corresponding heights are given in Table 4-4.

(a) Bucket weighing operations

(b) crushed bentonite being poured

(c) intermediate layer of pellets/crushed bentonite

(d) full vessel before lid is fitted

(e) vessel before lid is fitted

Figure 4-14 Bentonite and HUM/TEM sensor installation operations

Table 4-4 Filling characteristics for the REM vessel

Vessel cross-section (cm^2)	7854		Pellets	OCT1198	
Vessel height (cm)	100		Crushed bentonite	BB C65	
Target apparent density	1.568		Mean W (%)	5.0	

Fill no.	Layer no.	Height (cm)	Volume (cm^3)	Pellet mass	Crushed bentonite mass (kg)	Total mass (kg)	Pellet bucket no.	Crushed bentonite bucket no.
1	1	3.2	25133	27.6	11.8	39.4	36-6	4
	2	3.2	25133	27.6	23.6	74.8	11 6	12
	3	3.2	25133	27.6			18 6	12
2		9.8	76969	86.2	35.4	121.6	38 31 14	19-4
3		9.8	76969	86.2	35.4	121.6	8 27 40 6	15-17
4		9.8	76969	86.2	35.4	121.6	25 19 28 13	5-17
5		9.8	76969	86.2	35.4	121.6	23 21 9 28	3-5
6		9.8	76969	86.2	35.4	121.6	3 32 22 34	1-14
7		9.8	76969	86.2	35.4	121.6	2 26 39 34	16-14
8		29.1	228551	86.2	36.9	123.1	20-30-4-12-7-529-16-15-17-37	2-20-10-11
9				86.2	36.9	123.1		
10				94	57	151		
	Empty	2.5	19635	-	-	-	-	-
Total			**785400**	866.4	378.6	**1245**		
				% pellets	**% crushed bentonite**			
		ρ	1.585	69.6	30.4			
		ρ_d	1.510					

Note: reducing the fill density while maintaining good layer uniformity was a delicate operation. The final 30 cm were filled simultaneously to reach the maximum height permitted in the vessel, and to avoid exceeding it. This led to a residual summital void of 2.5 cm between the bentonite upper surface and the surface of the top sintered disc.

At the end, the overall dry emplacement density in the vessel turned out to be at 1.51 g/cm^3, which is slightly above the target density (1.50g/cm^3) or that effectively obtained at end in FSS (1.48 g/cm^3).

4.4 Vessel closure

4.4.1 Installation of the lid and top frame

The vessel was closed in accordance with the procedure planned during vessel design. The various parts required for closure were pre-positioned on a pallet in order of installation to avoid having to turn them over (Section 20):

- Top stainless steel lid and screwed sintered disc;
- Top bearing plate;
- Top retaining frame.

After cleaning and greasing the 2 O-rings on the top lid, these 3 parts were installed without incident, as illustrated in Figure 3-10. The weight of the top frame was sufficient to push down the lid, and the O-rings prevented it from falling fully.

Figure 4-15 Installation of the three vessel closure parts

4.4.2 Installation of force washers and locknuts

Force washers REM0050_FCE_01 to 04 were first positioned on the four tie rods, between two 10 mm thick 17-4PH steel washers (Figure 4-16). After this, the nuts were screwed in, initially by hand, until they locked. Each washer was then connected to a 10 Volt calibrator and tightened using the special key, controlling the output voltage until each sensor showed the same stress reading.

They were tightened for a second time just before the start of the test on 25/09/2014, after being connected to the data acquisition unit.

The measurements are given in Table 4-5.

Figure 4-16 Installation of force washers

Table 4-5 Results of measurements carried out with the force washers during preload distribution tests on the vessel lid

Measurements taken during assembly on 19/09/2014

					Preload			
					V	mV/V	kN	Bar
Name	**Serial no.**	**Position**	**Date of installation**	**Time**	**Power supply**	**Signal**	**Force**	**Pressure**
REM0050_FCE_01	S13102	N	18/09/2014	11:45	10	0.01786	15.666	0.199
REM0050_FCE_02	S13103	W	18/09/2014	11:45	10	0.01935	15.683	0.200
REM0050_FCE_03	S13104	S	18/09/2014	11:45	10	0.01835	15.483	0.197
REM0050_FCE_04	S13105	E	18/09/2014	11:45	10	0.02425	15.656	0.199

Measurements taken during assembly on 25/09/2014

					mV/V		
Name	**Serial no.**	**Position**	**Date of installation**	**Time**	**Signal**	**kN**	**Bar**
REM0050_FCE_01	S13102	N	18/09/2014	11:45	0.01786	Force	Pressure
REM0050_FCE_02	S13103	W	18/09/2014	11:45	0.01935	15.666	0.199
REM0050_FCE_03	S13104	S	18/09/2014	11:45	0.01835	15.683	0.200
REM0050_FCE_04	S13105	E	18/09/2014	11:45	0.02425	15.483	0.197

Note that the frame was slightly out-of-flatness.

4.4.3 Installation of axial load cells

Four axial pressure sensors, REM0040_FCE_01 to 04, were installed in the lid without incident. The pistons' O-rings were greased before being installed in the upper sandwich: lid + bearing plate. Assembly was carried out in the same way as for radial sensors: three threaded rods screwed in, load cells positioned on the piston's thrust piece, locknut screwed in (Figure 4-17).

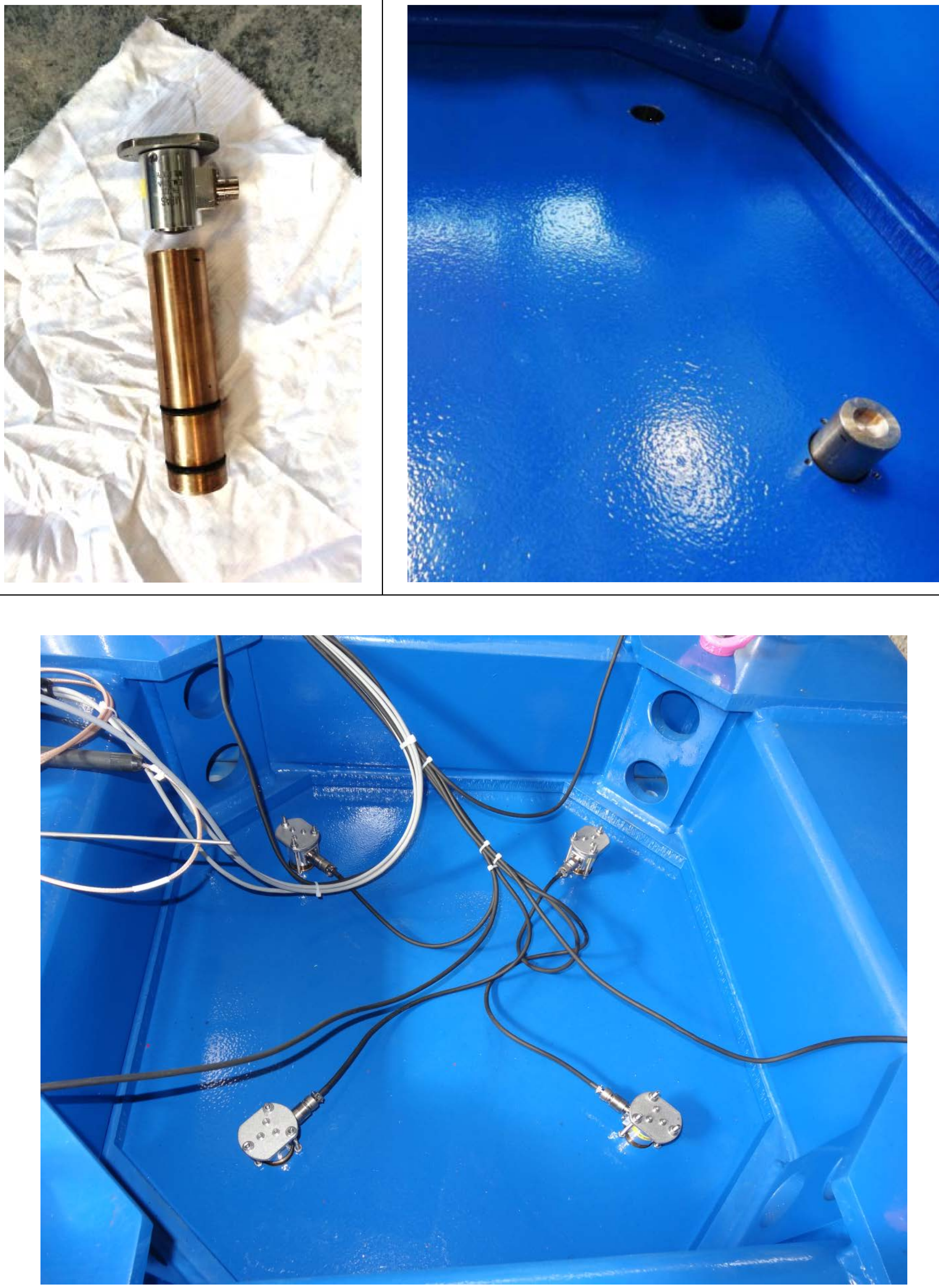


Figure 4-17 Installation of axial load cells

The sensor signal measurements were taken after installation and are given in Table 4-6.

Table 4-6 Results of measurements for axial load cells after installation

Name	Serial no.	Position	Date of installation	Time	Signal (mV)
REM0040_FCE_01	S130NU	N	18/09/2014	14:25	-0.0082
REM0040_FCE_01	S130NQ	W	18/09/2014	14:35	-0.0234
REM0040_FCE_01	S130PH	S	19/09/2014	14:20	-0.0001
REM0040_FCE_01	S130PM	E	19/09/2014	11:10	-0.0140

4.5 Installation of other components

Installation of equipment in the vessel continued with the installation of some final components:

- Installation of signal conditioning units for the relative humidity and temperature sensors (Figure 4-18);
- Installation of 1/8” ball valves on the water supply and air outlet circuits;
- Connection of the four supply circuits and four outlet circuits;
- Installation of humidity and temperature sensor REM0060_HUM/TEM_01 on the outlet circuit;
- Connection of flowmeter REM0080_DAI_01 to the outlet circuit.

It should be noted that humidity and temperature sensor SET0090_HUM/TEM_01 was added to the top frame to measure ambient humidity and temperature.

Figure 4-19 shows the position of axial load cells and force washers on the lid.

Figure 4-18 Humidity and temperature sensor (REM0060_HUM/TEM_01) and flowmeter (REM0080_DAL_01) in-line on the outlet circuit

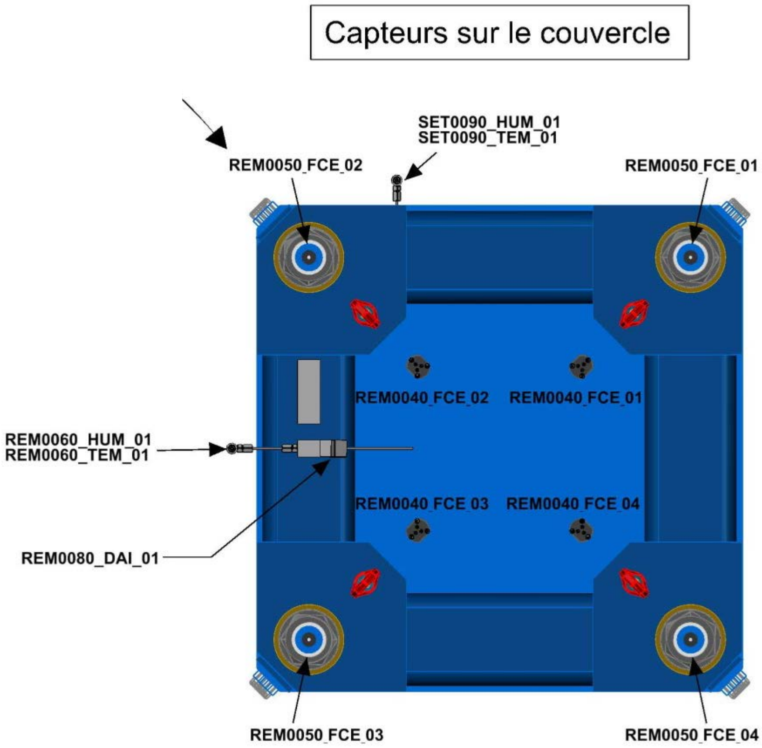


Figure 4-19 Position and nomenclature of sensors on the top lid

4.6 Installation of the water supply system

The water supply system comprises a pump and supply tank placed on top of scales (Figure 4-20). The mass of water injected in the vessel is recorded over time.

At first, the pump flowrate is set to 2.083 cm^3 per hour (50 cm^3 per day). A pressure relief valve set to 2 bars is placed on a branch line of the pump's discharge circuit to return some of the supply water to the tank if the flowrate absorbed by the bentonite core falls below 50 cm^3 per day.

This assembly is linked to the vessel’s southern valve by a PTFE tube. Later, the pump can be easily shunted to connect the vessel directly to the tank. To prevent loss of prime, the scales can be elevated to position the tank above the vessel.

The water used for bentonite core imbibition is taken from on-site borehole FTP 1101 (Section 3.2).

Figure 4-20 Picture of the vessel's on-site water supply system

After installing the 30 signal conditioning units for the humidity and temperature sensors in the vessel, the 71 sensors were connected to the SAGD case placed just behind the vessel on the west side. This represents approximately one hundred cables that required stranding and connection. All sensors and communication to the SAGD were then tested via the data acquisition unit. Figure 4-21 illustrates these operations. Figure 4-22 presents the vessel following installation.

Figure 4-21 End of REM model installation with sensor cable connection and operational tests

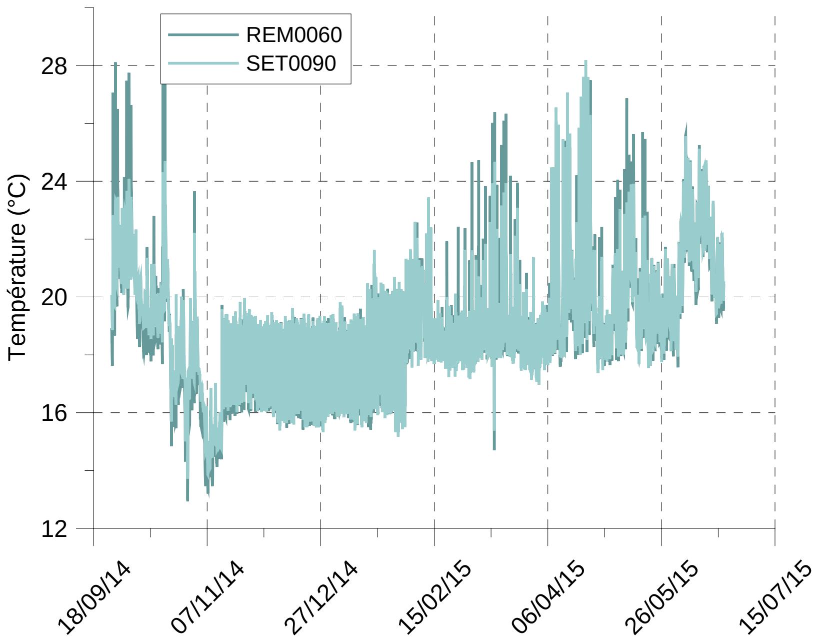
Figure 4-22 REM cell following complete installation

5. Presentation of initial measurements

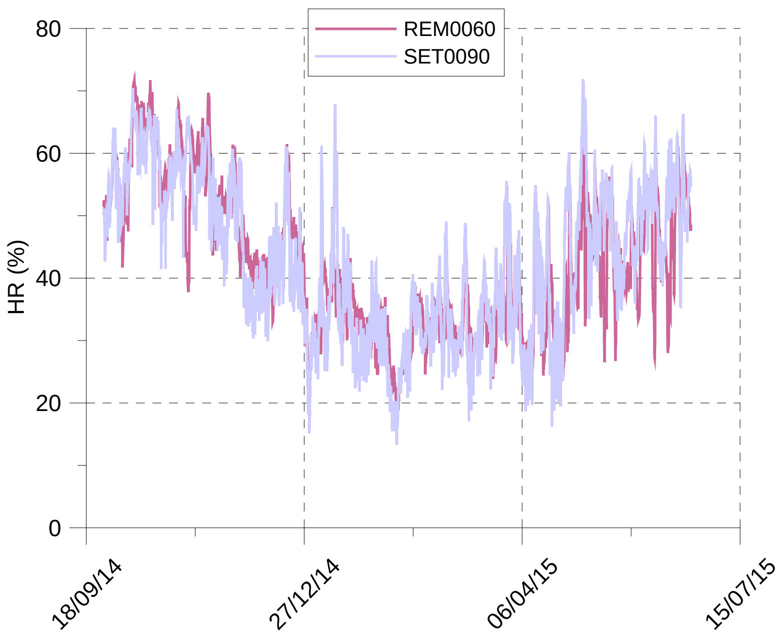
5.1 Climate conditions in the technological area

Two humidity/temperature sensors were installed outside the vessel to measure the climate conditions around the experiment. These measurements are given in Figure 5-1, from the start of hydration.

Overall, variations are fairly insignificant and can be easily attributed natural seasonal variations.



(a)



(b)

Figure 5-1 Temperature (a) and relative humidity (b) recorded in the technological area

5.2 Hydration water monitoring checks

Hydration was launched on 25/09/2015. As previously mentioned, the vessel is currently hydrated at a constant flowrate of 50 ml per day using a pump connected to a 4 l water tank. The water tank is placed on scales to monitor injection (see Section 3.4).

The water from borehole FTP will be supplied on demand in line with experiment needs. To begin, a 30 l tank was provided from which a sample was taken and sent to the Hydro-isotope laboratory for analysis (see Table 8). In order to facilitate tank changeover on the scales, 4 l tanks were prepared and referenced in advance. Table 5-1 lists the samples and their date of use. The first 4 l tank was not referenced.

Table 5-1 Reference of the first water samples from borehole FTP injected into the REM experiment

Borehole	Andra reference	Quantity (ml)	Location	Date
FTP1101	EST04198F1	100	HYDRO-ISOTOPE	
FTP1101	EST04198F2	100	ANDRA SITE EAST	NA
FTP1101	EST04198F3	4000	REM	15/12/2014
FTP1101	EST04198F4	4000	REM	24/02/2015
FTP1101	EST04198F5	4000	REM	11/05/2015
FTP1101	EST04198F6	4000	REM	NA
FTP1101	EST04198F7	4000	REM	NA
FTP1101	EST04198F8	4000	REM	NA

5.3 Experiment operation

The entire experimental set-up was operational after the first eight months.

There were, however, two non-serious incidents following launch of hydration:

- On 30/09/2014 (5 days after the start of hydration), a leak was discovered on the water distribution baffle with oxidation marks showing the presence of humidity; it was immediately decided to stop hydration. On 01/10/2014, CEA injected Araldite glue into the four grooves on the stainless steel baffle. On 02/10/2014, hydration was restarted. No new leaks have since been detected.
- On 03/03/2015 (158 days after the start of hydration), an injection problem appeared, resulting in a change of gradient on the weight curve (see Figure 5-2), with 30 ml per day instead of the intended 50 ml per day.
    - ➢ The first operation that same day sought to evacuate any suspected air bubbles in the supply pipes upstream of the pump (between the tank and pump) or on the pump valves, but this attempt failed. During this operation, white deposits (probably salt the in water) in the pipes are clearly visible.
    - ➢ Following the second operation (05/03/2015) during which the pipes and pump were cleaned and purged again, injection was stopped as the pump was no longer working. The CEA corrective maintenance operation on 10/03/2015 was unable to restart the pump despite total disassembly. The pump was finally sent back to LECBA (CEA) with a suspected problem with the valve. The pump head was disassembled and all parts were

observed under the laboratory magnification system, in particular the O-rings, which were all correct. However, during analysis of the valve under the magnification system, it was seen to be composed of several elements that were strongly stuck together by the same white deposits, which had formed a very adhesive paste. The valve's connecting duct was blocked. After scraping, cleaning in an ultrasound tank for 30 minutes and reassembly, the pump worked again. Injection was restarted after the pump was reinstalled and the circuits purged on 12/03/2015, with no further incidents since then. Note that this incident occurred following the replacement of the first tank, which was replaced after the tank had been totally empty for around two or three days. It is believed that salt appeared due to the evaporation of the water remaining in the pipes. After this problem, an alarm has been installed on the SAGD to prevent the situation from happening again.

These two events had no notable consequences on measurements (see the following sections).

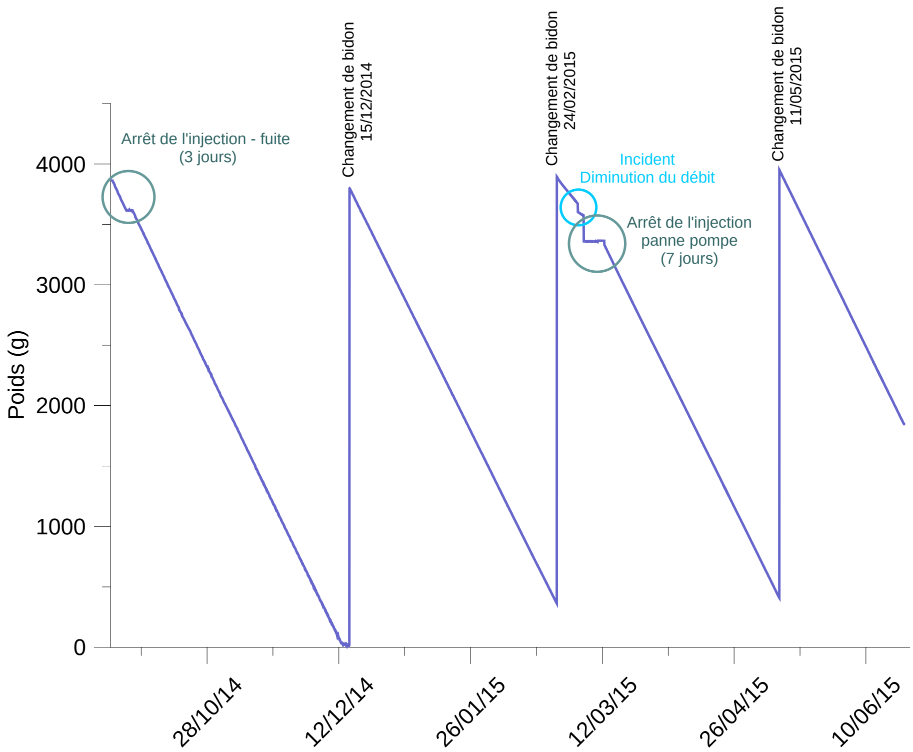


Figure 5-2 *Mass of water injected into the REM experiment*

5.4 Relative humidity and temperature in the vessel

30 humidity/temperature sensors were installed in the vessel as previously stated (see Section 4.3.2.2). Relative humidity measurements are presented in Figure 39 and Figure 40. These figures also show the period of pump failure which caused injection to be stopped. A diagram showing sensor location is given in Figure 5-3. To facilitate comprehension of the results, measurements are broken down by section (section 1: Figure 5-4; section 2: Figure 5-5) as shown on Figure 5-3.

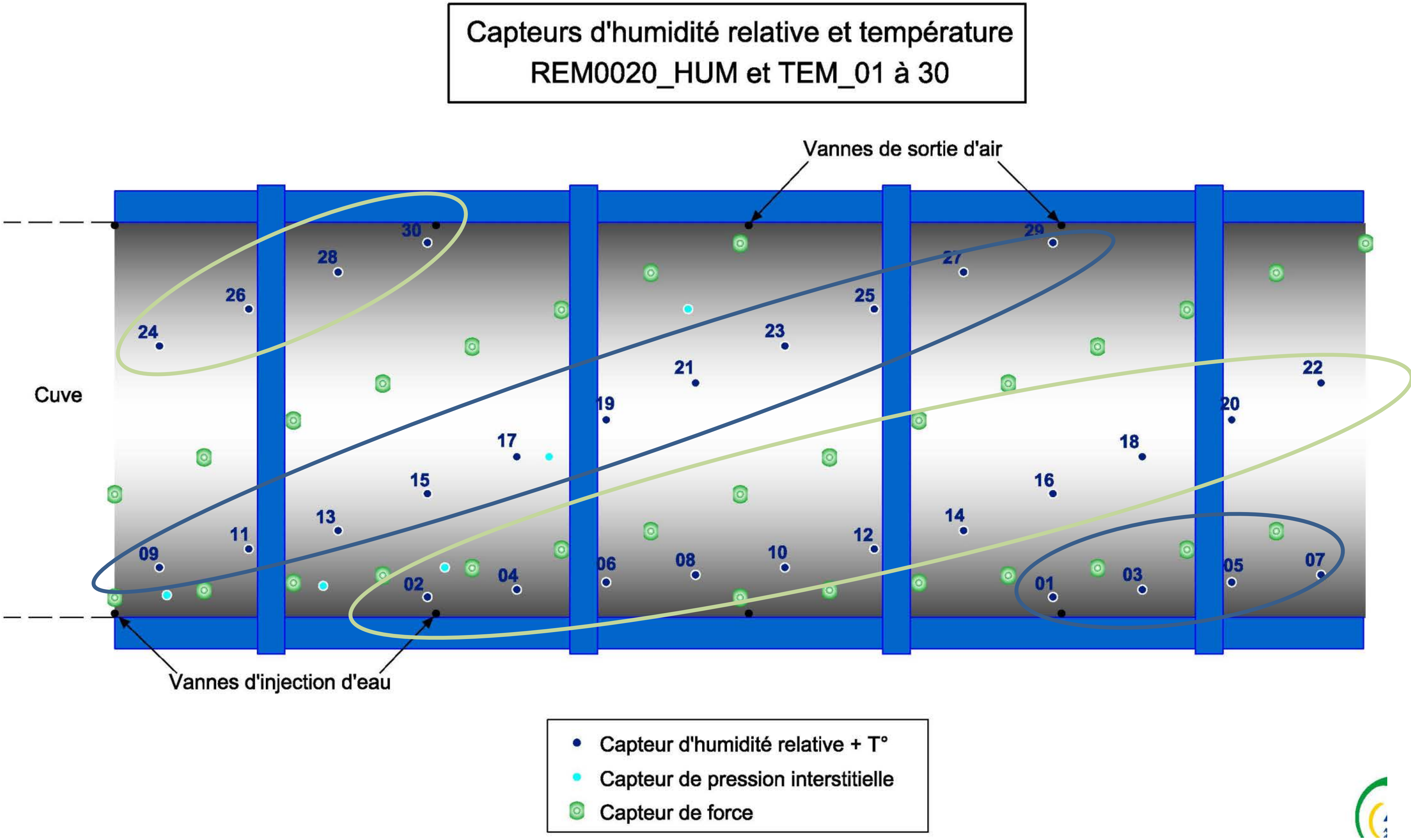


Figure 5-3 Position of humidity and temperature sensors on the REM vessel – Section 1 in blue – Section 2 in green

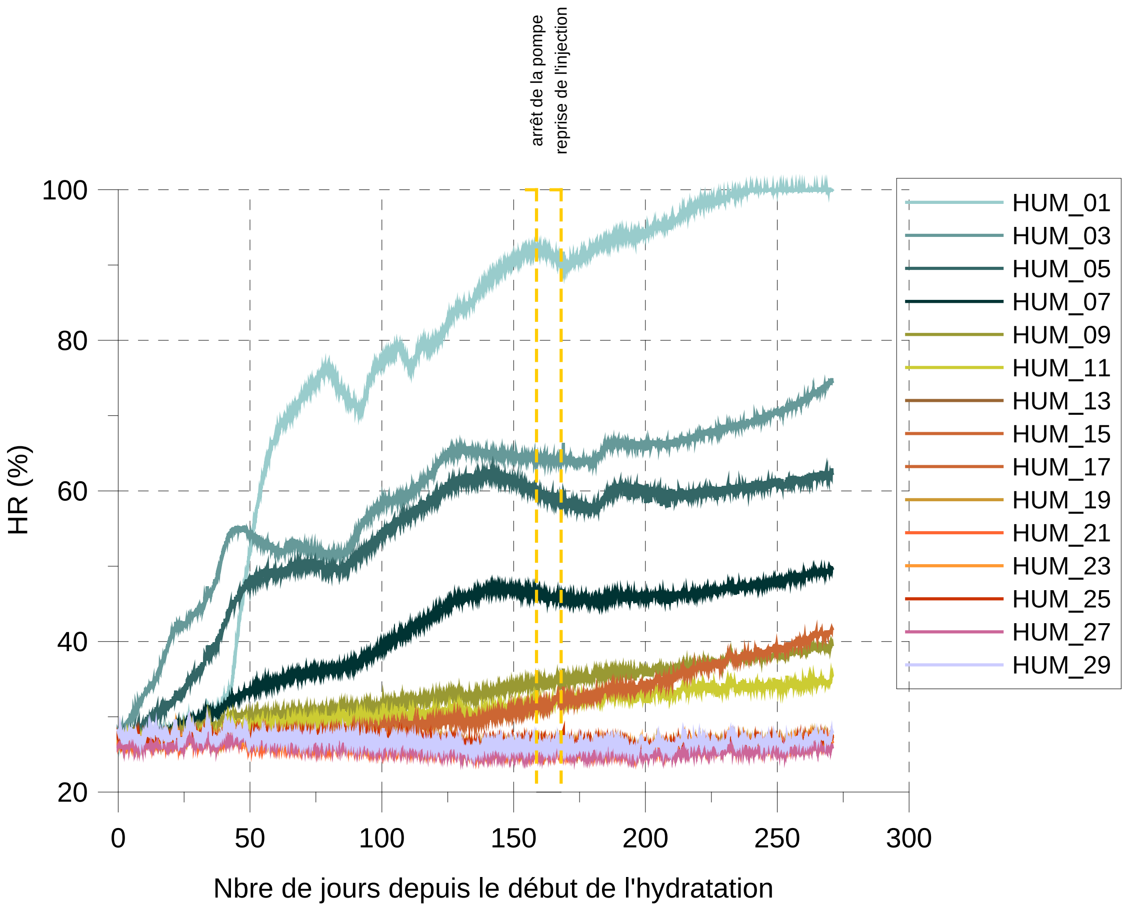


Figure 5-4 *Relative humidity measurements in the REM vessel-section1 (cf. Figure 5-3)*

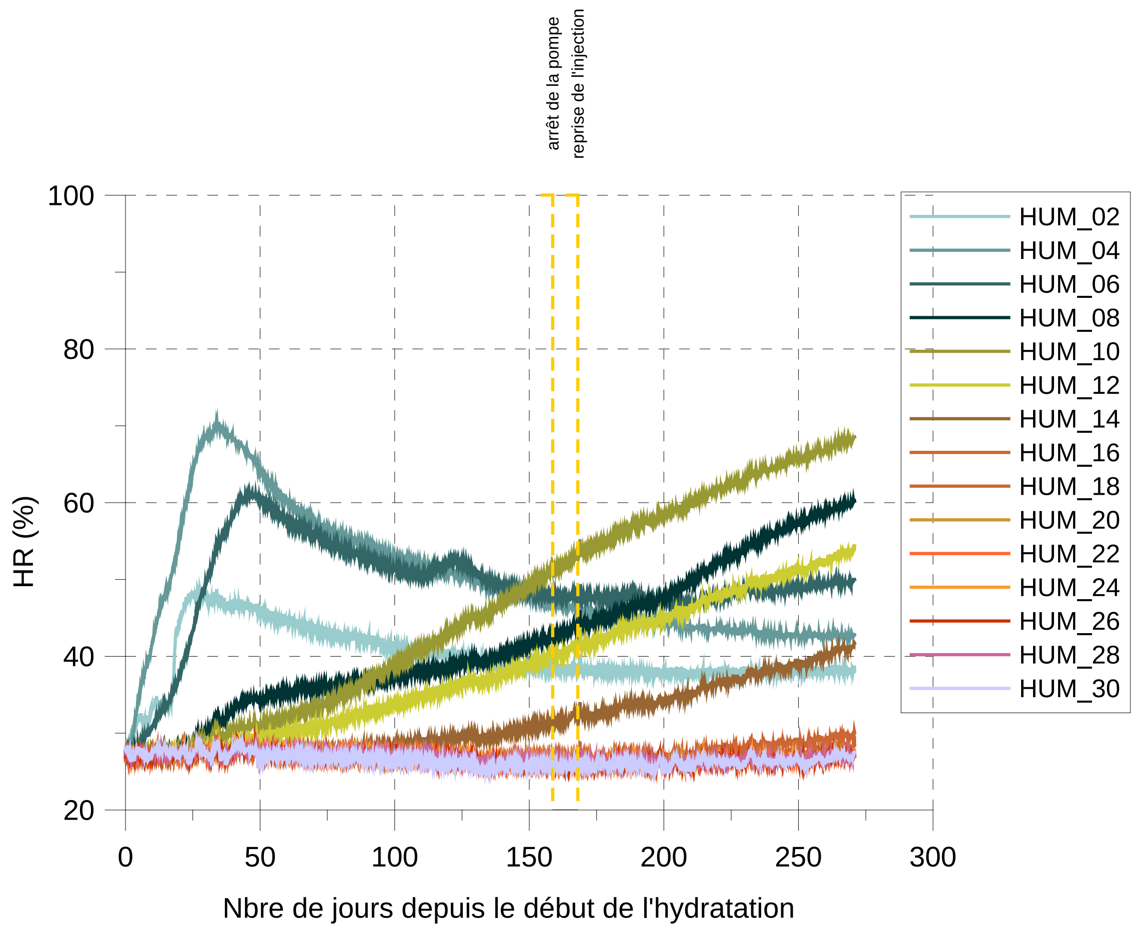


Figure 5-5 *Relative humidity measurements in the REM vessel-section2 (cf. Figure 5-3)*

On average, RH was at 27% at the start of hydration. The most reactive sensors were sensors 01/03/05/07 in section 1. Recently, sensor 01 has even reached 100%. This is due to their proximity to the injection system and they were also the only sensors to react to when injection was stopped following pump failure. Sensor 01 will be removed and its position resealed in order to avoid backflow and leaks along this sensor.

The other sensors that react, both in section 1 and section 2 are also located at bottom of the vessel and close to the point where water enters the sintered metal. *Above 300 mm, the sensors react very little or not at all.* Analysis of the curves shows that hydration in the vessel is not uniform. If the sensors located at the same depth are compared, not only is the hydration kinetics different, but also the amplitudes. To illustrate this observation, the values measured by sensors 01 and 02, 03 and 04 and 05 and 06 are shown in Figure 41. As indicated in Table 3, they are located around the vessel at 20 mm, 40 mm and 60 mm from the bottom of the vessel. Sensors 02, 04 and 06 show comparable kinetics, with a fairly significant increase during the first 40 days (up to 70% for sensor 04), followed by a drop of up to over 20% for the same sensor. The sensors in section 1 react differently; the initial phase is more gradual and then RH increases very rapidly up to values of over 60% for all three sensors. In light of these results, it is clear that the homogenisation process will probably be long, as suggested by the estimations (30 to 60 years to reach total saturation).

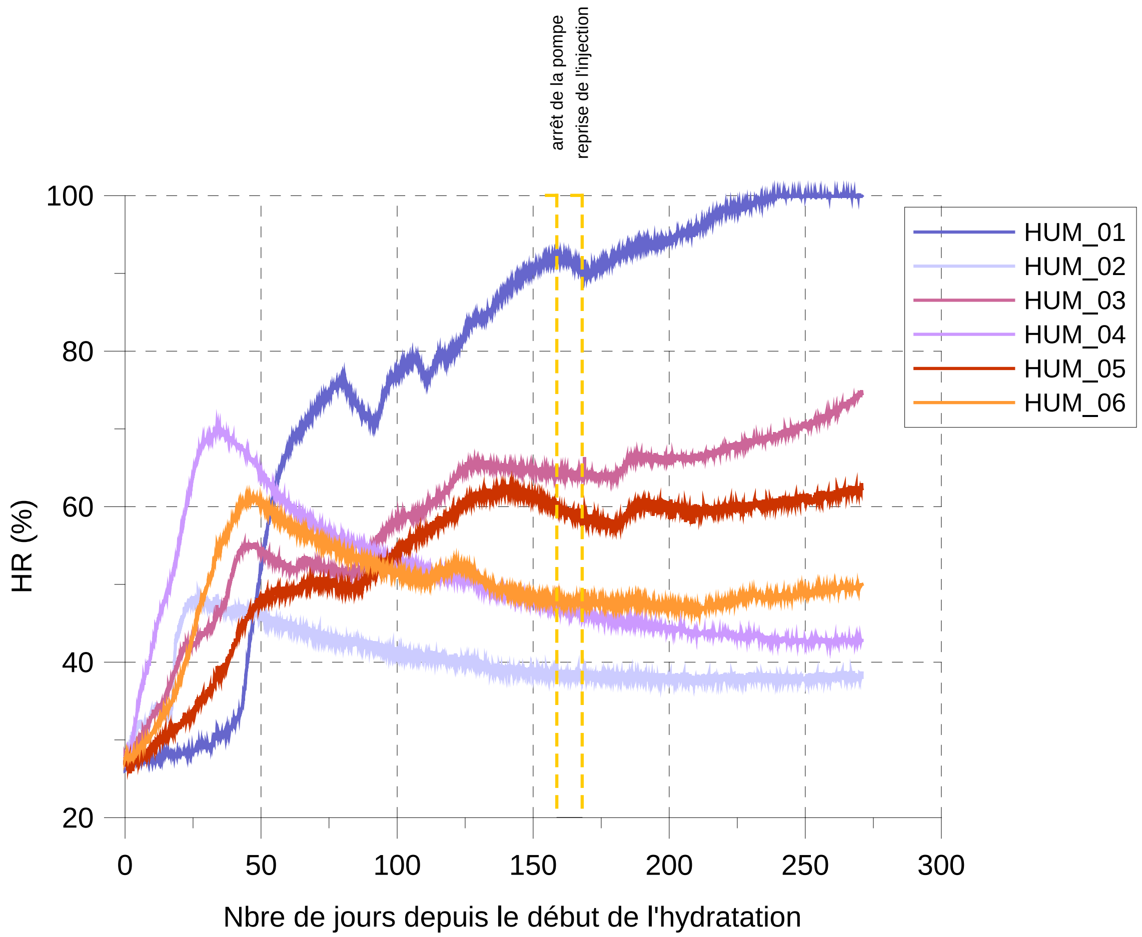


Figure 5-6 *Comparison of sensors located at the same height in the vessel (01 and 02; 03 and 04; 05 and 06)*

Temperature measurements are presented section-by-section in Figure 5-7 and Figure 5-8. The measurements generally follow the trends recorded outside of the vessel, but with less pronounced contrasts due to the protective nature of the bentonite.

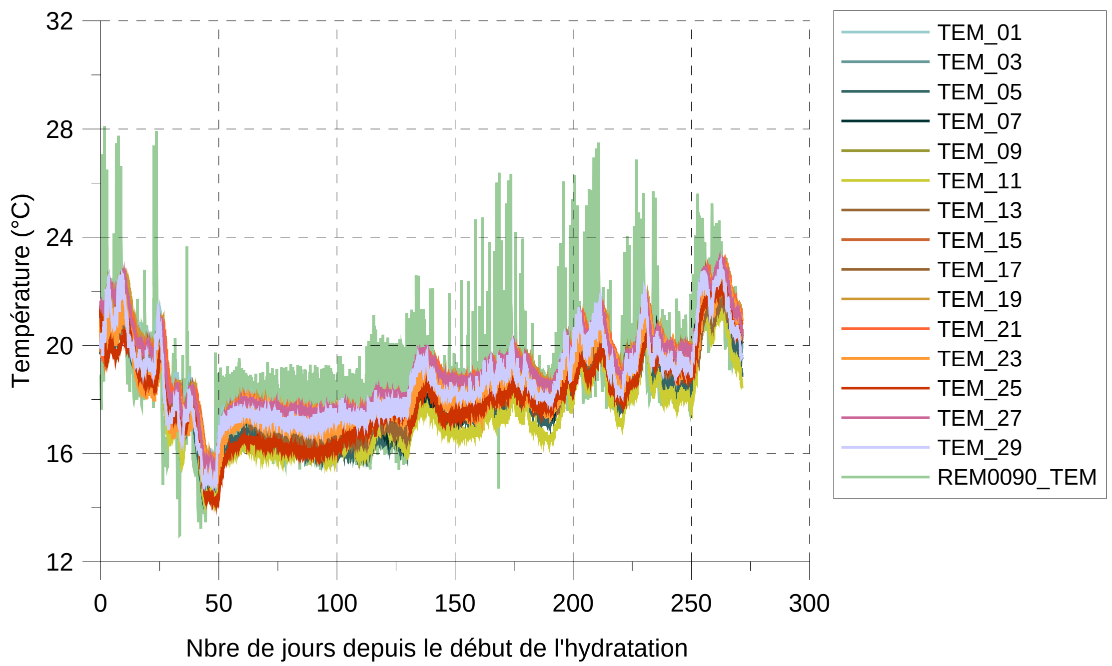


Figure 5-7 *Temperatures measured on section1 sensors & outside the vessel (green).*

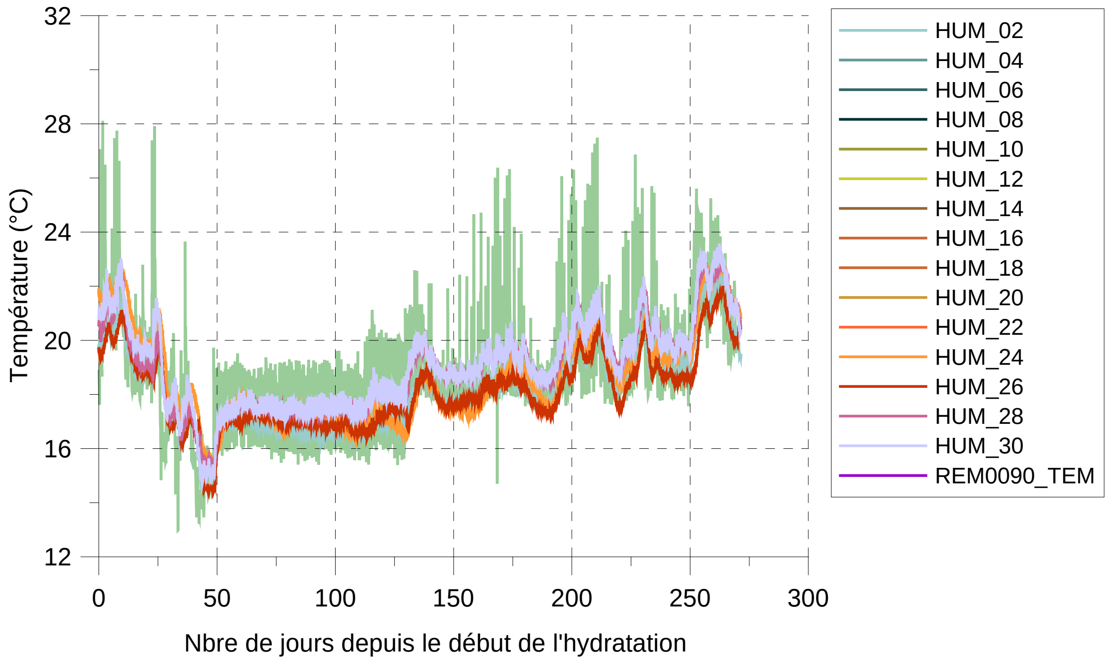


Figure 5-8 *Temperatures measured on section2 sensors & outside the vessel (green).*

In order to check the influence of these temperature variations, the relative humidity and temperatures measured on sensors 01 and 03 are shown on Figure 5-9 and Figure 5-10 respectively. The variations in relative humidity do not appear to be linked to temperature variations.

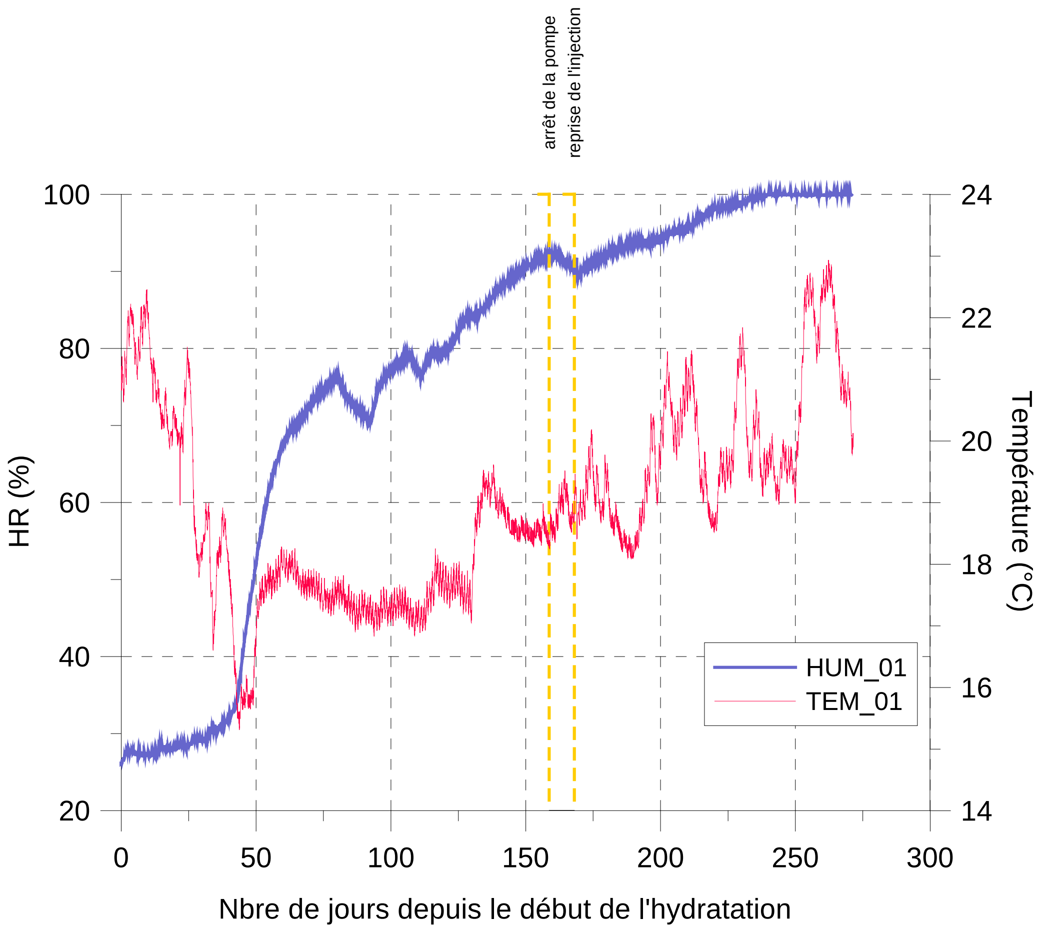


Figure 5-9 *Relative humidity and temperature measured on sensor 01.*

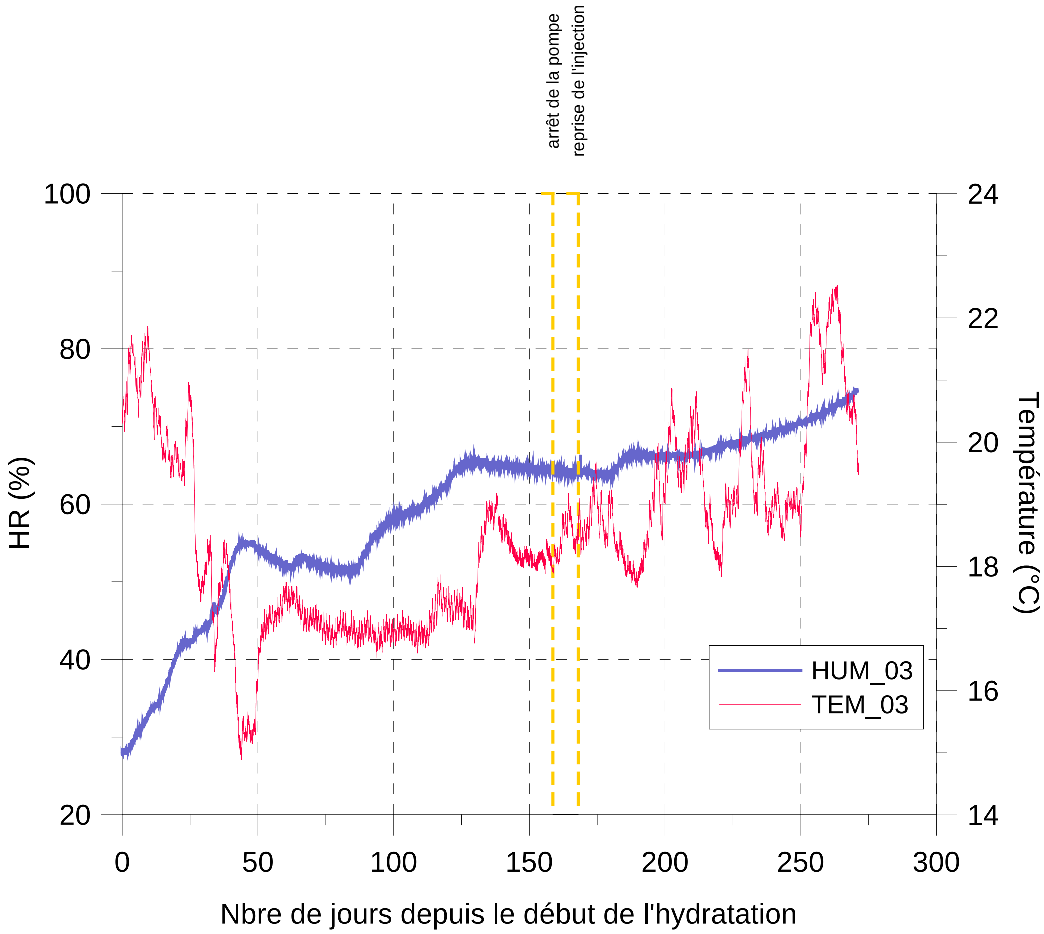


Figure 5-10 Relative humidity and temperature measured on sensor 03.

5.5 Total pressure in the vessel

30 load cells were installed in the vessel as previously stated (see Section 3.3.1.1). These measurements are presented section-by-section as shown in Figure 48, which once again gives the position of these sensors located in a radial direction around the vessel. As expected, variations are very small or zero.

Currently, the bentonite is in the volume expansion phase and the macro-pores are gradually closing.

Logically, once all the macro-voids have closed, the load cells should start to react.

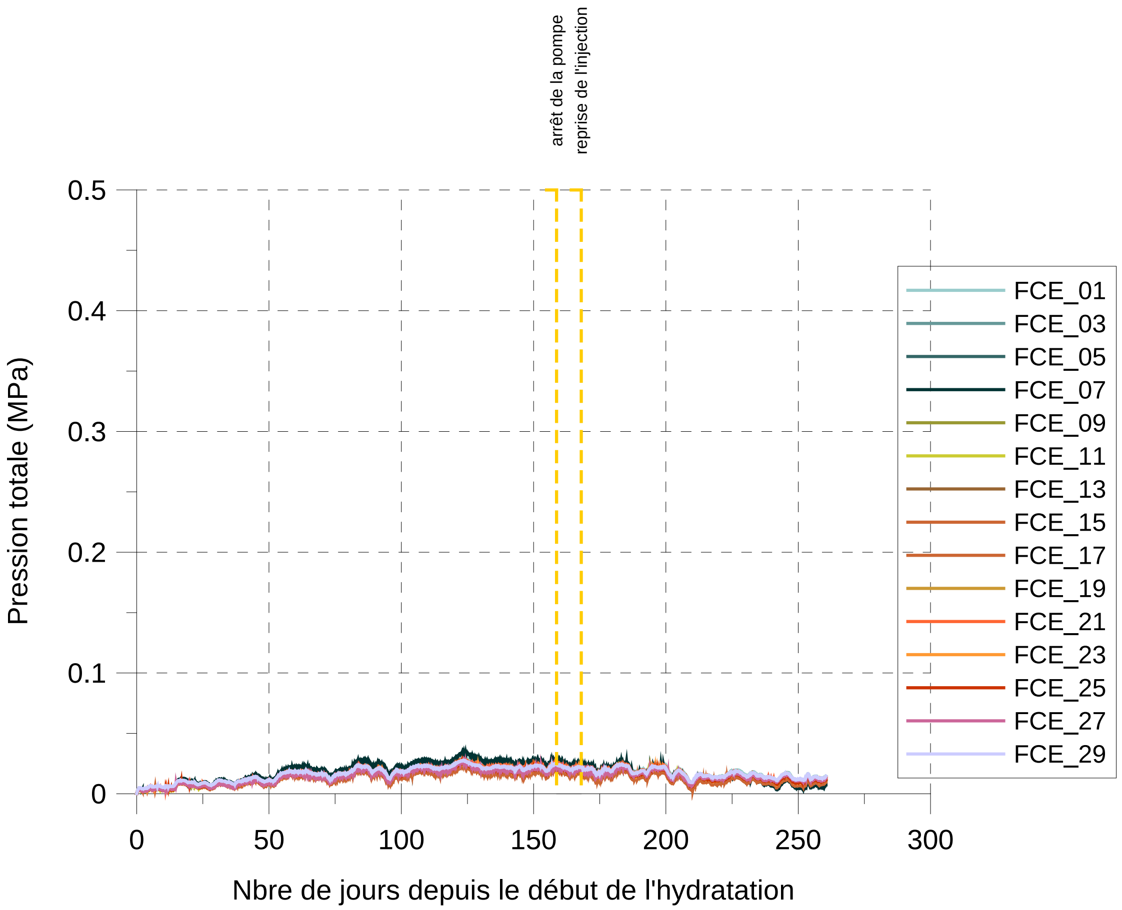


Figure 5-11 Pressure measurements in the vessel - section 1 (cf. Figure 5-13)

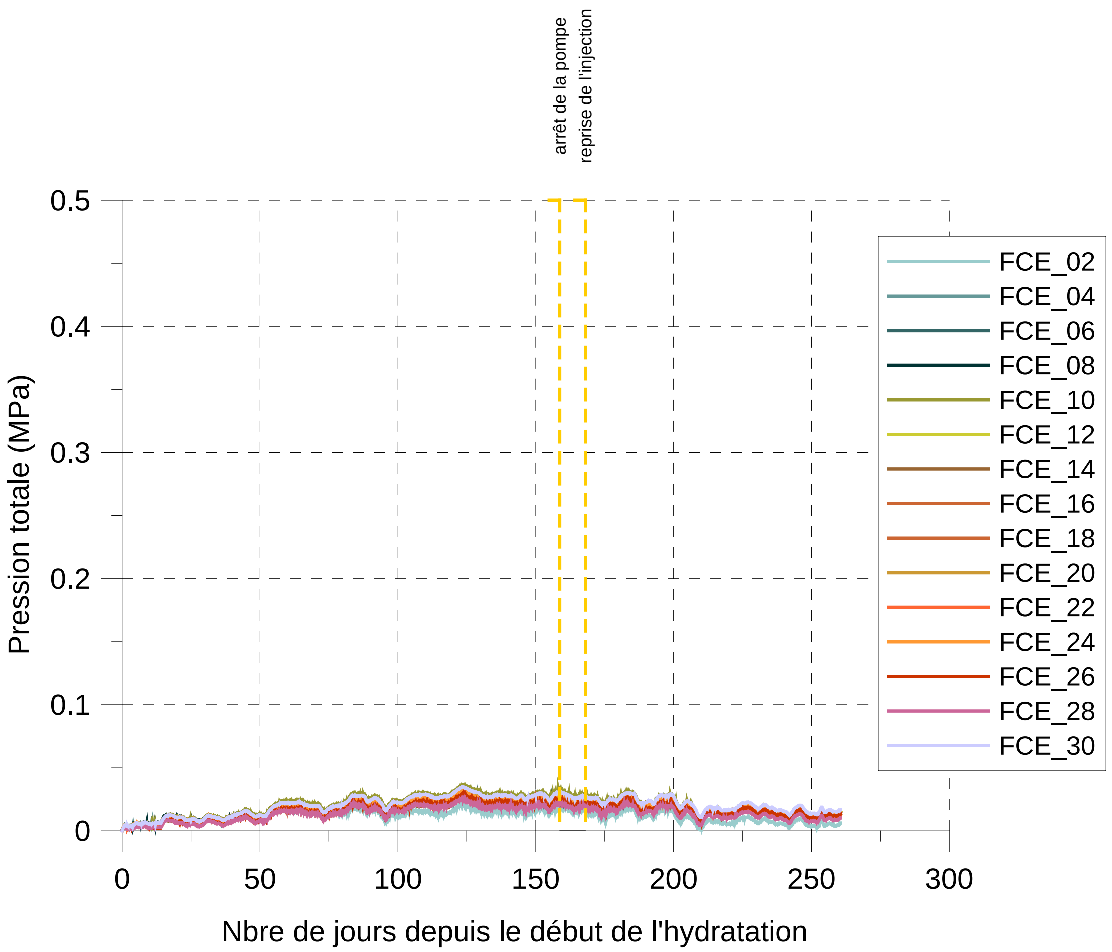


Figure 5-12 Pressure measurements in the vessel - section 1 (cf. Figure 5-13)

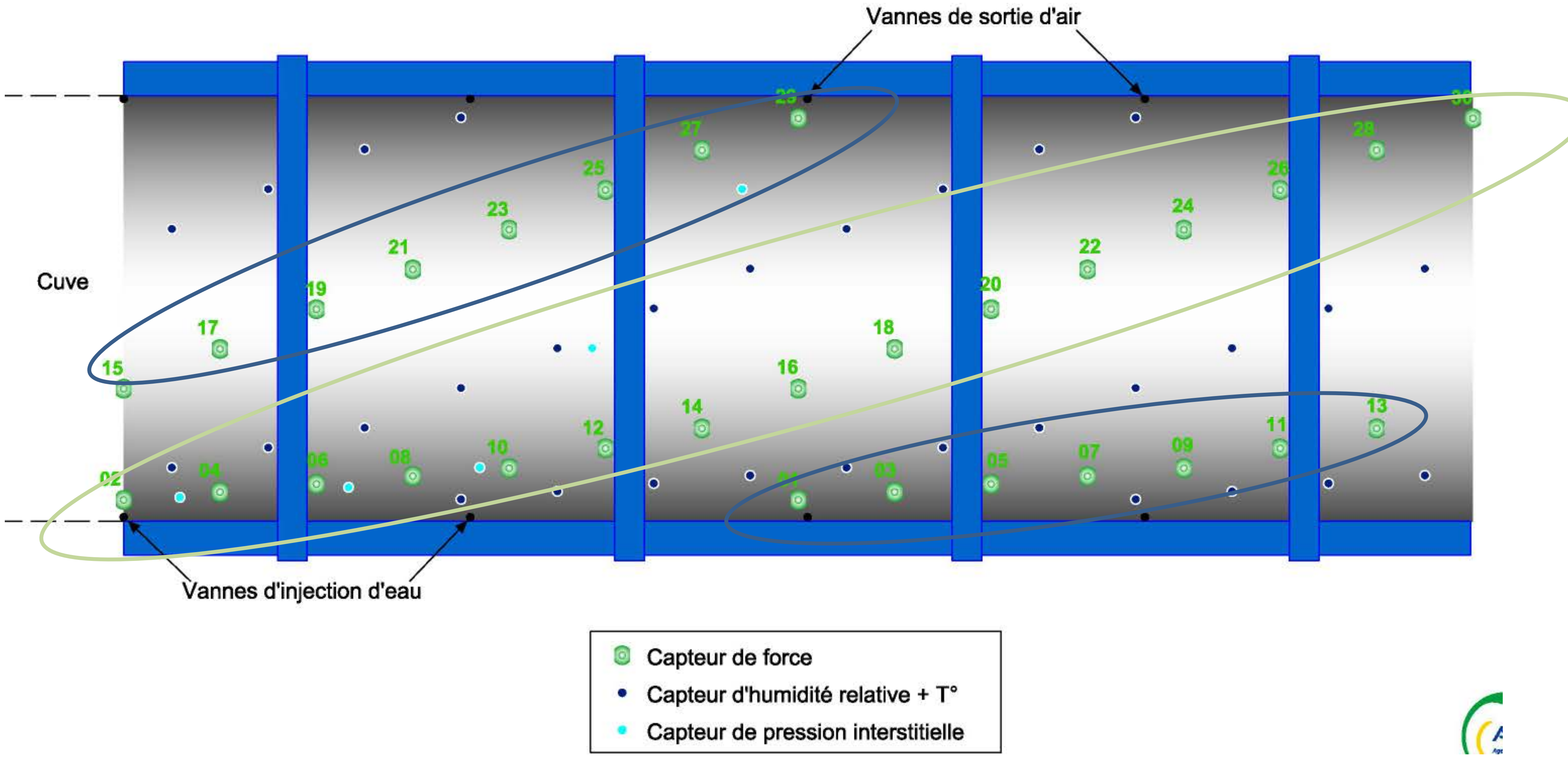


Figure 5-13 Position of humidity and temperature sensors on the REM vessel – Section1 in blue – Section2 in green

5.6 Total pressure on the lid

4 load cells were installed on the lid along with 4 force washers on the tie rods (see Figure 4-19). The measurements obtained by these sensors are presented in Figure 5-14 and Figure 5-15 respectively. For the same reasons mentioned above, the variations recorded are minimal.

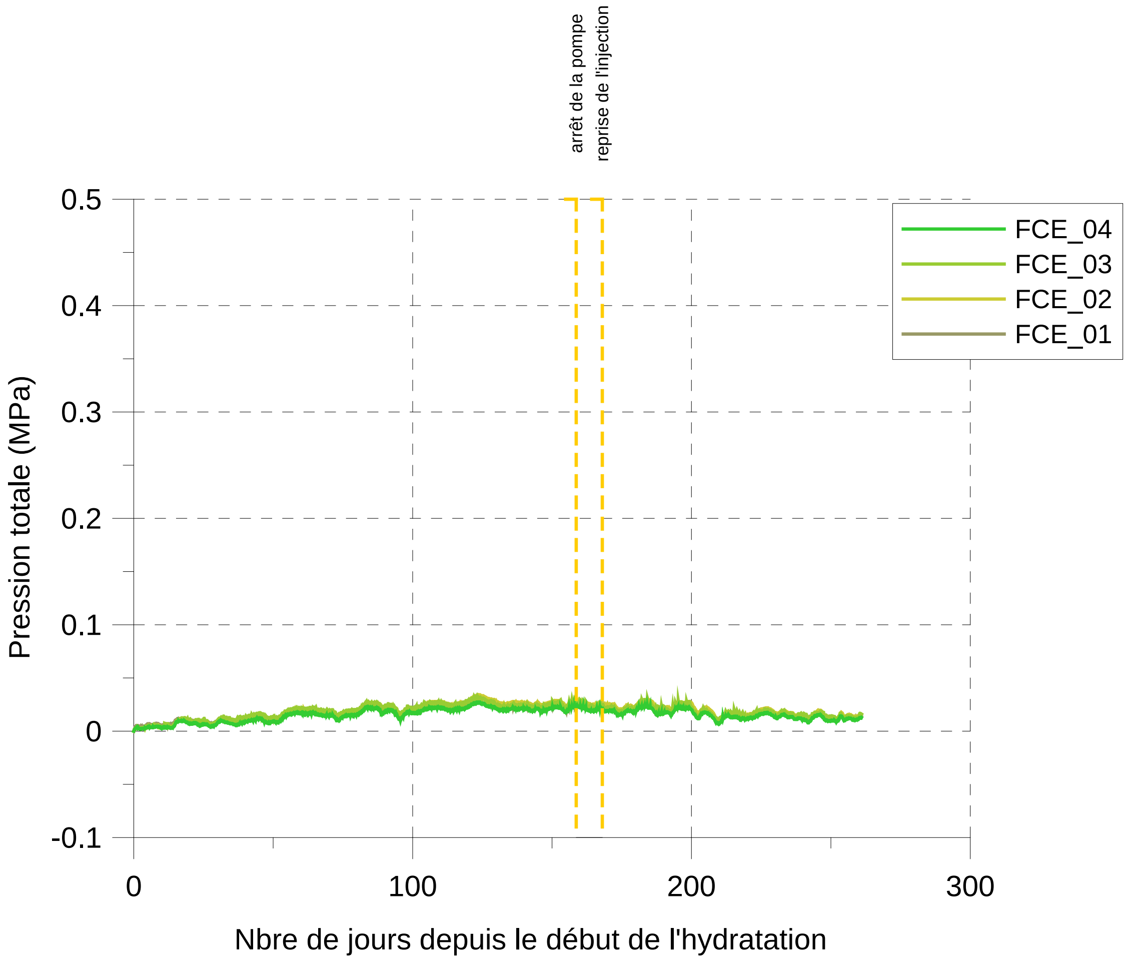


Figure 5-14 Pressure measurements on the lid (see Figure 4-19)

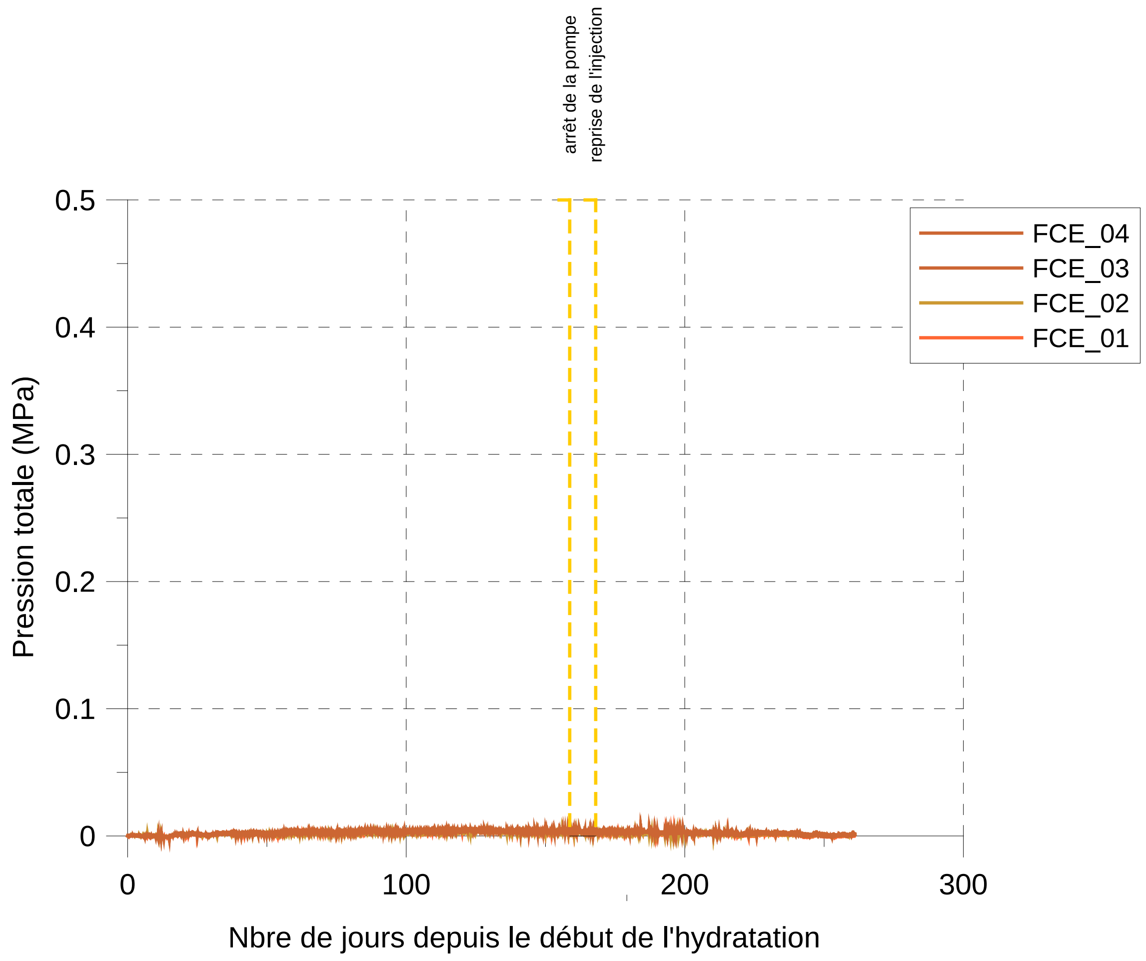


Figure 5-15 Pressure measurements on the tie rods (see Figure 4-19)

5.7 Pore pressure

5 pore pressure sensors have been installed in the vessel, as shown in the diagram given in Figure 5-17.

As detailed in Section 3.3.3, these measurements are relative and at first they measure the variation in air pressure in the pores between pellets. The measurements are given in Figure 5-16. As expected, there has been no variation in air pressure since the experiment launch, indicating that no air has been trapped in the model and that it can exit freely.

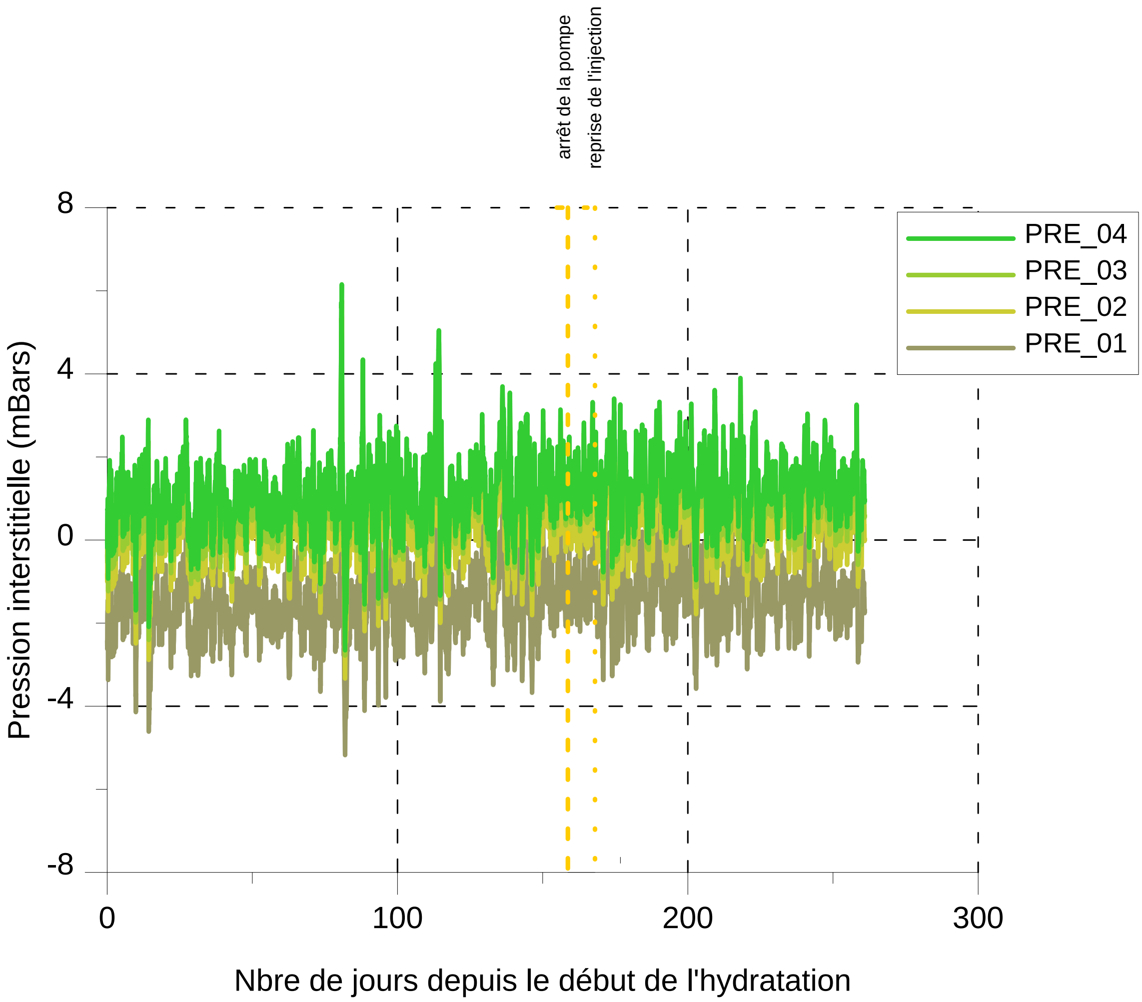


Figure 5-16 *Pore pressure measured in the model*

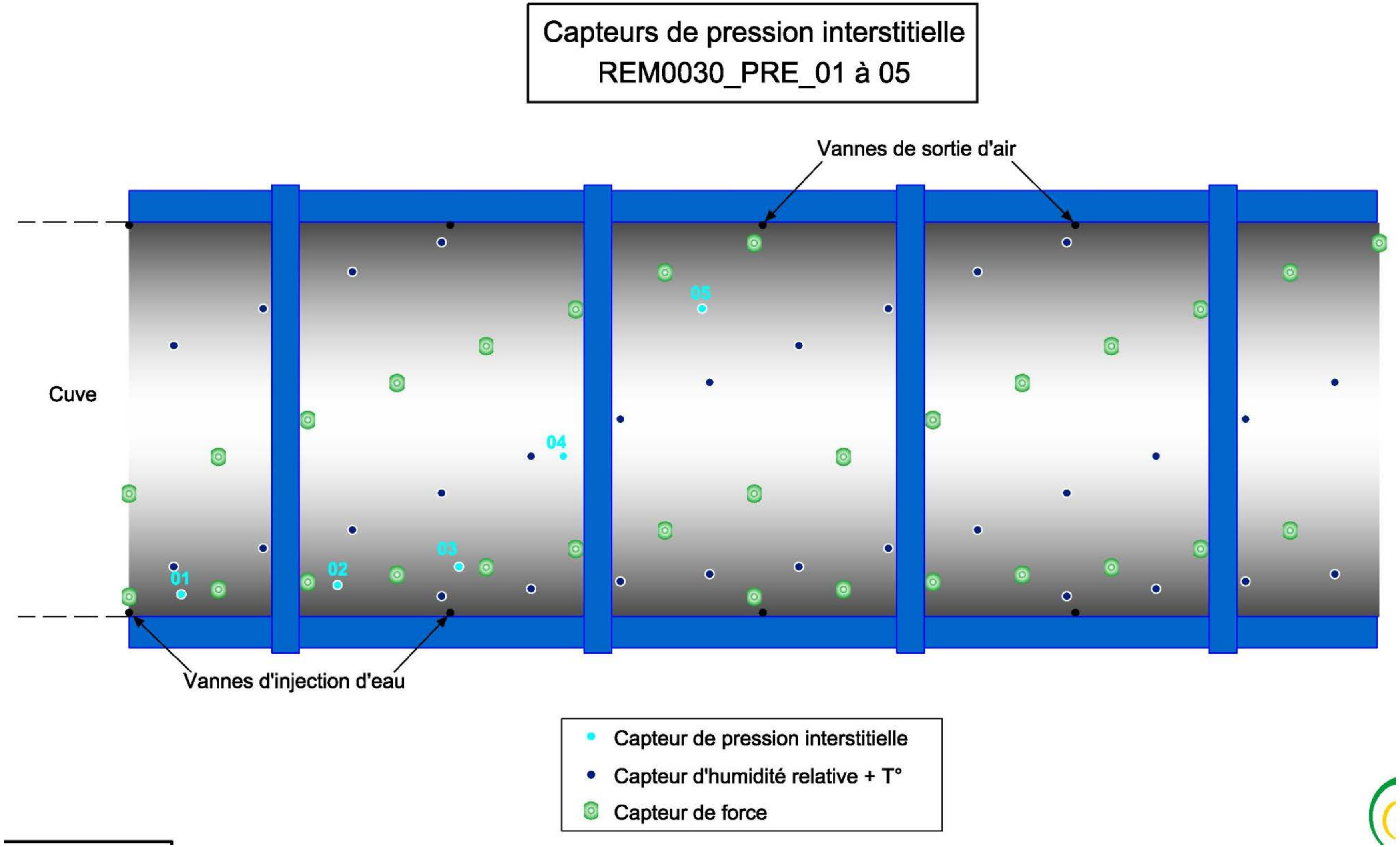


Figure 5-17 *Diagram showing the position of pore pressure sensors*

5.8 Airflow

As stated in Section 3.5, a porous disc collects air from the core's upper surface. A relative humidity sensor identical to the sensors installed in the vessel is fitted in-line on the nozzle and monitored by a flowmeter to measure the output airflow and compare it with the input flow. Measurement frequency (1 measurement per hour) does not allow for precise analysis of these measurements. However, as expected, air has regularly left the vessel since the start of hydration. The pump shutdown does not seem to have had an impact on measurements.

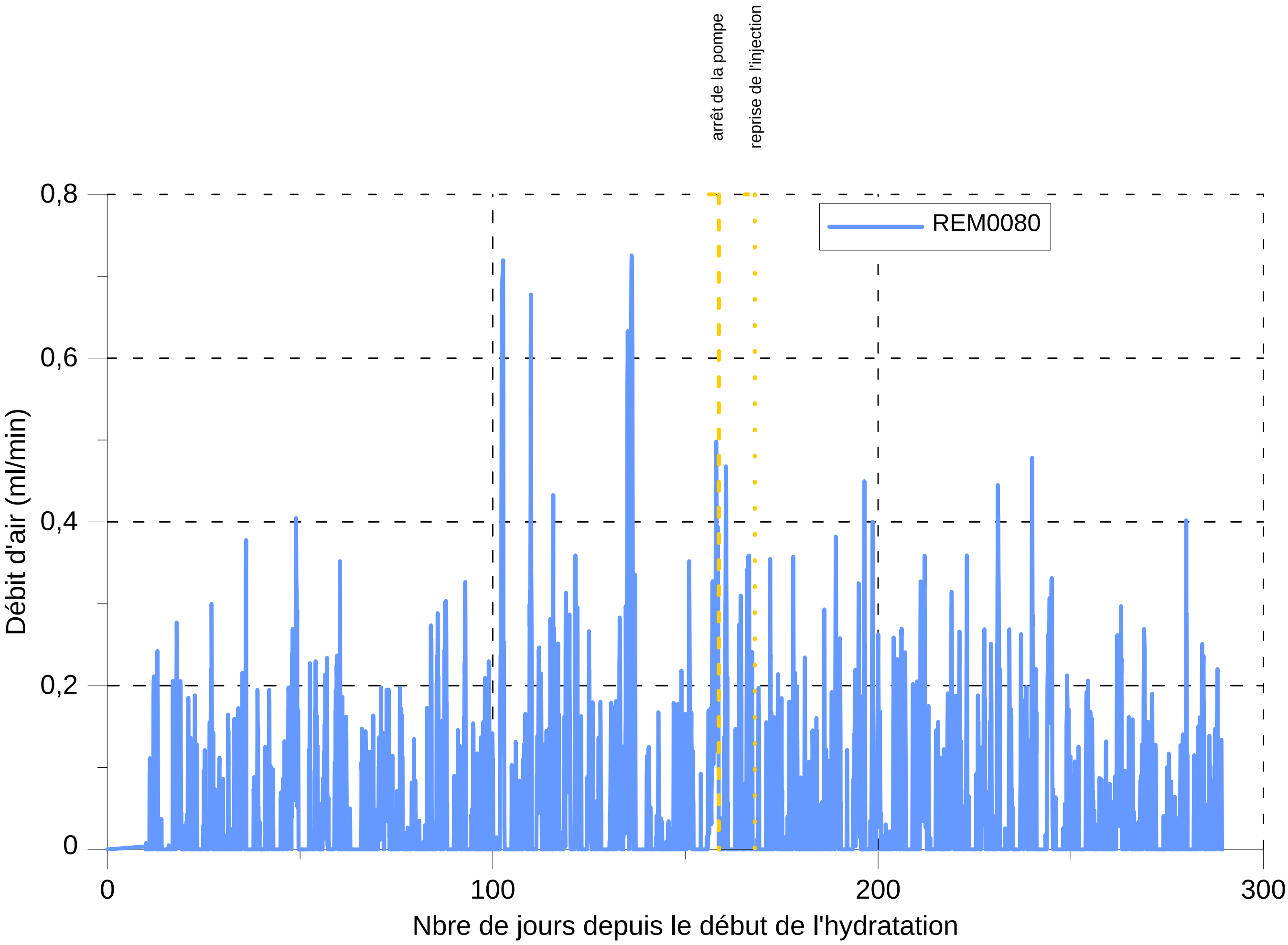


Figure 5-18 Airflow measured at vessel outlet since start of hydration

6. In-laboratory swelling tests

6.1 Objectives

During disposal, the seals will be saturated with water from the clay stones. However, a considerable proportion of this water will travel through concrete before reaching the pellet mixture. Its chemical characteristics will have changed substantially, particularly the pH, which will be highly alkaline.

The chemical characteristics of concrete pore water can significantly disrupt the hydro-mechanical performance of the pellet and powder mixture after saturation, especially if emplacement takes place at a low saturation level (very dry material like FSS and REM). It is therefore important to test this influence on swelling pressure and permeability by using representative samples. All the samples tested have a dry density of approximately 1.50 g/cm^3, similar to the FSS/REM admixtures.

The swelling tests were carried out by LECBA in 4 types of confinement cells, frequently used in this laboratory:

- 57 mm axial hydration cell, with one 32 mm pellet and crushed bentonite;
- 120 mm axial hydration cell, containing approximately twenty 32 mm pellets and crushed bentonite;
- 120 mm radial hydration cell;
- 240 mm axial hydration cell, containing approximately one hundred and twenty 32 mm pellets and crushed bentonite.

As the formulation of the supporting concrete in the drifts is still unknown, the tests were carried out using two types of cement water: water from CEM I-type concrete and water from low pH concrete. The reference water used was synthetic on-site water.

"Low pH" concrete, named after the pH value of the pore solution, is chemically different from "conventional" cement-based concrete as its formulation makes extensive use of mineral additives that significantly modify its physical and chemical properties. A very large variety of materials is possible. The scope of possible materials must be restricted by only focussing on typical compositions for materials whose characteristics make them a reference for these concrete studies.

For REM, the composition of cement waters (low pH or not) was chosen in accordance with report C.NT. ASCM. 09. 0010. B, which includes all the important information required to reconstitute "cement water" solutions for experiments in environments representative of these materials.

A fourth type of water from borehole FTP1101 (see Section 3.2), used to hydrate the REM model in the technological area, is also being tested for comparison with synthetic water.

6.2 Composition of hydration water

The compositions of the four types of water used for the swelling tests are given in Table 6-1, Table 6-2, Table 6-3 and Table 6-4. All water types were generated by CEA. The compositions for the concrete water types were taken from report CNTASCM090010B, solutions S1 (pH>13.5) and S5 (pH>11) respectively.

Table 6-1 Composition of on-site synthetic water

Elements	**Concentration (mol/l)**	**Salts used**	**Salt mass per litre of solution (mg)**
Cl	39.61×10^{-3}	$NaHCO_3$	281
Na	19.86×10^{-3}	Na_2SO_4	426
K	3.66×10^{-3}	NaCl	615
Ca	7.36×10^{-3}	KCl	77
Mg	6.67×10^{-3}	$CaCl_2$, 2 H_2O	1082
C	3.34×10^{-3}	MgCl2	1356
S	3×10^{-3}	AgCl	0.14
Ag	10^{-6}		

Table 6-2 Composition of standard CEM I concrete water (pH 13.5)

Elements	**Concentration (mol/l)**	**Salts used**	**Salt mass per litre of solution (mg)**
Na	6.09×10^{-2}	NaOH	2361.47
SO_4	1.80×10^{-3}	Na_2SO_4	255.39
Cl	1.00×10^{-3}	NaCl	58.5
K	3.66×10^{-1}	KOH	20519.2
Ca	8.37×10^{-4}	$Ca(OH)_2$	62.01

Table 6-3 Composition of low pH concrete water (pH 10.8)

Elements	**Concentration (mol/l)**	**Salts used**	**Salt mass per litre of solution (mg)**
Na	4.7×10^{-3}	Na_2SiO_3	73.236
K	1.5×10^{-3}	Na_2SO_4	177.55
Mg	2×10^{-6}	K_2SO_4	130.694
Ca	4.7×10^{-3}	$CaSO_4$	639.858
Si	6×10^{-4}	NaOH	39.997
SO_4	6.7×10^{-3}		
Al	4×10^{-6}	HCl	32.086
OH	10^{-3}		

The pH is modified by gradually adding hydrochloric acid. The resulting pH is 10.8 (+/- 0.2).

After preparation, concrete water types are stored in inactinic flasks in a nitrogen or argon atmosphere to avoid carbonation.

Table 6-4 Concentration of the main elements dissolved in water from borehole FTP1101

Elements	Concentration (mg/l)	Concentration (mol/l)
Cl	1610	45.4×10^{-3}
Na	1280	55.7×10^{-3}
K	46	1.2×10^{-3}
Ca	324	8.1×10^{-3}
Mg	181	7.4×10^{-3}
HCO3	132	2.2×10^{-3}
SO4	1990	20.7×10^{-3}
Ag	Not measured	Not measured

6.3 Tests in the 57 mm cell

Two tests for the pH 13.5 concrete water, one test for the low pH concrete water, and two tests for the synthetic on-site water were carried out in the 57 mm diameter cells. The samples were maintained hydrated long enough to monitor the variation in swelling pressure over time.

The purpose of these tests in the 57 mm diameter cell (size of a standard cell at LECBA) was to quickly obtain results, in order to prepare tests on a more representative scale. In the 57 mm confinement cylinder, the sample is composed of one 32 mm pellet surrounded by crushed bentonite, emplaced at the same dry density as FSS and REM, i.e. approximately $1.50 g/cm^3$ (Figure 6-1). A pellet is placed in the cell on the bottom piston's sintered disc and then crushed bentonite is poured into the annulus between the pellet and confinement cylinder wall. The top piston must lie on top of the pellet, which determines the sample height. Using this procedure, a slight void is left above the crushed bentonite, which is necessary to meet the target density value.

The materials used come from the batches supplied by LAVIOSA MPC, referenced at LECBA under numbers RE14-002 and RE14-003.

Table 6-5 summarises all the initial characteristics of the three samples. Hydration was carried out via the sample's inner surface at atmospheric pressure + approximately 1 m head of water. The upper circuit was open to bleed the air trapped in the sample and circuits.

Variations in piston force and displacement were recorded over time and the results are given in Table 6-7 and commented on in Section 6.5. Figure 6-3 compares the swelling kinetics of the samples.

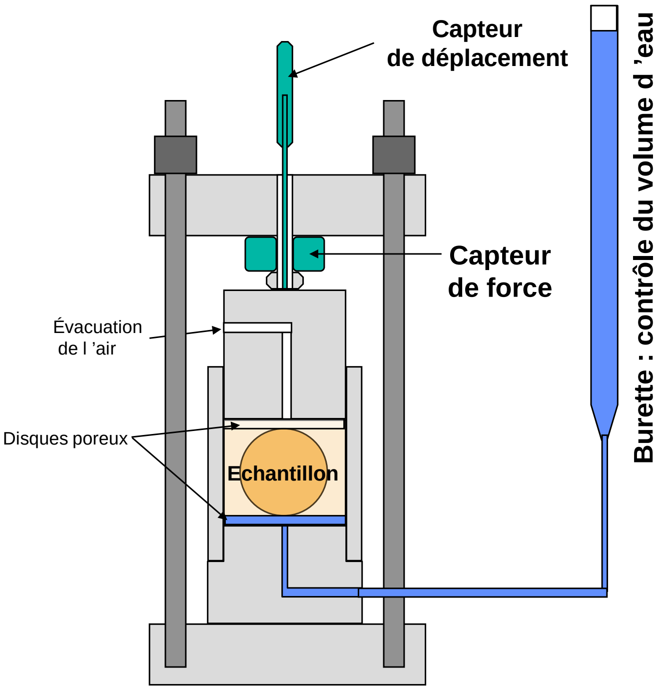


Figure 6-1 *Schematic representation of the 57 mm cell tests*

Table 6-5 Initial characteristics of the samples hydrated using three types of water in 57 mm units

		Synthetic on-site water		**Concrete water pH 13.5**		**Low pH concrete water pH 10.8**
Sample no.		3446 m	3493m	3444 m	3494 m	3445 m
Pellet	Mass (g)	43.085	86.060	43.113	43.190	43.083
	w (%)	4.52	4.52	4.52	4.52	4.52
	% total dry M	32.8	37.4	32.6	32.9	32.6
Crushed bentonit e	Mass (g)	88.372	144.08 5	89.067	88.060	89.178
	w (%)	4.40	4.4	4.4	4.4	4.4
	% total dry M	67.3	62.6	67.4	67.1	67.5
Total dry mass (g)		125.869	220.35 1	126.562	125.671	126.639
Height (mm)		32.69	56.78	32.82	32.58	32.77
Volume (cm^3)		83.425	144.85 5	83.757	83.136	83.629
Apparent density (g/cm^3)		1.576	1.588	1.578	1.579	1.582
Dry density (g/cm^3)		**1.509**	**1.521**	**1.511**	**1.512**	**1.514**

6.4 Tests in the 120 mm axial hydration cell

LECBA carried out two tests for the two types of concrete water. Two saturation tests are still currently under way at LECBA with synthetic water and water from the FTP borehole, under the same conditions as the previous tests in the 57 mm diameter cell, using the same materials.

The LECBA 120 mm diameter swelling cells have been designed and produced using the same principles as the 57 mm cells. They qualify a large enough volume to be representative of the 32 mm pellet/crushed pellet mixture from the FSS and REM experiments. Eight to ten 32 mm pellets take up the 113 cm^2 surface area of the cell. The height decided for the samples corresponds to 2 layers of pellets (approximately 20 pellets) or approximately 65 mm. A 3-layer height of approximately 96 to 100 mm would take approximately 500 days to saturate if water is added from one surface only.

The challenge is to prepare the samples so that the dry density is around 1.50 g/ cm^3, while ensuring the essential voids are evenly distributed (Figure 6-2).

Table 6-6 summarises all the initial characteristics for the samples produced for these 4 tests. The results are given in Table 6-8 and analysed in Section 0. The hydration kinetics are shown in Figure 6-4.

Pellet layer 1

Pellet layer 2

Final sample

Figure 6-2 Preparation of sample 3467m in 120 mm cell

Table 6-6 Initial characteristics of the samples hydrated using the four types of water in the 120 mm cells

		Synthetic on-site water	Water from FTP borehole	Concrete water pH 13.5	Low pH concrete water pH 10.8
Sample no.		3495m	3496m	3467m	3466m
Pellets	W (%)	4.47			
	Mass layer 1 (g)	426.2	425.5	426.057	423.973
	Mass layer 2 (g)	427.3	426.6	429.122	428.176
	Total dry mass (g)	816.98	815.64	818.6	815.69
	% total dry mass	70.7	70.7	70.6	70.6
Crushed bentonite	W (%)	3.69			
	Mass layer 1 (g)	176.1	175.1	176.685	176.459
	Mass layer 2 (g)	175.3	175.0	176.106	176.626
	Total dry mass (g)	338.9	337.64	340.24	340.52
	% total dry mass	29.3	29.3	29.4	29.4
Total dry mass (g)		1155.88	1153.28	1158.824	1156.208
Sample height (mm)		67.36	67.31	67.42	67.31
Volume (cm^3)		761.82	761.26	762.45	761.20
Apparent density (g/cm^3) (ρ_h)		1.582	1.579	1.584	1.583
Dry density (g/cm^3) (ρ_d)		**1.517**	**1.515**	**1.520**	**1.519**
Porosity* (%)		45.42	45.50	45.32	45.36
Degree of saturation (%)		14.17	14.12	14.20	14.07

* where $\rho_s = 2.78\ g/cm^3$ (according to Push, 2002)

6.5 Analysis of the first tests

The results of the five tests in 57 mm cells are perfectly coherent and reproducible, with the sole exception of the density measurements (Table 6-7, Figure 6-3). The impact of standard concrete water (pH 13.5) on swelling pressure is significant in comparison with low pH concrete water (pH 10.6), 22% and the on-site water, 28%.

Table 6-7 *Results of swelling tests in the 57 mm cell for three types of hydration water*

	Synthetic on-site water		**Standard concrete water pH 13.5**		**Low pH concrete water pH 10.8**
Sample no.	3446m	3493m	3444m	3494m	3445m
Test duration (days)	175	168	201	168	147
Final height (mm)	32.80	56.93	32.89	32.64	32.88
Final dry density (g/cm3) (ρ_d)	**1.504**	**1.517**	**1.508**	**1.510**	**1.509**
Swelling pressure (MPa)	**5.0**	**5.0**	**3.6**	**3.7**	**4.6**

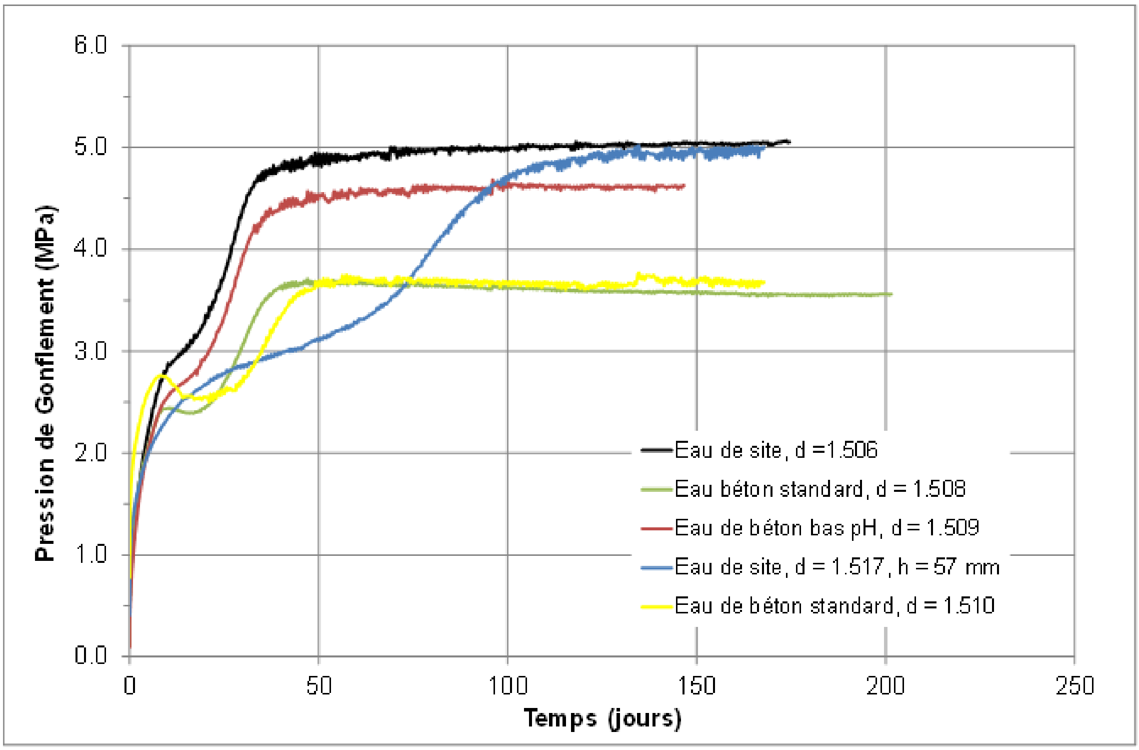


Figure 6-3 *Comparison of swelling kinetics in the 57 mm cell tests according to the hydration water type*

This difference was much smaller for the tests in 120 mm cells, with only 6.4 % difference between the two different concrete waters (Figure 6-4, Table 6-8). However the order is the same in both cases: hydration of the pellet-crushed bentonite mixture with high pH water tends to reduce swelling pressure at saturation. The small difference in the 120 mm cell tests could be explained by the sample height and by the saturation protocol via the bottom surface of the sample. It may be that the first few cm of bentonite serve as a filter or barrier to liquid hydration water, causing the upper layers to start saturation in vapour phase. A salinity gradient would thus be established within the sample and the upper layers whose saturation would have started with less basic (higher pH) water, which would lead to the final swelling pressure value.

Table 6-8 Results of swelling tests in the 120 mm cell for the two types of concrete water

	Synthetic on-site water	**Water from FTP borehole**	**Concrete water (pH 13.5)**	**Low pH concrete water (pH 10.8)**
Sample no.	3495m	3496m	3467m	3466m
Test duration (days)	101 (in progress)	101 (in progress)	178	182
Final height (mm)	-	-	67.66	67.54
Final dry density (g/cm^3)	**-**	**-**	**1.528**	**1.514**
Swelling pressure (MPa)	**-**	**-**	**4.05**	**4.35**

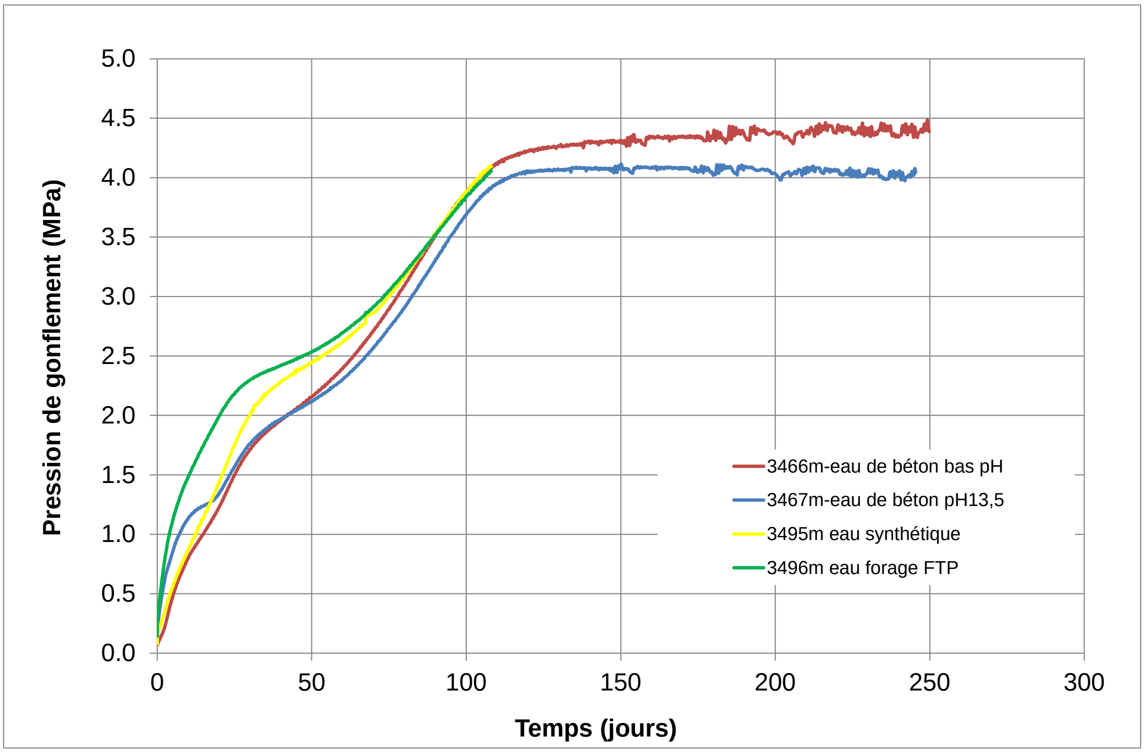


Figure 6-4 Comparison of swelling kinetics in samples 3466m, 3467m, 3495m, 3496m, hydrated with the four types of water, in the 120 mm cell. The tests on samples 3495m and 3496m are still in progress (yellow and green curve)

It is difficult to provide a more relevant explanation since the results seem dispersed even though the tests in the 120 mm cell can be considered as more representative because they include significantly more pellets and the height is double that of the 57 mm cells.

In the 57 mm cell tests, collapse is only seen in the hydration kinetics for the two tests with concrete water at pH 13.5, while in the 120 mm cells, the kinetics for all waters show a turning point at the same time and swelling pressure. This similar behaviour confirms that the results obtained with the 120 mm cells are reliable, but the difficulty in implementing high precision tests with these heterogeneous materials should not be forgotten.

6.6 Tests in the 120 mm radial hydration cell

The purpose of this test was to examine the impact of using concrete water to saturate a sample of the FSS pellets-crushed bentonite mixture on its permeability at saturation. In the event of centripetal hydration, which is expected in the CIGEO drift seal, the initial hydration water will be pore water from the concrete lining of the drift. The impact of this water will be at its highest in the sealing area close to the inner wall of the drift. This seal core zone may have hydro-mechanical behaviour that is significantly different to the behaviour at the heart of the core.

6.6.1 Saturation phase

A 120 mm diameter cell was built specifically for this measurement, based on those used in the previous tests, but allowing radial hydration of the sample (Figure 6-5).

Sample no. 3482m was hydrated with standard concrete water at pH 13.5. The initial characteristics of this sample are given in Table 6-9 and the results in Table 6-10.

Figure 6-6 shows variation in the swelling pressure over time, in comparison with the other tests with concrete water at pH 13.5.

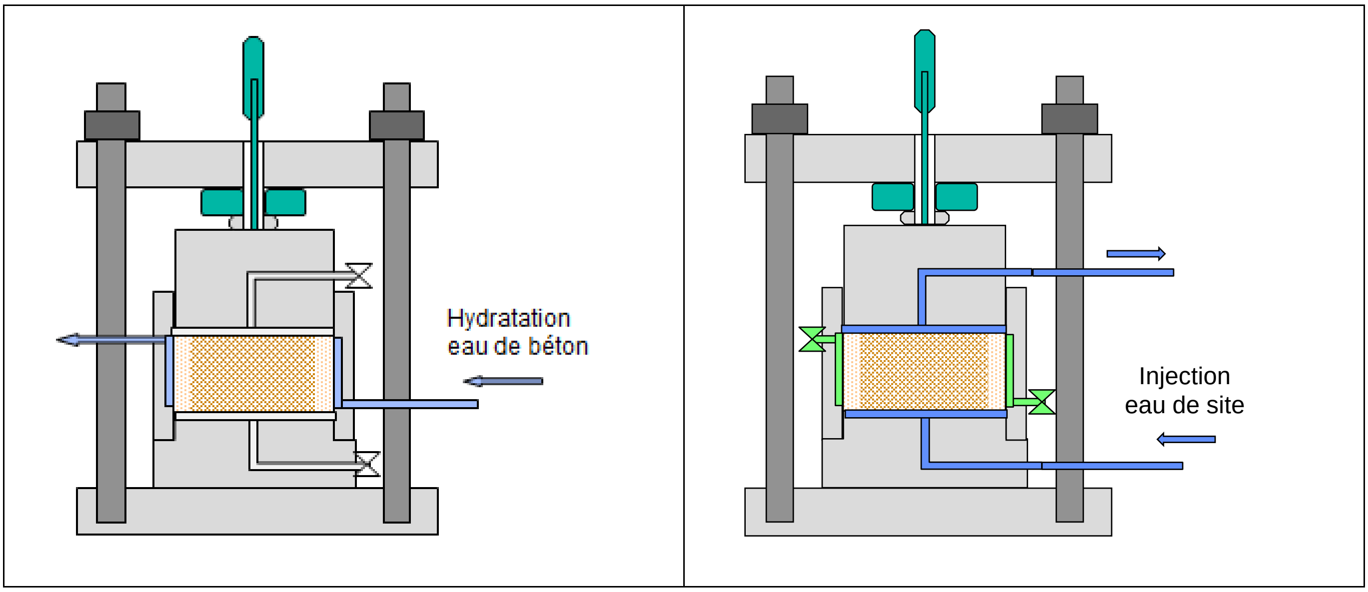


Figure 6-5 Schematic representation of the radial saturation test and the saturation permeability test

Table 6-9 *Initial characteristics of the sample radially hydrated with concrete water (pH 13.5)*

Sample 3482m Hydration with concrete water pH 13.5		
Pellets	w (%)	4.41
	Mass layer 1 (g)	427.00
	Mass layer 2 (g)	425.80
	Total dry mass (g)	816.78
	% total dry mass	70.70
Crushed bentonite	w (%)	4.45
	Mass layer 1 (g)	176.70
	Mass layer 2 (g)	176.80
	Total dry mass (g)	338.44
	% total dry mass	29.30
Total dry mass (g)		1155.22
Sample height (mm)		66.85
Volume (cm^3)		756.06
Apparent density (g/cm^3)		1.596
Dry density (g/cm^3)		**1.528**
Porosity (%)		45.04
Degree of saturation (%)		15.00

Table 6-10 *Results of swelling tests in the 120 mm radial hydration cell*

	Concrete water pH 13.5
Sample no.	3495m
Duration of hydration phase (days)	103
Final height (mm)	67.02
Final dry density (g/cm3)	**1.512**
Swelling pressure (MPa)	**3.57**

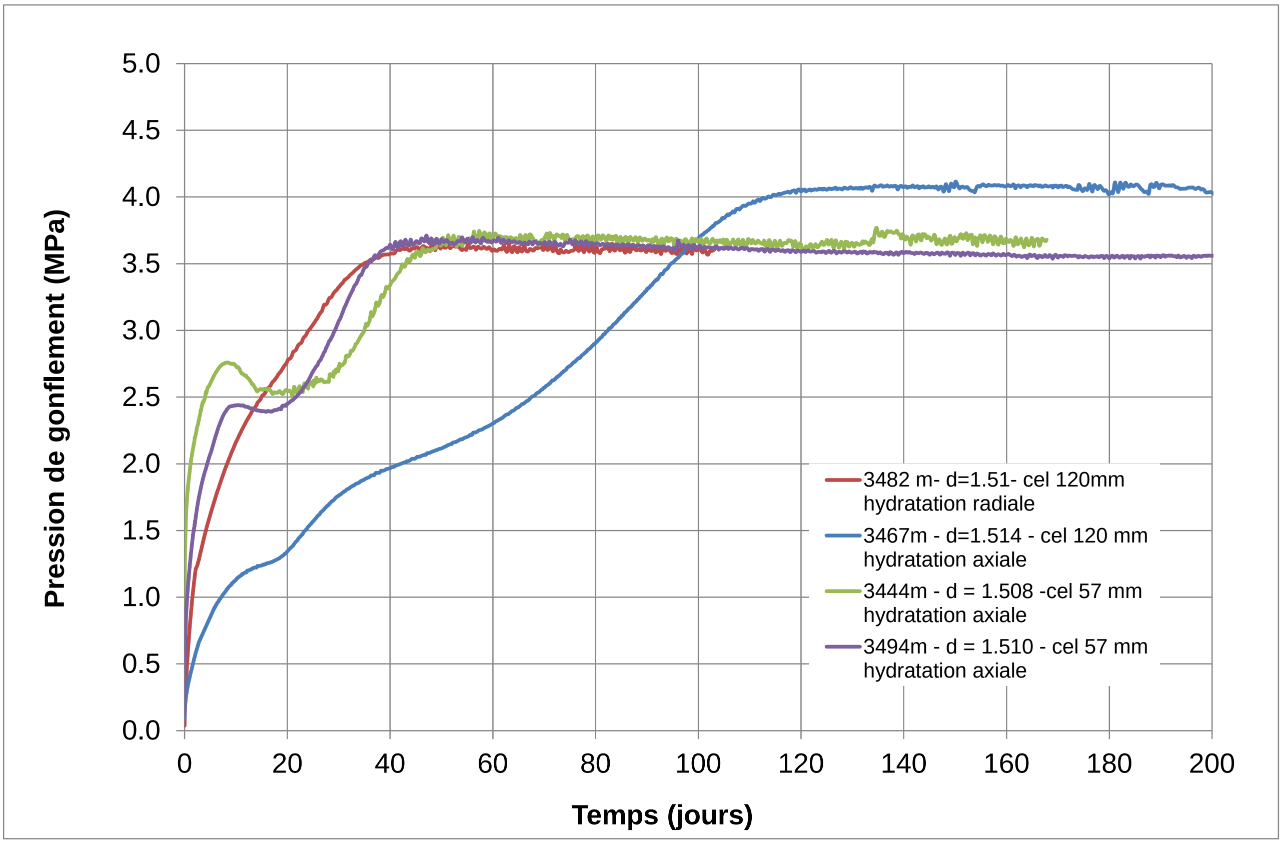


Figure 6-6 *Comparison of swelling kinetics in the samples hydrated radially and axially with concrete water at pH 13.5, in the 57 mm and 120 mm cells*

6.6.2 Measurement of permeability at saturation

After saturation with concrete water, the radial hydration circuit is purged, dried and then filled with a hydrocarbon (n-dodecane) that is not miscible in pore water and that does not penetrate saturated bentonite. The circuit is slightly pressurized then closed with two valves (inlet and outlet valve).

The saturation permeability test is performed with synthetic on-site water (see Table 6-1) via the axial circuit, using an ROP double-head pump to impose a pressure differential between either side of the sample by controlling both flowrate and pressure (see Figure 6-5 and Figure 6-7). Since the pump can work at constant pressure, pressure is maintained on the bottom surface, while the top surface is kept at a lower pressure. When the gradient has been achieved and the sample is perfectly saturated, the injected volume should be equal to the suction volume. If this is the case, the measurement is considered to be reliable.

Two series of measurements were performed with two pressure differentials (0.4 MPa and 0.8 MPa) between the upstream (injection) side and the downstream (outflow) side of the sample.

Balancing the flowrate on the upstream and downstream sides of the sample takes a long time, in order to establish the gradient and achieve a steady state.

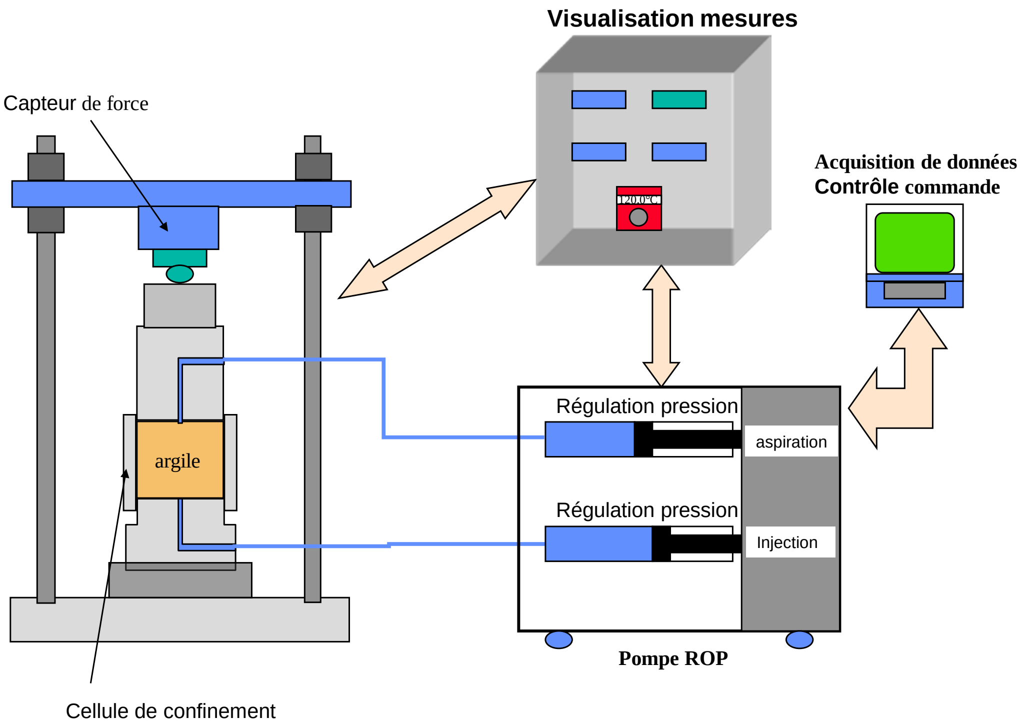


Figure 6-7 *Operating diagram of the hydraulic conductivity measurements*

6.6.2.1 Measurement 1 (injection pressure 0.6 MPa, outflow pressure 0.2 MPa)

The sample was initially subject to water pressure of 0.4 MPa on both sides, in order to verify saturation. The pressure set points on the injection pump (pump 1) and the suction pump (pump 2) were then set to 0.6 MPa and 0.2 MPa respectively. The PID controllers of the two pumps act to maintain these pressure values, either by injecting or by extracting water. The injection and suction volumes are measured over time. The measurement is considered to be valid when the input and output flowrates are linear and coincident.

The coefficient of hydraulic conductivity, k_w, is calculated using a simplified Darcy's law:

$$Q = k_w \times i \times S$$

where

Q is the flowrate percolating through the sample, expressed in m^3/s,

$\boldsymbol{k_w}$ is the coefficient of hydraulic conductivity, expressed in m^3/s,

I is the hydraulic gradient, expressed in m/m (head of water in m divided by sample thickness),

S is the sample cross-sectional area in m^2.

The balancing operation took approximately 34 days and the measurement operation slightly over 15 days. The results of measurement 1 are given in Table 19. Figure 61 shows the period selected for measurement.

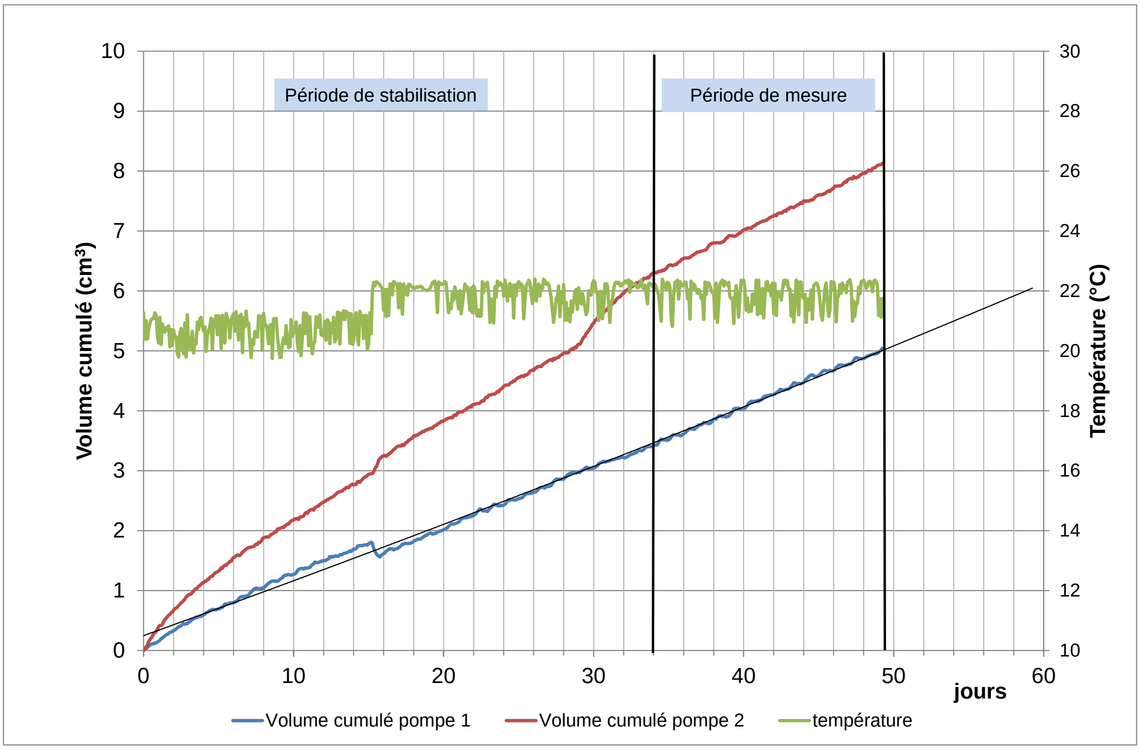


Figure 6-8 *Measurement of permeability at saturation 1: water volumes flowing through the sample over time*

Note: sample cross-section was 1.14 x 10^{-2} m^2

Table 6-11 *Permeability at saturation test results for sample 3482 - Measurement 1*

Measurement 1		
H (mm)	67.03	
Pg (MPa)	3.6	
Injection pressure (MPa)	6.00	
Outflow pressure (MPa)	2.00	
Measurement duration (s)	1317623	
$V_{injection}$ (m^3)	1.5774 x 10^{-6}	
V_{output} (m^3)	1.8601 x 10^{-6}	
Gradient	609	
	Injection	**Output**
Flowrate (m^3/s)	1.19716 x 10^{-12}	1.4117 x 10^{-12}
K_w (m/s)	**1.72 x 10^{-13}**	**2.03 x 10^{-13}**

Note: sample cross-section was 1.14 x 10^{-2} m^2

6.6.2.2 Measurement 2 (injection pressure 1 MPa, outflow pressure 0.2 MPa)

For the second measurement, the injection pressure was increased to 1 MPa while the output pressure was kept at 0.2 MPa. The injection pressure should not exceed 30% of the swelling pressure value in order to avoid adding to mechanical strain in the sample, which could distort the measurements or test conditions.

This test is still in progress. Calculations based on the initial results are coherent with the previous measurement. The flowrate is proportional to the pressure gradient under test conditions.

Figure 6-9 shows the period selected for measurement. The results of measurement 2 are given in Table 6-12.

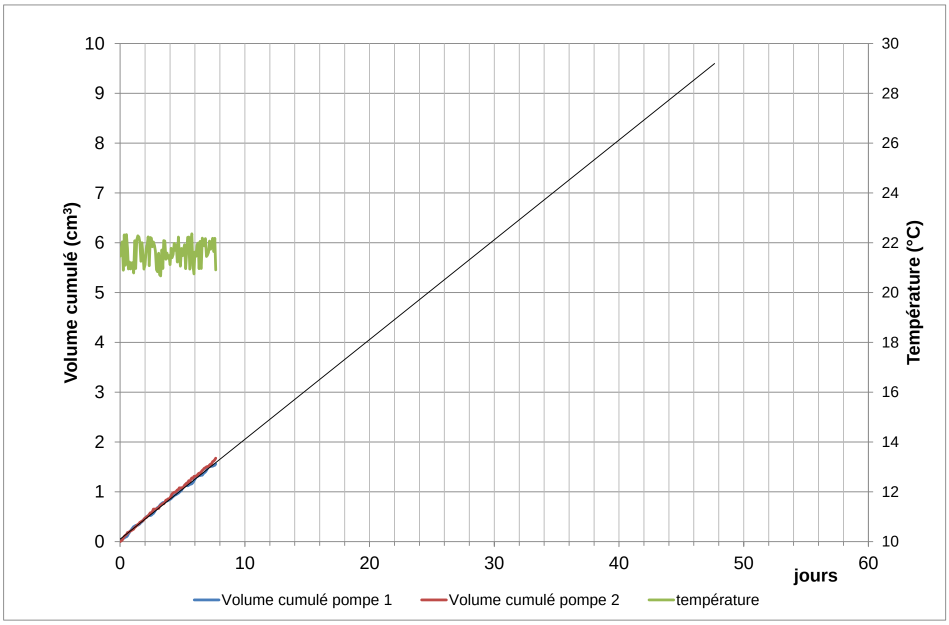


Figure 6-9 Measurement of permeability at saturation 2: water volumes flowing through the sample over time

Table 6-12 Permeability at saturation test results for sample 3482 – Measurement 2

Measurement 2		
H (mm)	67.05	
Pg (MPa)	3.6	
Injection pressure (MPa)	10.00	
Outflow pressure (MPa)	2.00	
Measurement duration (s)	662412	
$V_{injection}$ (m^3)	1.5610×10^{-6}	
V_{output} (m^3)	1.6745×10^{-6}	
Gradient	1217	
	Injection	**Output**
Flowrate (m3/s)	2.35654×10^{-12}	2.5279×10^{-12}
K_w (m/s)	**1.70×10^{-13}**	**1.82×10^{-13}**

Note: sample cross-section was 1.14×10^{-2} m^2

6.7 Mini-model swelling test (tests in 240 mm cell)

The purpose of this supplementary "mini model" test, alongside the metric test, is to generate preliminary experimental data for the DAC 2016 (Date of License application is incompatible with the resaturation times of the REM test).

The test will be performed by LECBA with the same material that is used in the REM vessel, with the aim of obtaining a composition and emplacement density similar to those found on the FSS. The hydration water is taken from borehole FTP1101 (see Table 6-4).

The 240 mm swelling cell developed for FSS is used and slightly modified for the test, with humidity and total pressure sensors. The aim is to compare results with the REM test results.

9 radial holes were drilled around the stainless steel confinement cylinder in order to install the sensors (see Table 6-14):

- 5 RH/T sensors placed at +20, +40, +60, +80 and +100 mm on the z axis (height), in the same way as for the REM vessel.
- 4 miniature total pressure sensors placed at heights of +20, +40, +60, and +80 mm.

Experience from tests performed as part of the FSS experiments (Gatabin, 2014) and the metric REM test will be used to inform implementation of this test. The aim is to reproduce the REM metric test, so particular care will be taken in building the sample and in verifying its emplacement density. At the time of writing, the test has not yet started, but the preparation and sample emplacement process are presented below.

6.7.1 Test set-up

The design of the 240 mm diameter swelling cell, specially developed for the FSS reference mixture, represents a trade-off between various considerations:

- The cell has a sufficiently large diameter to be representative of the diameter of a pellet. In general, the representative elementary volume (REV) is 10 times the volume of the basic constituent, i.e. 10 x 32 mm in both directions for a confinement cylinder,
- The pistons-cylinder assembly must withstand internal pressure of the order of 7 MPa without deformation,
- The saturation time for the emplaced sample must be acceptable for the target objective,
- The cost and weight (for handling in the lab) of the assembly must remain reasonable.

6.7.2 Apparatus

The test cell comprises one confinement cylinder, one base and a 304L stainless steel mobile piston. The assembly is inserted into a retaining frame (flanges). A load cell between the piston and the upper flange measures the swelling pressure transmitted by the piston. The base and the piston both have a device allowing an even distribution of water inflow over the surface of the sample via a porous sintered stainless steel disc.

A displacement sensor measures the mobile piston travel as a result of the retaining flange rod elongation.

A water tank containing on-site water from borehole FTP 1101, placed 1 m above the base on a constant weighing mechanism, provides the hydration source, with a slight pressure differential (approximately 10 kPa).

Hydration is provided *via* the base, while the piston circuit remains open in order to allow any occluded air in the sample to escape.

All the sensors are connected to a data acquisition/signal conditioning unit driven by a program in a PC. All measurements are logged over time.

6.7.3 Sensor calibration

The relative humidity (RH) sensors also include temperature (T) measurement. They are identical to the sensors used in the REM mode - miniature ROTRONIC HC2-C05 probes inserted in a metal tube with a cylindrical sintered stainless steel cap at the end. The tube diameter is 8 mm. The combined RH/T sensors are calibrated for 3 RH points on delivery. Their measuring range is from 0 to 100% RH. The probes are shown in Figure 6-10 at the time of installation on the confinement cylinder. They were not recalibrated.

The total radial pressure sensors are miniature membrane pressure sensors, made to order such that the measurement membrane is in tangential contact with the inner surface of the confinement cylinder. Their measuring range is from 0 to 15 MPa.

The total pressure sensors were recalibrated in the laboratory using the same system as was used for the model sensors: an AOIP calibrator for excitation and the signal, and a calibration pump and pressure gauge for the pressure. Table 6-13 presents the recalculated sensitivity values for the four total radial pressure sensors.

Table 6-13 Recalculated sensitivity values for the total radial pressure sensors.

Serial no.	Sensor no.	Factory sensitivity (mV/FS)	LECBA sensitivity (mV/full scale)
Z1404Q	PT1	11.300	11.414
Z1404R	PT2	11.330	11.421
Z1404T	PT3	11.520	11.491
Z1404U	PT4	11.120	11.131

6.7.4 Sensor installation

The radial sensors are first screwed to the confinement cylinder in a watertight manner. Table 6-14 gives the reference numbers and position of the sensors on the confinement cylinder. Zero height (z=0) corresponds to the bottom surface of the sample.

The base with its porous disc is then screwed to the confinement cylinder with the 9 radial sensors (see Figure 6-10 and Figure 6-11) and is sealed with an O-ring.

Table 6-14 Sensor locations in the mini-model

Height Z (mm)	Sensors	Angular position (°)	Penetration into sample (mm)
20	HR1/T1	0	40
	PT1	0	0
40	HR2/T2	72	70
	PT2	90	0
60	HR3/T3	144	100
	PT3	180	0
80	HR4/T4	216	70
	PT4	270	0
100	HR5/T5	288	40

Figure 6-10 Confinement cylinder set-up, radial sensor installation

6.7.5 Materials emplacement

The materials are placed in the cell layer by layer, starting with a bed of pellets representing 70% of layer mass, and crushed bentonite (30% of layer mass) is then poured over the pellets, with care taken to ensure that voids are left in order to avoid exceeding the target dry density value of 1.51g/cm^3 (see Figure 6-11).

Three layers are arranged in the cell in this way. The final sample height is slightly higher than 103 mm, which enables the final RH sensor, whose centreline is at h = 100 mm to be immersed.

Figure 6-11 illustrates the process used to produce sample MM1. The height of the sample is difficult to accurately control, which is why the voids are mainly in the peripheral areas and the centre is kept more compact to receive the piston.

The final image of Figure 6-11 shows the confinement cell complete with the piston in place.

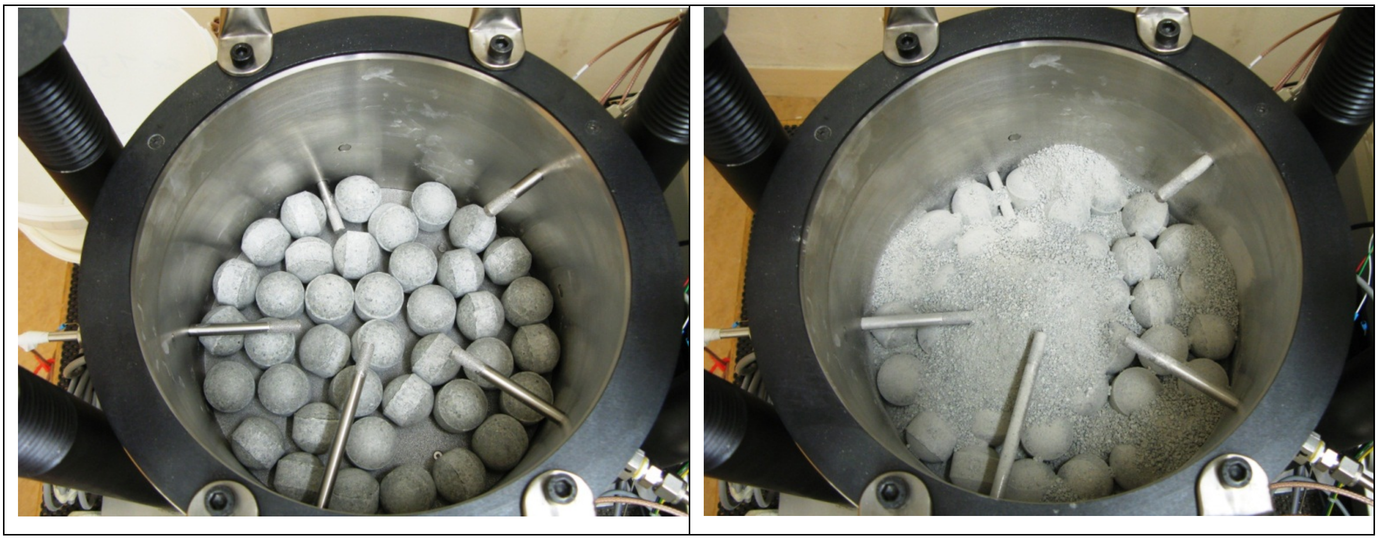


Figure 6-11 Emplacement of MM1 sample in the 240 mm cell

6.7.6 Cell closure

The final stage of cell assembly is the installation of the load cell, the retaining bar and the displacement sensor.

All the sensors are then connected to their respective signal conditioners. Once the measurements have been verified, the acquisition program is run, before connecting the hydration circuit to the base of the cell.

The sample height is once again checked. The height of the emplaced sample is slightly lower than the target height, which will require pressure in the sample to be released one or more times at the start of the swelling process. These low amplitude pressure release operations adjust the sample height to achieve the target value. Pressure is released by unscrewing the flange screws on the retaining bar, while monitoring variation in height with the displacement sensor.

Figure 6-12 shows the mini-model ready for the experiment.

6.8 Characteristics of sample MM1

The materials used for the mini-model sample come from the FSS production run. They are strictly identical to the materials used for the model and are part of the LECBA reference batch.

32 mm pellets batch: RE14-002.

Crushed pellets batch: RE14-003.

The initial characteristics of sample MM1 are given in Table 6-15.

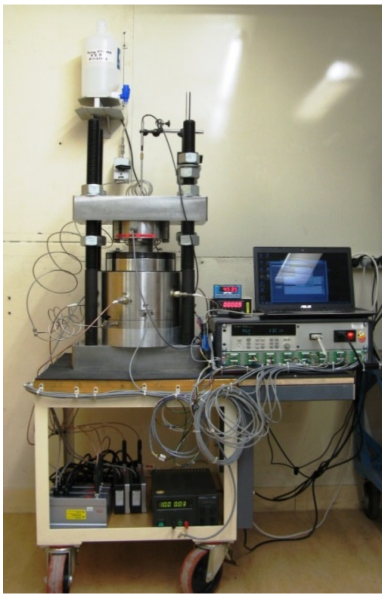


Figure 6-12 Overview of the REM mini-model

Table 6-15 Initial characteristics of sample MM1

	Pellets		**Crushed bentonite**	
Water content W (%)	4.09		4.55	
Mass (g)	**Wet**	**Dry**	**Wet**	**Dry**
Layer 1 (39 pellets)	1661.00	1595.73	682.90	653.18
Layer 2 (38 pellets)	1610.50	1547.22	716.10	684.94
Layer 3 (39 pellets)	1647.70	1582.96	713.40	682.35
Layer 4 (8 pellets)	339.90	326.54	163.90	156.77
Total	5259.10	**5052.45**	2276.30	**2177.24**
Total sample mass (g)	7535.40			
Total dry mass (g)	**7229.69**			
% pellets	69.88			
% crushed bentonite	30.12			
Sample height (mm)	103.60			
Cell cross-section (cm^2)				
Initial volume (cm^3)				
Apparent density (g/cm^3)				
Dry density (g/m^3)				
Porosity (%)				
Degree of saturation (%)				

6.9 Conclusion from swelling tests

The full set of results is summarised in Table 6-16. **The table also reports test results from the same mixture obtained in the Bentogaz programme and the FSS test**.

The swelling curve for the FSS test in the 240 mm cell is shown in Figure 6-13.

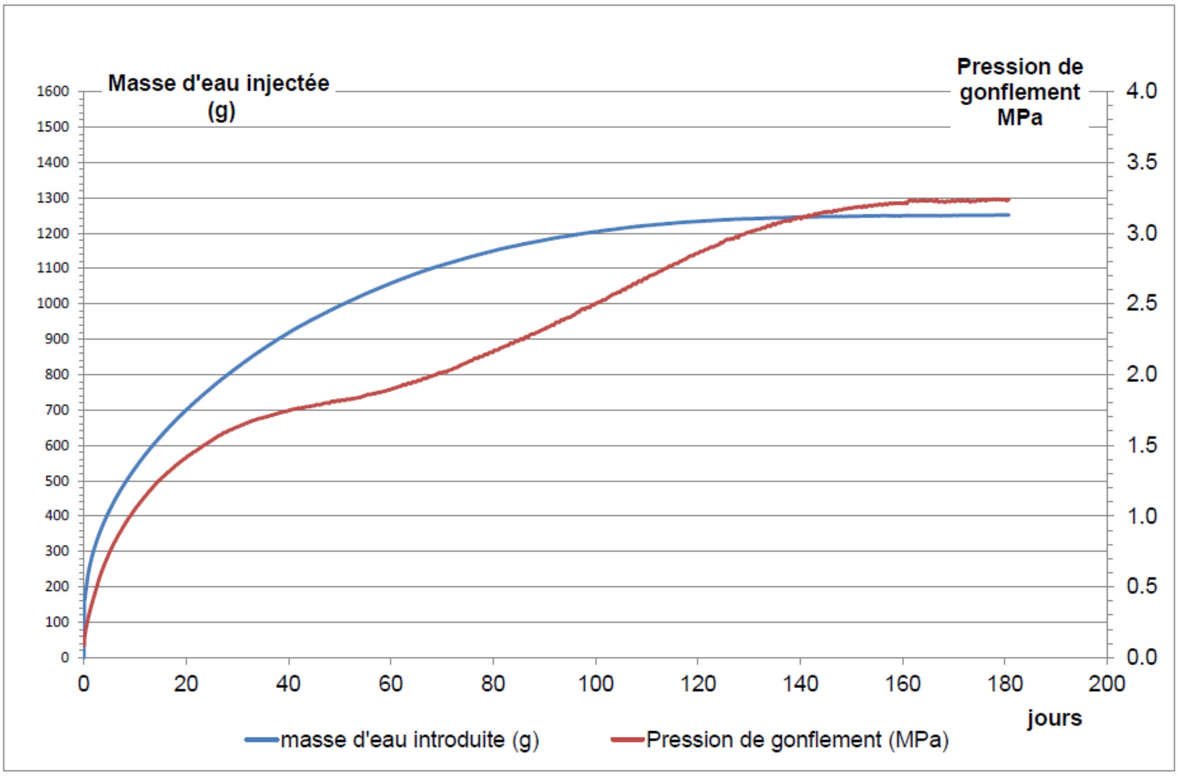


Figure 6-13 *Hydration kinetics and swelling of sample FSS-gonf-03*

Each result is presented by hydration water type: synthetic water, FTP1010, pH 13.5 and low pH (10.8).

The swelling pressure values are reported in Figure 6-14.

Although not all the tests have been completed, it can nonetheless be stated that for all cell sizes tested, the mixture saturates and re-homogenises perfectly.

In terms of water chemistry, the use of high pH concrete water (pH 13.5) significantly reduces swelling pressure. However, low pH concrete water (pH 10.8 used in our tests) has almost no negative influence on swelling pressure. Resaturation with water from the FTP borehole leads to no difference in swelling pressure compared with reconstituted water.

With the exception of the 57 mm cell test, in which the initial volume is difficult to manage, no effect of scale was observed and swelling pressure remains of the same order of magnitude. It should be noted that the final dry densities for the FSS in the 240 mm cell were lower than the target value of 1.50, which led de facto to a lower swelling pressure. The failure to achieve this dry density target value is due to the need to create artificial voids in the sample, while keeping it homogenous, in seeking to achieve this density value. The sample surface is therefore uneven, making it very difficult to measure height. This, together with the weight of the piston and various parts of the cell, it is difficult to comply with a given height. Comparison of all the results nonetheless highlights good overall coherence. By extrapolating the swelling pressure for a density of 1.50 g/cm^3, LECBA obtains a swelling pressure value of 3.88 MPa.

Table 6-16 Summary of the tests performed with four different hydration water compositions

	Synthetic on-site water						**Water from FTP borehole**	**Concrete water pH 13.5**				**Low pH concrete water**	
Test programme	REM	REM	Bentogaz	REM	FSS	FSS	REM	REM	REM	REM	REM	REM	REM
Cell diameter (mm)	57	57	120	120	240	240	120	57	57	120	120.5	57	120
Sample no.	3446u	3493m	Bento-1-2	3495m	FSS-1	FSS-2	3496m	3444m	3494m	3467m	3482m	3445u	3466m
Final height (mm)	32.80*	56.93	67.70*	67.36	68.56	67.23	67.31	32.89	32.63	67.66	67.02***	32.88	67.65
Final dry density (g/cm^3)	1.504	1.517	1.515**	*1.513*	1.451	1.475	*1.511*	1.508	1.509	1.528	1.512***	1.509	1.511
Swelling pressure (MPa)	5.0	5.0	3.9*	*4.10* *In progress*	2.39	3.24	*4.06* *In progress*	3.56	3.68	4.05	3.60	4.63	4.39

* not measured

** test performed with the same materials under the Bentogaz programme, but hydrated via both sides with occluded air removed via a filter in the centre of the sample.

*** permeability test in progress, measurement to be taken on removal

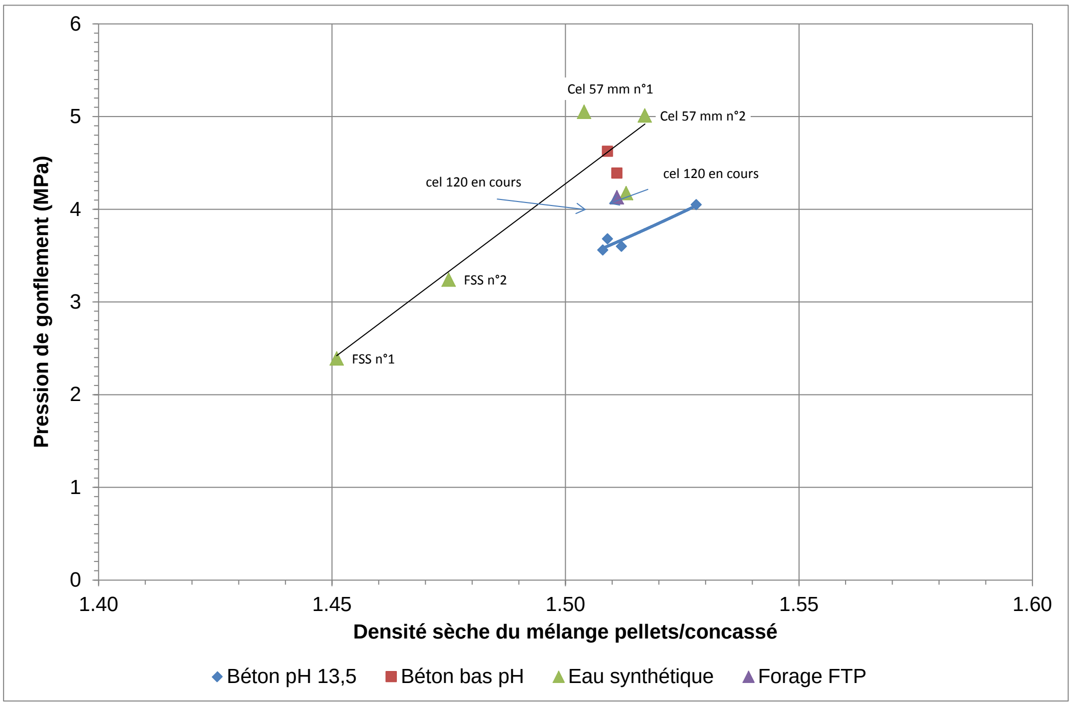


Figure 6-14 *Summary of all swelling tests with the FSS-REM mixture, hydrated with different types of water*

7. Conclusion and outlook

The REM experiment is complementary to the FSS experiment and should make it possible to study the feasibility of resaturating the mixture used in FSS and analyse the behaviour of an admixture of 32 mm pellets and crushed pellets (powder) during resaturation at a scale that is difficult to achieve with standard laboratory equipment (decimetric scale at most).

The REM experiment has two parts: the construction and operation of a metric-scale model, and the performance of in-laboratory hydro-mechanical tests (centimetric and decimetric scale).

The metric-scale model was installed and hydration was initiated in September 2014. All the operations took place without incident. The measurements taken since the start of hydration also show that the test has operated correctly. The total pressure measurements are currently very low or zero, which is consistent with the recorded relative humidity values which show saturation conditions that are still very low. Above 300 mm, the relative humidity sensors react very little or not at all. The whole experimental set-up is operational.

The LECBA test results give an initial idea of the phenomenology and resaturation kinetics affecting the pellet/bentonite mixture for various sample sizes from 57 mm to 240 mm. The mixture re-saturates and re-homogenises very well. Different types of water were used to test their influence. No change in swelling pressure was noted with the use of on-site water, compared with reconstituted water. However, the use of high pH concrete water (pH 13.5) significantly reduces swelling pressure. No effect of scale was identified.

At the time of writing, a test similar to the REM model, but in a 240 mm cell has just begun. This test should generate preliminary results and help to interpret the measurements obtained in the REM experiment.

8. Bibliography

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