Large scale Vertical SEALing (VSEAL) test: Impact of gas migration on bentonite based vertical seals

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Abstract. The Institute for Radiological protection and Nuclear Safety (IRSN) has launched the VSEAL project to investigate the impact of gas migration on the long-term performance of bentonite based vertical sealing systems. This project relies on in-situ experiments emplaced in IRSN´s Underground Research Laboratory (URL) in Tournemire (South France) and small-scale tests conducted in laboratory. The studied material is mixture of MX80 bentonite high density pellets and powder which are being evaluated as possible sealing materials in deep geological repositories. The test is still in progress, but the collected set of data provides already valuable information of the hydro mechanical behavior of Vertical sealing systems during hydration.

1 Introduction

Vertical Sealing Systems (VSS) of a deep geological disposal, composed of bentonite-based materials, are one of the key elements for the safety of a facility such as the Cigéo project since they would constitute the main potential pathway between the nuclear wastes and the biosphere. Understanding migration processes of gas through these sealing systems is of great importance for performance assessments. If the gas production rate exceeds the dissolved gas diffusion rate in the pore water of the host rock and the engineered barriers, a gas phase will form and accumulate until the associated pressure build-up becomes sufficiently large to migrate through the surrounding material (host rock and/or engineered barrier systems) [1][2].

The transport of gases in clay-based buffer / sealing systems has been the subject of different international research programs during the last decades. In bentonite, this process is controlled by the saturation history of the material [3] [4] [5]. The French ‘Vertical Sealing Systems’ (VSS, Cigeo) will undergo complex hydration scenarios: fast hydration from the upper surface by water from the Calcareous Oxfordian formation-water pressure is expected to reach ~4 MPa- and slower hydration in the lateral direction. These distinct hydrations will induce gas entrapment with time at the bottom of the seal, which will also be affected by gas generated by long-term metallic corrosion processes [6]. In this context, the Institute for Radiological protection and Nuclear Safety (IRSN) has launched Vertical SEALing (VSEAL) project to investigate the impact of gas migration on the long-term performance of bentonite based vertical sealing systems. This project relies on two in-situ experiments (VSEAL1 and 2) emplaced in IRSN´s Underground Research Laboratory (URL) in Tournemire (South France) and small-scale tests conducted in laboratory. The VSEAL in situ experiments aim to (i) investigate the impact of gas migration during saturation of the bentonite vertical seal, (ii) study gas migration processes through the saturated bentonite core. The experiments were equipped with several wired and wireless sensors at the bentonite/rock interface and within the vertical seal. In parallel, mock-up test was designed and carried out in the laboratory at a scale of 1/10 of the large scale VSEAL in situ experiments and at a scale of 1/100 of VSS. The cell allows applying hydraulic and gas loadings, both asymmetric. This paper presents a description of the design, installation and first hydration results of the first VSEAL in situ test (VSEAL 1) together with hydration result of the 1/10 small scale test.

2 Description of VSEAL experiment

The VSEAL experimental program was launched to study the impact of gas migration on the long-term performance of vertical sealing systems. The VSEAL Project relies on two in situ experiments at a scale of 1/10 of the VSS (Fig. 1) conducted in IRSN’s Tournemire URL, located in a Mesozoic sedimentary basin on the western edge of the French Causses (southern part of France). These experiments aim at studying the vertical barrier’s asymmetric hydration process and its consequences on gas migration at different hydraulic states.

Installation and drilling are based on the previous experience obtained from the SEALEX experiments [7]. Each experiment consists of a bentonite- based core (with a length of 3.5 m) mechanically confined at both ends, which represents a generic seal mock-up (1/10 VSS), except for the artificial saturation system.

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The first in situ test VSEAL1 is a reference test, used to observe bentonite re-saturation without gas perturbation. However, a gas testing phase is foreseen after reaching full saturation. For the second in situ test VSEAL2, gas will be injected from the bottom surface during the re-saturation phase to mimic the bottom gas pressure increase on the upper saturated layer of the VSS under in situ conditions.

For each VSEAL test multiple pore pressure, total pressure, Relative Humidity (RH) sensors are installed within the bentonite core and at the bentonite/rock interface to follow swelling pressure evolution and water saturation. In order to avoid potential flow paths along cables and sensors within the bentonite core, wireless sensors have been preferred to classical wired sensors. The installation phase of VSEAL1 including the drilling phase was undertaken from September 2019 to August 2021. The artificial hydration phase was launched in October 2021 and is currently on going. The installation of VSEAL 2 is foreseen in early 2023.

2.1 Test design and geometry

The general layout of VSEAL1 in-situ experiment is based on a swelling clay core composed of mixture MX80 bentonite pellets and powder (80/20 in dry mass) confined between two containers (lids) (Fig. 1). These elements are inserted in a vertical borehole excavated in Tournemire URL argillite. Borehole diameter was 1.005 m while the maximum reached depth was 9.6 m. The bentonite core was built between the depth of 5.72 m and 9.22 m, underneath the damaged zone (EDZ) that is present around the gallery drift. The shaft walls and the bentonite core were provided by several sensors to follow the Hydro-Mechanical (HM) performance. The water is injected from the top surface by means of injection lines connected to the top lid which will slowly saturate the upper part of the bentonite core. After reaching full saturation, gas will be injected from the bottom surface to observe the perturbation induced by gas. This will be done thanks to an inclined borehole, intersecting the main borehole at its bottom. Additional boreholes were drilled to extract the cables of the instrumentation installed at the rock/clay core.

2.2 Material and test's components

The investigated material is a mixture of pellets and powder of MX80 bentonite (Wyoming, USA) with a proportion of 80 pellets/20 powder in dry mass prepared at a dry density, ρ_d=1.49 Mg/m^3 [8]. Pellets were produced by compacting bentonite powder instantaneously into a mold of 32 mm diameter and 32 mm high at a dry density ρ_d = 2.12 Mg/m^3. Powder is produced by crushing pellets.

The VSEAL1 confinement system is constituted of a bottom and top lid, a confinement tube and a closure plate (Fig. 2). The bottom lid rests on the bottom of the shaft, providing gas and water tightness as well as mechanical support to the bentonite core on top of it. It has a side opening with a passthrough plate with fittings to allow the passthrough of gas injection lines from the inclined borehole to the injection points and the passthrough of cables from the sensors in the lid to the gallery. The lid is filled up almost to the top with resin to enhance the gas tightness and the mechanical strength of the lid.

The top lid rests on the top face of the bentonite core, providing gas and water tightness to the bentonite core, as well as mechanical confinement (Fig. 2). The top lid has the same mechanical structure as the bottom lid but with a few differences in the lower plate: it a chamfer to house a soft rubber peripheral o-ring on top of the buffer. All cables and lines pass through holes drilled in the top plate. The lid is filled up almost to the top with the same resin used for the bottom lid (Fig. 2). The central confinement tube provides mechanical confinement by transmitting the vertical swelling force exerted by the bentonite on the top lid to the external closure plate. Finally, a circular plate on top of the tube closes the shaft. It consists of a 50 mm thick round plate measuring 1 800 mm in diameter with a central round opening measuring 600 mm in diameter to grant service access to the shaft (Fig. 1).

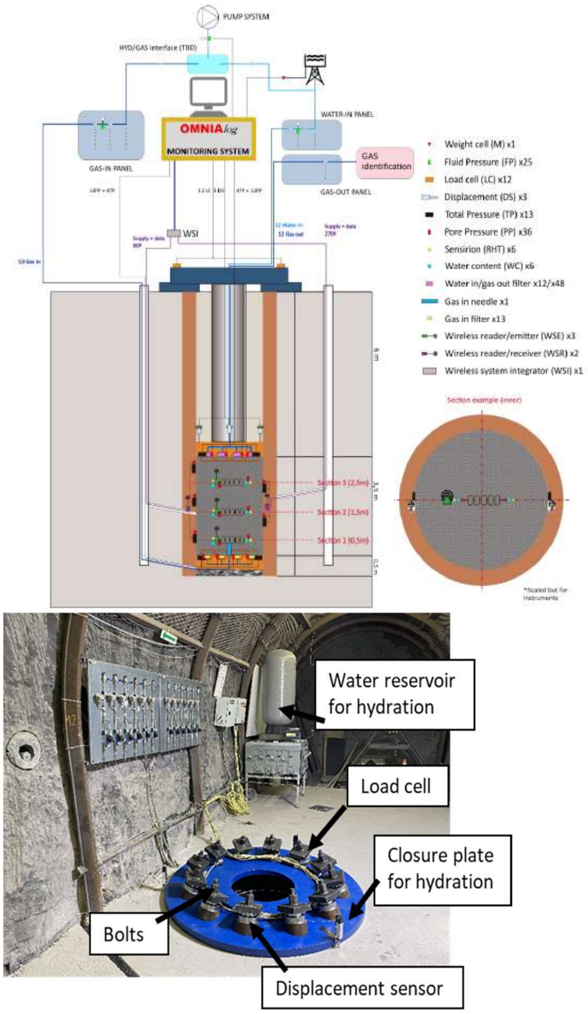

Fig. 1. General lay out (left) and picture (right) of the VSEAL 1 in situ test.

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The main function of hydration is to ensure an inflow of water enabling saturation of the core from the top side during the testing period (10-15 years), without compromising the global tightness of the system. The gas injection system allows gas inflow at the bottom of the bentonite core and gas outflow at the top of the bentonite core. The hydration and gas injection systems are embedded into the top and bottom lid.

Filters are installed in the top and bottom lids. They are composed of a sintered porous metal. The water filters have a small pore size (40 µm) to prevent bentonite intrusion and ensure an easy water injection. The filters used for gas injection prevents water transfer (pore size of 0.2 micron) and avoid any water bypass.

In term of instrumentation, a total of 76 sensors were installed in VSEAL 1 in situ test. Eighteen wireless sensors were installed within the bentonite-based core to monitor pore pressure (6 sensors), relative humidity (6 sensors) and water content (6 sensors). The bentonite sensors are distributed in three sections located at different depth. The instrumented sections have been deployed so to obtain a homogenous sensing field.

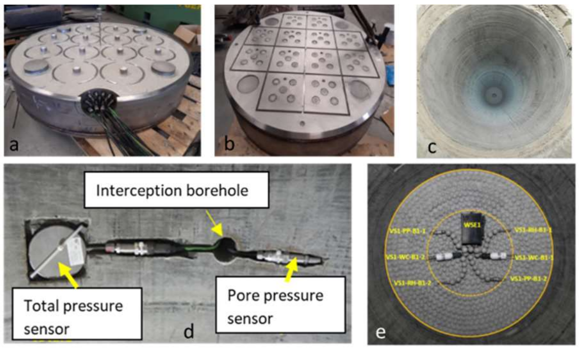

Fig. 2. Key components of the VSEAL 1 experiment: a/ Bottom lid with gas injection system; b/ Top lid with water injection system; c/ The borehole; d/ Rock sensor section: total pressure and pore pressure sensors inserted into slots mechanized in the rock interface; e/ Arrangement of sensors in layer 10 for instrumented set up installed at 8.9m depth.

The installation of VSEAL 1 started on September 2020, one year after the boreholes drilling. The main installation operation consisted into the building of the bentonite core with a length of 3.5 m (1/10 VSS) at a target dry density of 1.49 Mg/m^3. A special preparation protocol, consisting in placing the mixture layer by layer, was adopted to minimize initial structural heterogeneities as suggested by [7].

3 Description of 1/10 mock-up of VSEAL in situ test

The layout of the small-scale infiltration/gas injection cell (mock-up test cell) is presented in Fig. 3. The dimensions correspond to 1/100 of VSS at real repository conditions (100 mm in diameter and 350 mm in height). The mock-up test is carried out under constant volume conditions. Liquid pressure can be applied radially to simulate water coming from the clay formation, and axially to simulate water coming from the calcareous formation.

The designed experiment consists of several parts: i) the mechanical part that hosts the soil sample; ii) the hydraulic part that enables water and gas injections iii) the measurements part with all the sensors (total pressure, force transducer, relative humidity sensor) and the acquisition system (data logger and computer).
The testing cell (100 mm in diameter and 350 mm high) is composed of four transparent cylinders, made of Perspex to visualize processes occurring at the interface during the hydration and gas injection phases.

The mock-up cell is designed in such a way that fluid injection (water or gas) are allowed independently from top, bottom and lateral sides to mimic real saturation conditions (a rapid increase of water pressure on top under controlled lateral hydraulic boundary conditions and gas injection on bottom). The mock-up cell is equipped with Six total pressure sensors, three water pressure and RH sensors.

The sample was prepared directly into the cell following the layer-by-layer protocol as in VSEAL 1 in situ test.

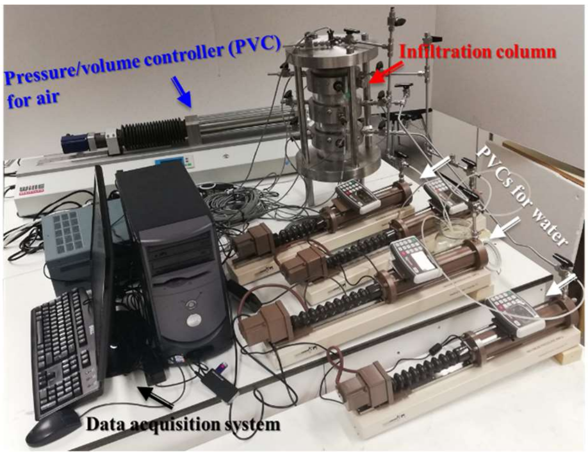

Fig. 3. General set up of VSEAL mock-up test.

4 Preliminary Results

For VSEAL 1 in situ test, the hydration phase (without water pressure) started by opening the water tank valves. One hydration started, the water volume increased rapidly and reached 30.5 l in few hours suggesting the existence of technological gaps and preferential flow paths where some water infiltration could have occurred.

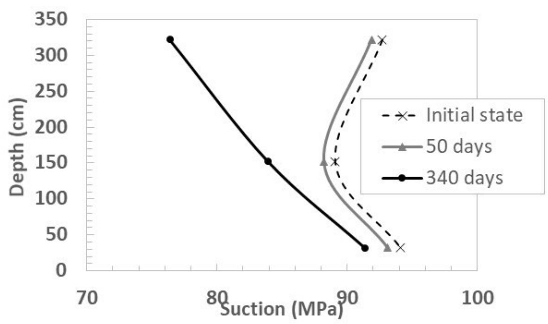

Fig. 4. Profiles of suction after 50 and 340 days of hydration measured at different depth of the clay core.

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The Six relative humidity sensors installed in the bentonite core at three sections located at 318, 198 and 28 cm respectively allowed to deduce suction profiles after 50 and 340 days (Fig. 4). Initial suction values range between 89 to 94 MPa. The overall evolution of the curves shows a slow decrease of suction due to the saturation progress with lower suction values at short distance from the top hydration source as time increases. A slight increase of relative humidity is also observed at at the central zone of the bentonite core. At this zone, hydration of the mixture is probably driven by vapor transfer from the hydrated zone (outer layers) to the dry center of the bentonite core. During hydration, both axial and radial swelling pressures are monitored using thirteen load cells. Fig. 5 shows mean axial swelling pressures at top and bottom (at 350 cm) lids and radial swelling pressures measured at different depths. After 100 days, the measured values ranged between 0.1 to 1.96 bar, the highest values being registered at the top lid where hydration takes place. After 340 days, an increase in swelling pressure is registered at all locations except at the top lid where a decrease in the mean value is measured. This decrease is due to sensors misfunctioning. At the bottom lid the measured mean swelling pressure increased to a value of 1.75 bar after 340 days suggesting that some water infiltration could have occurred inducing some local swelling at the bottom layer of the bentonite mixture.

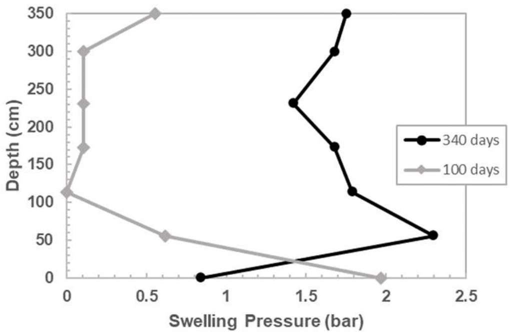

Fig. 5. Profiles of swelling pressure after 100 and 340 days of hydration measured at different depth of the clay core.

Two hydration methods were adopter to saturate the mock-up sample. Initially sample hydration was performed using a vapour equilibrium technique. The objective here is to recover the initial suction of the material measured before the mixture preparation. After 101 days, a water flow rate of 0.166mm^3/s was imposed on the top side to ensure the axial fast hydration of the mixture. After almost 116 days water pressure reached 4 MPa at the top. A lower flow rate was imposed at the lateral boundaries to simulate the delayed radial hydration of VSS.

Variations with time of total suction measured at different distances from the axial hydration front are displayed in Fig.6. At 101 days, once axial hydration started, total suction decreased rapidly at the top sensor and reached zero after 160 days. Total suction at the middle and bottom sensors started to increase once lateral injection started at 116 days. It reached 0 MPa after almost 250 days.

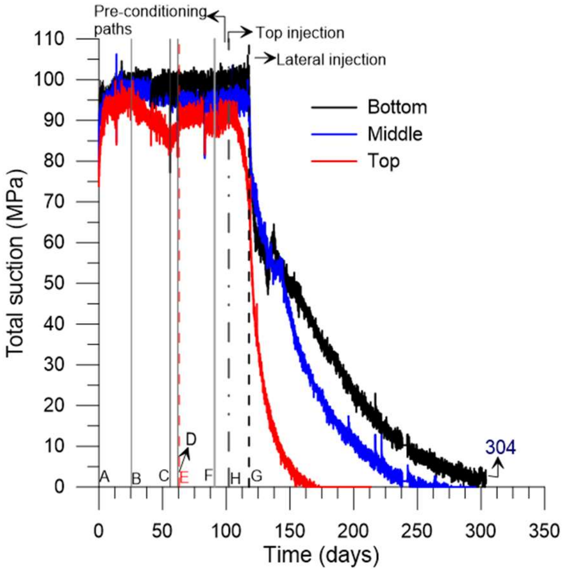

Fig. 6. Evolution of total suction at different points within the mixture.

5 Conclusion

In the framework of the VSEAL project, a large-scale in situ vertical sealing test, VSEAL1 have been installed in the Tournemire URL to investigate the impact of gas migration on the long-term performance of bentonite based vertical sealing systems and a 1/10 mock-up test was conducted at the laboratory. For both tests, a specific protocol was adopted to construct the bentonite seal in order to minimise as much as possible initial structural heterogeneities induced by the installation process and to reach the target dry density of 1.49 Mg/m^3. VSEAL 1 is the unique in situ sealing test with a well-known initial structural distribution of the pellets and the powder within the tested mixture. The knowledge of the test initial structural distribution is valuable for analysis of the results, especially during the gas injection phase and for future numerical modelling. The small scale 1/100 VSS allowed to apply the real boundary condition (4MPa water pressure on the top) of VSS which was not possible for VSEAL in situ test due to the low in situ stress at Tournemire URL (2~4 MPa). The preliminary results of both tests allows to have insight on the saturation kinetics of the testes mixture. Future analysis of the results during the hydration phase in terms of injected water volume, relative humidity, water content and swelling pressures (axial and radial) will allow to understand the hydromechanical behavior of such sealing system.

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