D5.1.1

SPECIFICATIONS FOR BEACON WP5: TESTING, VERIFICATION AND VALIDATION OF MODELS STEP 1- VERIFICATION CASES

DELIVERABLE D5.1.1
Report

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Content

1. Main objectives

The overall objective of the project is to evaluate the performance of an inhomogeneous bentonite barrier. Inhomogeneities are mainly due to initial distribution of dry density in link with technological voids, the simultaneous use of several forms of bentonite (for example, blocks and pellets), the setting up in granular form... Some external solicitations could also lead to heterogeneous evolution of these bentonite based engineered barriers such as non-uniform water flow or anisotropic stress field.

Understanding of swelling clay properties and fundamental processes that lead to its homogenization as well as improvement of capabilities for numerical modelling are essential for the assessment of the hydromechanical evolution and the resulting performances of the engineered barriers

The purpose of WP5 is to contribute to improvement of numerical models proposing several tests from small size tests (centimeters) to real scale experiments (several meters). The idea is to start with simple tests and progressively increase the complexity in terms of scale, coupled processes and initial/boundary conditions.

The present specifications describe step 1 of WP5 program. This first step is dedicated to verification and validation of models. The models used will be confronted to small scale experiments to validate the correctness of their implementation or to identify some limits considering HM processes involved including swelling pressure development in presence of heterogeneities.

The strategy proposed is to start with tests at laboratory scale where homogenization processes have been highlighted and which will constitute elementary bricks to tackle bentonite evolution modelling at a larger scale.

Three tests are proposed pick up from WP2 inventory work:

- swelling pressure tests for compacted plugs with free volume available – TEST B1.7 from Clay Technology AB, SKB
- Swelling pressure tests for pellets mixture – TEST B1.16 from CEA, Andra
- Swelling pressure tests for block and pellets structure – TEST B1.6 from Posiva

The choices about the selected tests will be discussed during WP3/WP5 meeting in January 2018.

2. General presentation of the proposed tests

2.1 TEST 1a - swelling pressure tests for compacted plugs with free volume available

The tests for the step 1a of WP5 are part of a SKB project set up to increase the knowledge about of homogenization processes in bentonite (Dueck and al, 2011 and 2014). The tests have been performed by Clay technology group and consist in one dimensional axial swelling tests.

The test geometry is presented in Figure 2-1. The swelling is axial in a device with constant radius and limited height. Variation of the height of the gap is controlled. The friction is minimized by use of mineral-oil based lubricant on relevant surfaces.

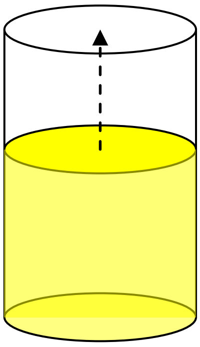

Figure 2-1 Illustration of the geometry of the test types carried out.

During the tests, axial and radial stresses are measured. Initial characterization concerns water content, dry density, void ratio, bulk density, water saturation.

At the end of the test, profile of dry density, void ratio and water content are available.

2.2 TEST 1b - Swelling pressure tests for Pellets mixture

In this test Swelling pressure tests were carried out using constant volume cells of three different diameters (ϕ57 mm, ϕ120 mm, ϕ240 mm) and different heights, resulting in different sample volumes (see Figure 2-2). The objectives of the experimental programme were to study the swelling pressure of a MX80 pellet/crushed pellet mixture in relation with Full scale demonstrator (FSS). Pellets are roughly spherical with a diameter of 32 mm.

Figure 2-2 Illustration of the 240mm diameter cell at installation

Total pressure, relative humidity evolution and water volume injected are monitor during saturation phase. Total pressure and RH are measured radially at 5 locations on the height, axial pressure is measured too. Post mortem analysis will be available for the 240mm diameter cell.

2.3 TEST 1c - Swelling pressure tests for block and pellets structure

In this test, a cylindrical cell is used to maintain the system at constant volume. Pellets are placed on the top of a MX-80 bentonite block (see Figure 2-3). The initial difference of density introduced will evolve during water saturation. The objective of the test is to follow the evolution of a block-pellets system which exists in KBS3v design. The interface between the host rock and the bentonite blocks surrounding the canister are filled with pellets, introducing initial heterogeneity in dry density.

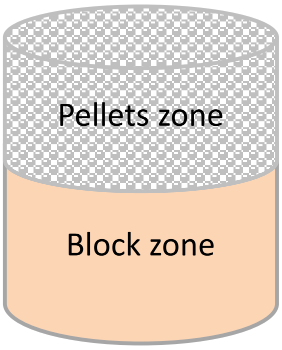

Figure 2-3 Illustration of the initial assemblage of pellets/block

Swelling pressure is measured during the test at two different levels radially and axially. Post mortem analysis gives the distribution of both final water content and dry density profiles.

3. Test 1a– Swelling pressure of bentonite plug with free volume

3.1 TEST 1a01- Swelling pressure of bentonite plug at constant volume followed with an increase of volume

This test includes two stages:

First part, correspond to a classical swelling pressure test at constant volume where both radial and axial stresses are measure. This first part is design for calibration of the tools.

Second part, following the test at constant volume, an increase of accessible volume for bentonite swelling is available and water is introduced in the cell. Variations of stress are followed till stabilization was obtained. Post mortem analysis gives access to water content profile and density distribution along the sample.

The test is referenced as A01-13 in SKB Report TR-14-25.

3.1.1 Equipment

The design of the test is shown in Figure 3-1. The device used for the axial swelling consists of a steel ring surrounding the specimen having filters on both sides. Two pistons are placed vertically, in the axial direction, above and below the specimen.

The bottom and top plates and the steel ring are bolted together to keep the volume constant. Two load cells are placed in the vertical and radial direction, respectively. The load cells are placed between a fixed plate and a movable piston where the small deformation required by the load cell is admitted. During the entire course of the tests the forces are measured by the load cells, which are calibrated prior to and checked after each test. By dividing the measured force by the surface area the total stress can be calculated.

3.1.2 Preparation of specimen

Cylindrical specimens are prepared by compaction of powder to a certain density. The dimension of the specimens used for the axial type of swelling is a diameter of 50 mm and a height of 20 mm.

3.1.3 Test procedure

The tests consist of two phases; the water saturation phase and the swelling phase. After mounting the specimen in the devices shown in Figure 3-1, de-ionized water is applied to the filters after air evacuation of the filters and tubes.

The specimens have free access to water during the water saturation. When only small changes in swelling pressure with time are noticed the water is evacuated from the filters and tubes and the second phase i.e. the swelling starts.

The upper piston is moved upwards and fixed with spacers admitting a certain volume for the swelling. After evacuation of air, the empty space and the upper filter are filled with water.

During saturation and homogenisation water was provided as stagnant water from above only, with a water pressure of approximately 2 kPa

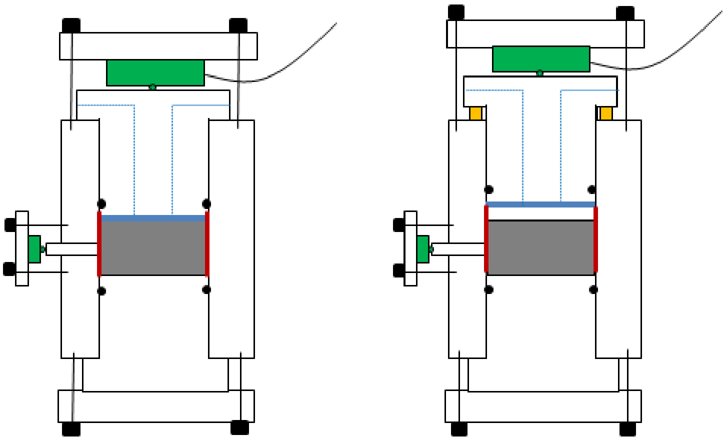

Figure 3-1 ***Set-up used for the axial swelling tests. The red lines represent the lubricated surfaces and the blue lines represent filters and water supply. The radial pressure transducer is placed 10 mm from the bottom end of the specimen***

After finished swelling and homogenization, i.e. when no or negligibly small changes are noticed in the swelling pressure with time, the specimen is dismantled and cut in slices for determination of the water content and density distribution in the direction of swelling.

3.1.4 Material

The material used in the test series is MX-80 bentonite powder. The powder is delivered with a water content of about 13%. The bentonite powder is compacted to specimen with intended density in compaction devices before installation.

For the determination of void ratio and degree of saturation the particle density ρ_s = 2780 kg/m^3 and water density ρ_w = 1000 kg/m^3 are been used.

3.1.5 Results test 1a01

The test results are presented with w, ρ_d and S_r as a function of the specimen height i.e. as distribution in the direction of swelling. The measured stresses are also shown and compared with a model of swelling pressure presented by Börgesson et al. (1995). The swelling ratio s is calculated according to Equation 3-1 where V_i, V_f, ρ_{di} and ρ_{df} are the initial volume, final volume, initial dry density and final dry density, respectively.

$$s = \frac{\Delta V}{V_i} = \frac{V_f}{V_i} - 1 = \frac{\rho_{di}}{\rho_{df}} - 1$$

(Eq 3-1)

The swelling ratio is also given as swelling after saturation (given in brackets in the tables) calculated from height before and after the swelling. The difference between the values is mainly caused by a small scatter and uncertainty in the initial density, swelling between the saturation phase and swelling phase and swelling at dismantling. In order to obtain a final dry density level which is consistent with the experimental data, it is therefore recommended that the initial dry density is adjusted to: $\rho_{di}(1+S_h)/(1+S_d)$, where S_h and S_d, denote the swelling ratios based on heights and densities, respectively. For test 1a01 this means a dry density of 1655*1.145/1.162 = 1631 kg/m^3.

Table 3-1 initial, intermediate and final properties of the sample

TEST 1A01	Constant Radius (mm)	Height mm	Dry density kg/m³	Axial stress kPa	Radial stress kPa	Swelling ratio ρ_{di}/ρ_{df}-1 (%)
Initial	25	20	1655	0	0	0
Intermediate	25	20	1655	8 604	9 994	0
final	25	22.9	1425	2 566	3 240	16.2 (14.5)

In Figure 3-2, Figure 3-3 and Figure 3-4, the distribution of w, ρ_d and e measured after termination of the test are shown. Details values are given in Table 3-2

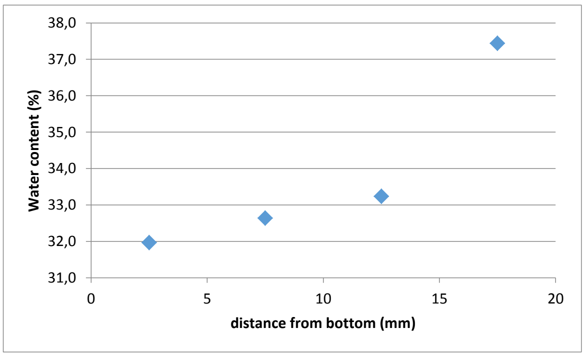

Figure 3-2 Distribution of water content over specimen height, from bottom end to surface

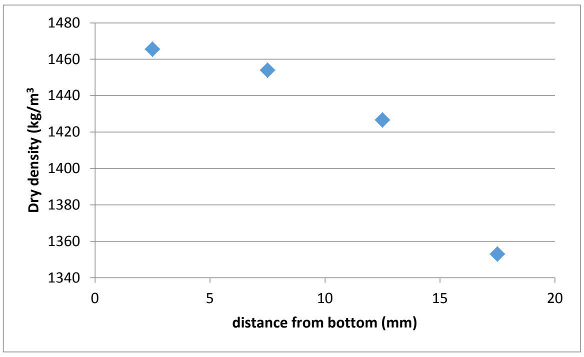

Figure 3-3 Distribution of dry density over specimen height, from bottom end to surface

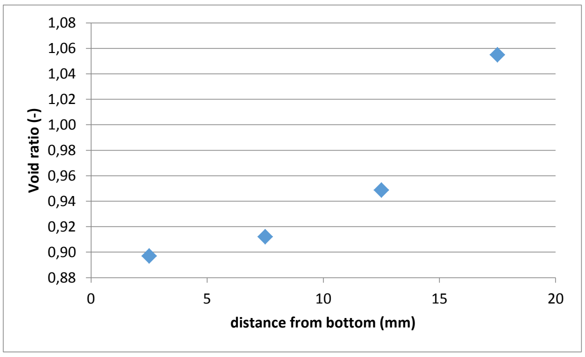

Figure 3-4 ***Distribution of void ratio over specimen height, from bottom end to surface***

The time evolution of the swelling pressure is shown in Figure 3-5. The two phases of the test are well defined: First swelling at constant volume and after increase of volume by about 14.5%. A difference between radial and axial stress persists throughout the test in both phases.

Figure 3-5 ***Time evolution of the swelling pressure***

Table 3-2 ***Final state at 4 locations in terms of dry density, water content and void ratio***

Final state								
from bottom mm	thickness mm	ρ_s kg/m^3	ρ_w kg/m^3	w %	ρ kg/m^3	ρ_d kg/m^3	e	S_r %
2,5	5	2780	1000	32,0	1934	1466	0,90	99
7,5	5	2780	1000	32,6	1928	1454	0,91	99
12,5	5	2780	1000	33,2	1901	1427	0,95	97
17,5	5	2780	1000	37,4	1859	1353	1,05	99
average				33,8	1906	1425	0,95	99

In Figure 3-6 the final swelling pressure is plotted as a function of dry density. The radially measured swelling pressure and the axial swelling pressure are plotted with the average dry density and for axial with an error bar corresponding to the maximum and minimum dry density over the specimen height. In addition, results from previous tests are shown.

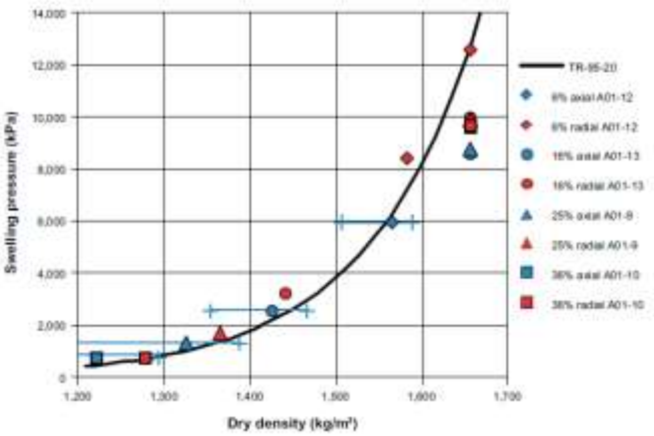

Figure 3-6 Measured axial and radial stresses (A01-13 on graph) after first saturation and after the second stage of the test. Results from other tests from (Dueck et al. 2011, and 2014).

3.1.6 Requested outputs

Requested outputs for each test are of two different natures:

- Brief description of the model, specific part of the model to deal with homogenization of the bentonite (in particular, the choice to represent the added volume at the beginning of the second step of the test), which parameter are used and how is calibrated the model for this specific test.
- Results from the test at several locations and for a predefined list of time. To facilitate the comparison of results, an Excel form will be provided to be filled by the participants.

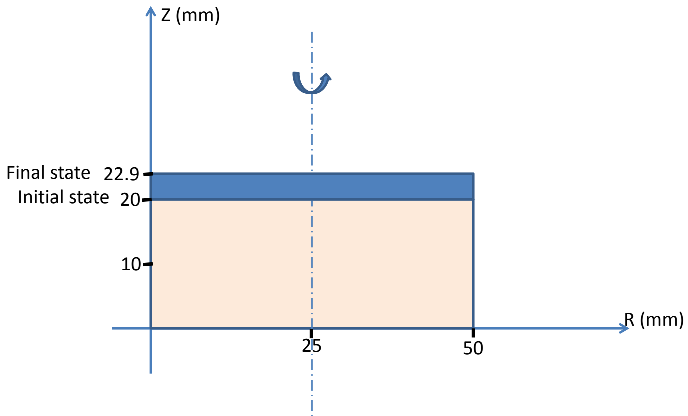

Figure 3-7 Schematic 2D-representation of the bentonite plug

The requested outputs from this test are:

- Total axial stress function of time at R=25mm
- Total radial stress function of time at z=5, z=10, z=15 mm
- void ratio and water content function of time at (R=25mm, z=5, 10, 15, 20, (23)mm)
- Void ratio and water content function of time at (R=10mm, z=5, 10, 15, 20, (23)mm)

- Void ratio and water content profile at R=10, R=25, z=5, z=10, z=15, 20, (23) mm for several times including t=4h, 67h, 340h, 375h, 520h, 720h.
- Total axial pressure and total radial stress profile at R=10, R=25, z=5, z=10, z=15, 20, (23) mm for several times including t=4h, 67h, 340h, 375h, 520h, 720h.
- Contour plots at different times including t=4h, 67h, 340h, 375h, 520h, 720h.
    - Void ratio and water content
    - Total axial stress and total radial stress

3.2 Test 1a02 – Swelling pressure of a bentonite plug in a cell with a free swelling volume

The test is referenced as HR-A1 in SKB Report TR-14-25.

3.2.1 Equipment

The device (Figure 3-8) consists of a steel ring surrounding the specimen. A movable piston is placed vertically, in the axial direction above the specimen. Radial pistons are placed in holes through the steel ring for measurement of radial forces. A steel filter is placed on the upper side of the sample

The bottom and top plates and the steel ring are bolted together to keep the volume constant. Load cells are placed in the vertical and radial directions. The load cells are placed between a fixed plate and the movable piston where the small deformation required by the load cell is admitted. During the entire course of the tests the forces are measured by the load cells which are calibrated prior to, and checked after, each test.

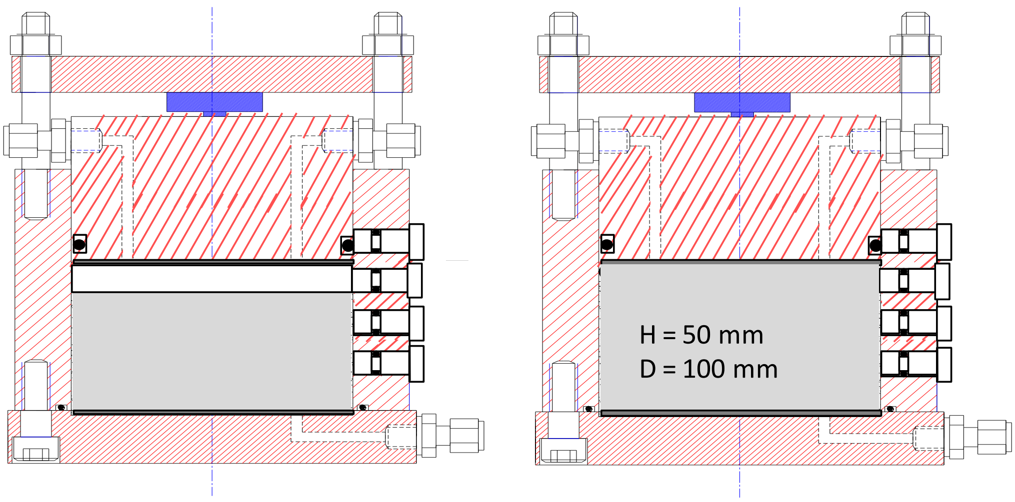

Figure 3-8 Set-up used for the axial swelling tests. Water is only supplied from a filter placed above the specimen

3.2.2 Preparation of specimens

The specimens are sawn and trimmed from larger blocks with the initial water content 24%. The initial height and diameter for the specimens are 40 mm and 100 mm, respectively.

For the determination of void ratio and degree of saturation the particle density ρ_s = 2780 kg/m^3 and water density ρ_w = 1000 kg/m^3 are been used.

3.2.3 Test procedure

The initial degree of saturation is very high (close to 100%) and for that reason the swelling started directly, i.e. no saturation took place in the test devices before the swelling phase. After preparation the specimens are mounted into the devices and de-ionized water is applied to the filters after air evacuation of the filters and tubes. After completed swelling and homogenization, i.e. when no or negligibly small changes were noticed in the measured swelling pressure, the specimens are dismantled and cut in slices for determination of water content and density distribution in the direction of swelling. Water was provided as stagnant water from above only, with a water pressure of approximately 2 kPa

3.2.4 Results test 1a02

The test results are presented with w, ρ_d and S_r as a function of the specimen height i.e. as distribution in the direction of swelling. The measured stresses are also shown and compared with a model of swelling pressure presented by Börgesson et al. (1995). The swelling ratio s is calculated according to Equation 3-1 where V_i, V_f, ρ_{di} and ρ_{df} are the initial volume, final volume, initial dry density and final dry density, respectively.

The swelling ratio is also given as swelling calculated from the height before and after the swelling (given in brackets in the table). The difference between the values is mainly caused by a small scatter and uncertainty in the initial density and swelling at dismantling. In order to obtain a final dry density level which is consistent with the experimental data, it is therefore recommended that the initial dry density is adjusted to: $\rho_{di}(1+S_h)/(1+S_d)$, where S_h and S_d, denote the swelling ratios based on heights and densities, respectively. For test 1a02 this means a dry density of 1666*1.26/1.32 = 1590 kg/m³

Table 3-3 Initial and final properties of the sample

	Initial w (%)	Initial ρ_d (kg/m³)	Constant Radius (mm)	Initial height (mm)	Final height (mm)	Swelling ratio ρ_{di}/ρ_{df}-1 (%)
TEST 1A02	23.7	1666	50	40	50	32 (26)

In Figure 3-9, Figure 3-10 and Figure 3-11, the distribution of w, ρ_d and e measured after termination of the test are shown.

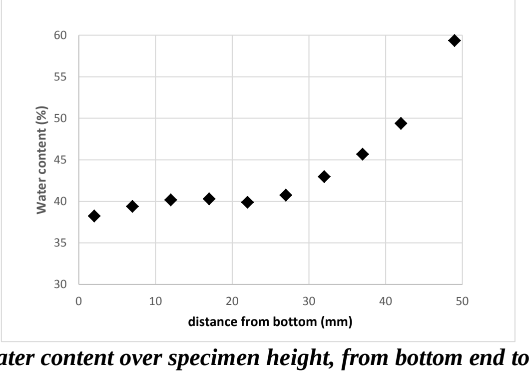

Figure 3-9 Distribution of water content over specimen height, from bottom end to surface

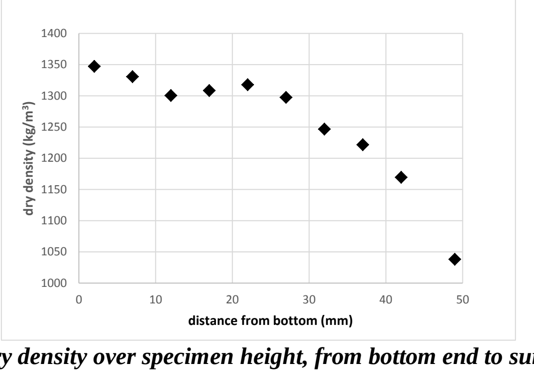

Figure 3-10 Distribution of dry density over specimen height, from bottom end to surface

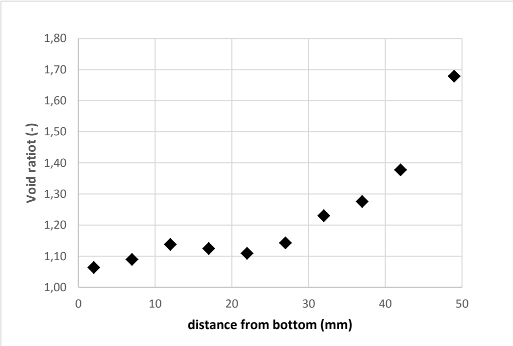

Figure 3-11 Distribution of void ratio over specimen height, from bottom end to surface

The time evolution of the swelling pressure is shown in Figure 3-12 for three radial locations and for axial direction.

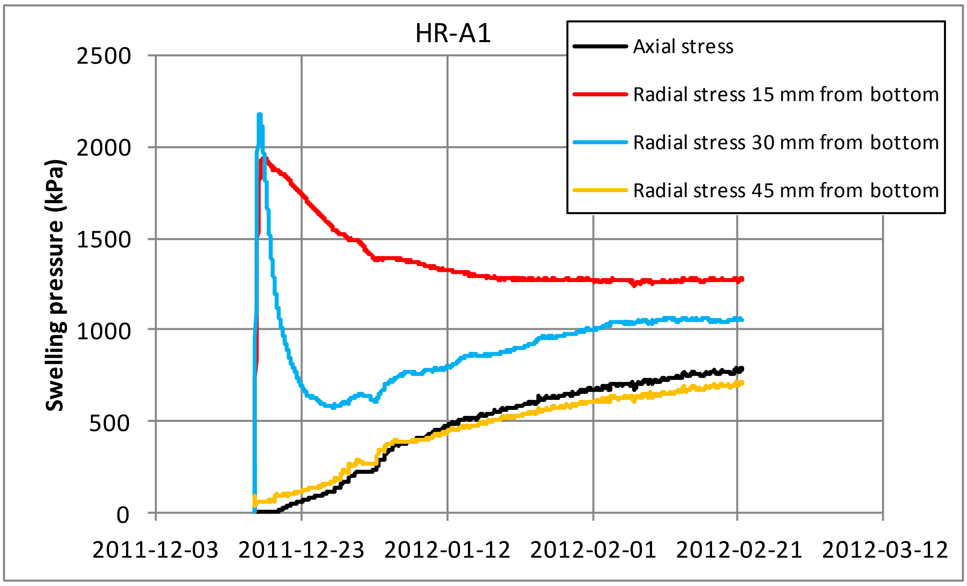

Figure 3-12 Time evolution of the swelling pressure

In Figure 3-13 the final swelling pressure is plotted as a function of dry density. The radially measured swelling pressures from test are plotted with the dry densities measured at the corresponding distances from the bottom surface. The axial swelling pressure from test is plotted with the average dry density and an error bar corresponding to the maximum and minimum dry density over the specimen height. In addition, results from the previous tests are shown.

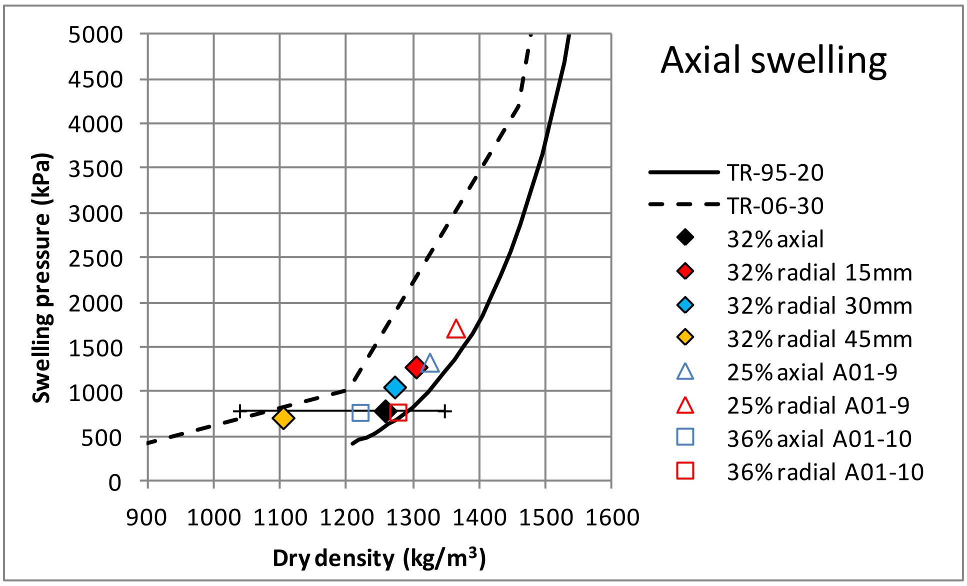

***Figure 3-13** Swelling pressure plotted as a function of dry density. The radially measured pressures are plotted with the dry density measured at the corresponding locations. Axially measured pressure is plotted with the average dry density. Also shown are results from the previous tests*

3.2.5 Requested outputs

Requested outputs for each test are of two different natures:

- Brief description of the model, specific part of the model to deal with homogenization of the bentonite (in particular, the choice to represent the free volume at the beginning of the test), which parameter are used and how is calibrated the model for this specific test
- Results from the test at several locations and for a predefined list of time. To facilitate the comparison of results, an Excel form will be provided to be filled by the participants.

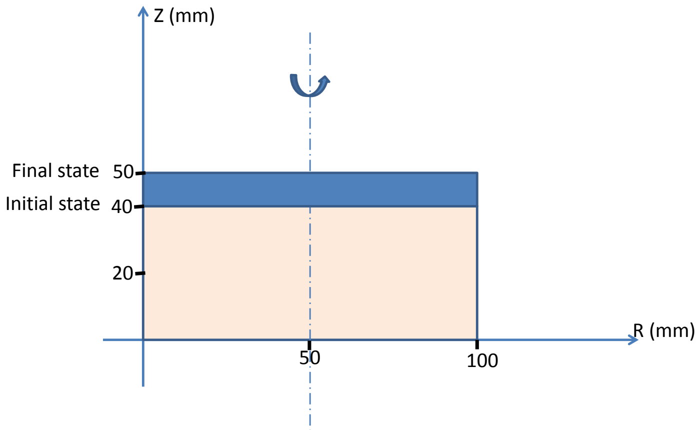

***Figure 3-14** Schematic 2D-representation of the bentonite plug*

The requested outputs from this test are:

- Total axial stress function of time at R=50mm
- total radial stress function of time at z=5, z=15, z=30, z=45 mm

- void ratio and water content function of time at (R=50mm, z=5, 15, 30, 45, 49mm)
- void ratio and water content function of time at (R=25mm, z=5, 15, 30, 45, 49mm)
- Void ratio and water content profile at R=25, R=50, z=5, 15, 30, 45, 49mm m for several times including t=15h, 30h, 300, 500h, 1000h, 1600h.
- Total axial pressure and total radial stress profile at R=25, R=50, z=5, 15, 30, 45, 49mm m for several times including t=15h, 30h, 300, 500h, 1000h, 1600h.
- Contour plots at different times including t=15h, 30h, 300, 500h, 1000h, 1600h.
  - void ratio and water content
  - total axial stress and total radial stress

4. Test 1b - Swelling pressure tests for Pellets mixture

This test has been developed by CEA (France) to study the behavior of pellets mixture during water saturation. The mixture used is the same as the one used for FSS demonstrator (Noiret et al, 2016) part of the DOPAS project (n° 323273).

4.1 Equipment

The device (Figure 4-1, Figure 4-2) consists of a confining cylinder, a fixed base and a mobile piston made of 304L stainless steel. The set is inserted in a clamping frame. A force sensor interposed between the piston and the upper flange measures the swelling pressure transmitted by the piston.

The porous disk in stainless steel at the base allows that injection of water is uniformly distributed on the face of the sample. A sensor measures the displacement of the mobile piston, consequence of the lengthening of the tie rods clamping. A water tank placed 1 m above the base on a continuous weighing device, allows hydration with a slight differential pressure (about 10 kPa). The hydration is carried out via the base, while the piston circuit remains open so that the air occluded in the sample can escape.

Four radial pressure sensors and five relative humidity/temperature sensors are installed in the cell. Pressure sensors are placed at the interface between the cell and the bentonite are four levels. The relative humidity sensors are five levels and different locations inside the bentonite (see Figure 4-2 and Table 4-1).

Table 4-1 Position of radial sensors in the cell

Sensor type and number	Vertical position	Angular position	Position in the bentonite (from the cell wall)
RH1/T1	20	0	40
PT1		0	0
RH2/T2	40	72	70
PT2		90	0
RH3/T3	60	144	100
PT3		180	0
RH4/T4	80	216	70
PT4		270	0
RH5/T5	100	288	40

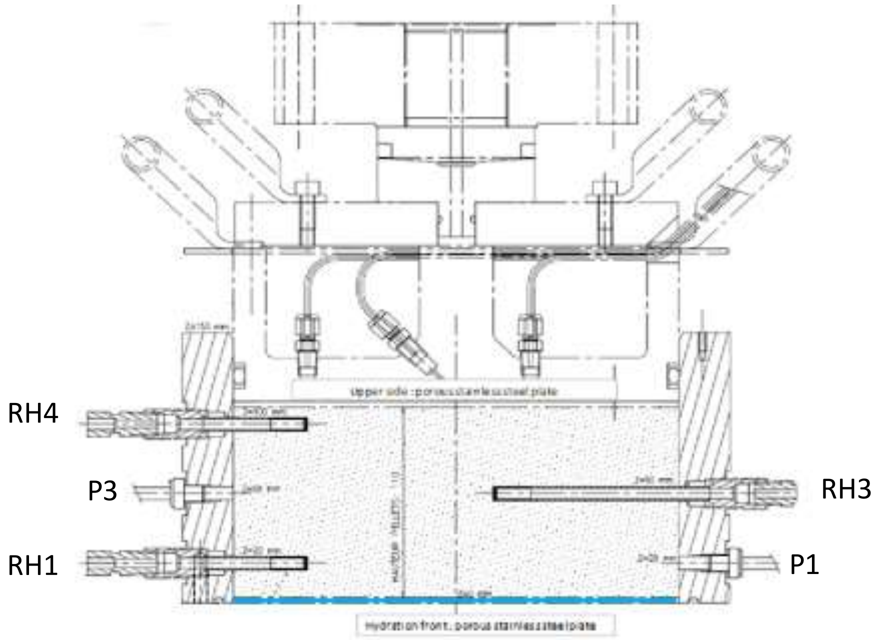

Figure 4-1 Vertical cut of the cell – water is supplied by a filter above the specimen

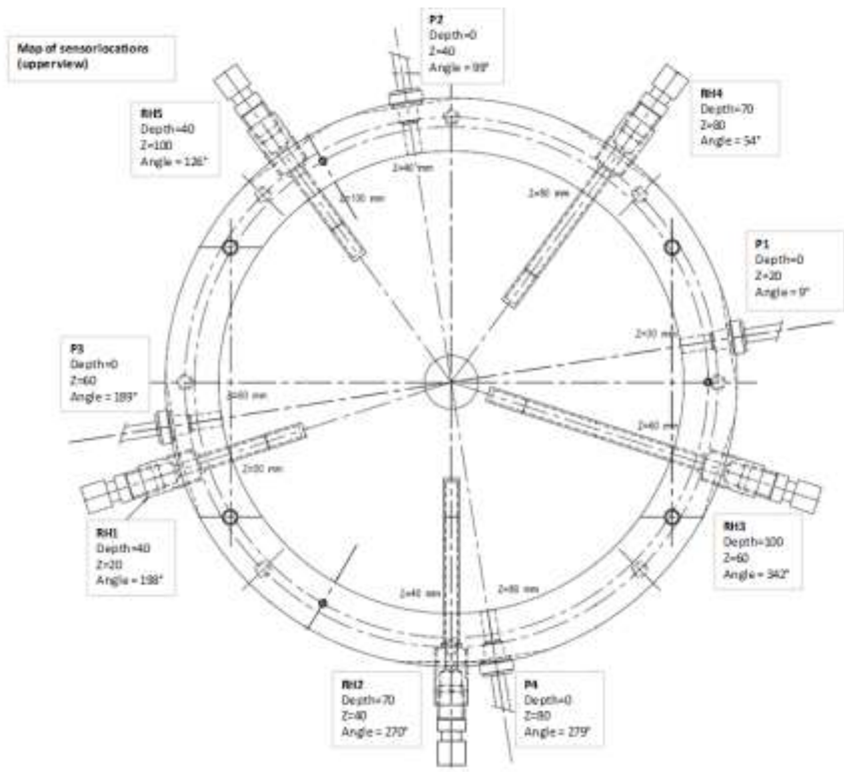

Figure 4-2 Radial cut of the cell with the location z, θ of the sensors – RH and Pressure (total)

4.2 Preparation of specimens

The materials are arranged layer by layer in the cell, beginning with a layer of pellets representing 70% of the mass of the layer, then the crushed pellets (30% of the mass of the layer) is poured on the pellets. The arrangement should not exceed the target for the dry density, which is 1.52g / cm^3. Three layers are thus arranged in the cell. A fourth layer is added with lower number of split pellets. The final height of the sample slightly greater than 103 mm allows to immerse the last HR sensor whose axis is located at h = 100 mm (see Figure 4-3).

 First layer of pellets	 First layer with crushed pellets
 Second layer of pellets	 Second layer with crushed pellets
 Third layer with pellets	 Fourth layer with pellets and crushed pellets

Figure 4-3 Installation of the material in the cell – layer by layer

The theoretical geometry of a pellet is represent on Figure 4-4. It is composed with a cylindrical central part and two spherical parts (with a radius of 18.5mm). The crushed pellets has a granulometry between 0 and 3 mm. Pellets and crushed pellets have been made with MX-80 (MX80 bentonite : Laviosa-MPC Expangel SP32). Dry density for one 32mm pellet is between 2.01 and 2.05 g/cm^3. Crushed pellets have a particle size between 0 and 2.5 mm.

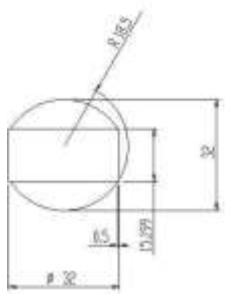

Figure 4-4 *Geometry of one pellet*

Grain distribution for the crushed pellets is given on Figure 4-5. The maximum diameter is about 2 mm.

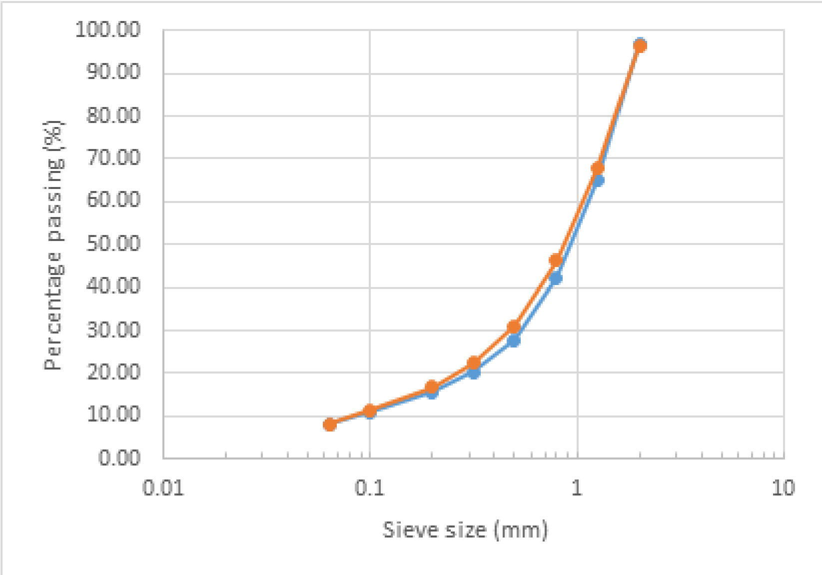

Figure 4-5 *Grain size distribution for crushed pellets*

Some details about microstructure for both pellets and crushed pellets can be found in : Agustin Molinero Guerra et al, 2017.

Table 4-2 *Initial material in the cell, initial characterisation of the sample*

	Pellets		Crushed pellets	
Water content (%)	4,090		4,550	
	Mass (g)	Dry mass (g)	Mass (g)	Dry mass (g)
Layer 1 : 39 pellets	1661.000	1595.734	682.900	653.180
Layer 2 : 38 pellets	1610.500	1547.219	716.100	684.935
Layer 3 : 39 pellets	1647.700	1582.957	713.400	682.353
Layer 4 : 8 pellets (split)	339.900	326.544	163.900	156.767

Total per constituent	5259.100	5052.455	2276.300	2177.236

Diameter (mm)	240.0
Surface (cm^2)	452.389
Initial height (mm)	103.6
Initial volume (cm^3)	4686.754
%pellets (mass)	69.885
% crushed pellets (mass)	30.115

Clay density (g/cm^3)	2.780
Total porosity (%)	44.5
Pore volume (cm^3)	2086.1
Initial water content (%)	4.23
Initial saturation (%)	14.65
Initial apparent density (g/cm^3)	1.608
Initial dry density (g/cm^3)	1.543

4.3 Test procedure

Water is in contact with the lower face of the sample with a pressure differential of about 10kPa. The upper face is at atmospheric pressure. The sample takes water as soon as it comes in contact with water. Swelling pressure (axial and radial) and water inflow are monitored. The test is continued even after stabilisation of both water flow and pressure.

4.4 Results of test 1b

Five sensors have been installed to measure the swelling pressure and five for relative humidity. Unfortunately, some failure in sensors have been observed:

- the relative humidity sensor RH1 – z=20mm failed after 40 days,
- the relative humidity sensor RH3 – z=60mm failed after 592 days,
- the swelling pressure sensor (P2 – z=40mm) failed after 25days.

Figure 4-6 shows the evolution of swelling pressure in function of time. It can be seen that a stabilize state is obtained after about 500 days. Oscillations on the plateau are due to small variations of temperature. At the beginning of the test (few days after hydration started), variations in swelling pressure are induced by adjustments of the initial volume. Geometry and estimated properties after this adjustment are given in Table 4-3.

Table 4-3 Estimated properties after volume adjustment

Diameter	240.0
height after adjustment (mm)	105.15
Volume after adjustment (cm^3)	4756.8
%pellets (mass)	69.885

Total porosity (%)	45.3
Pore volume (cm^3)	2154.8
Water content (%)	4.23
Apparent density (g/cm^3)	1.584

% crushed pellets (mass)	30.115

Dry density (g/cm³)	1.52

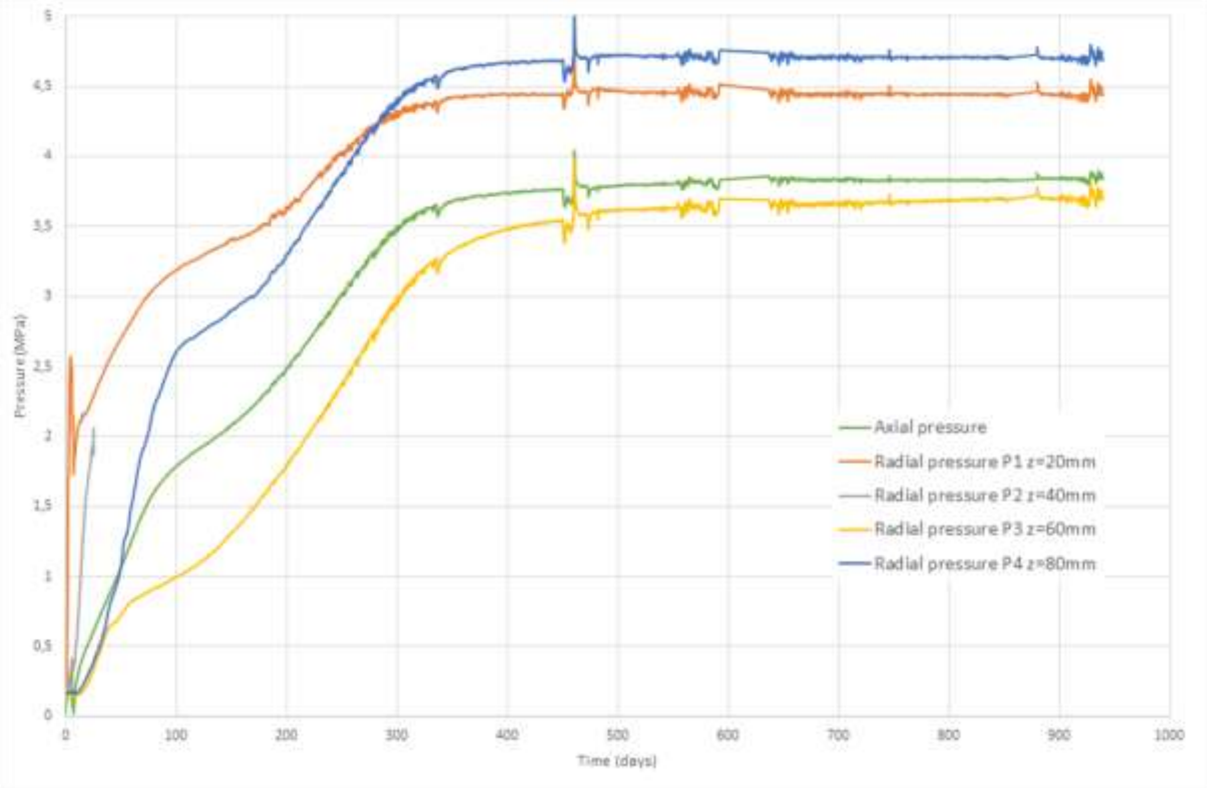

Figure 4-6 Swelling pressure measured radially and axially

Figure 4-7 shows the relative humidity evolution at five levels in the sample during the test. Figure 4-8 gives the variation of temperature in the sample.

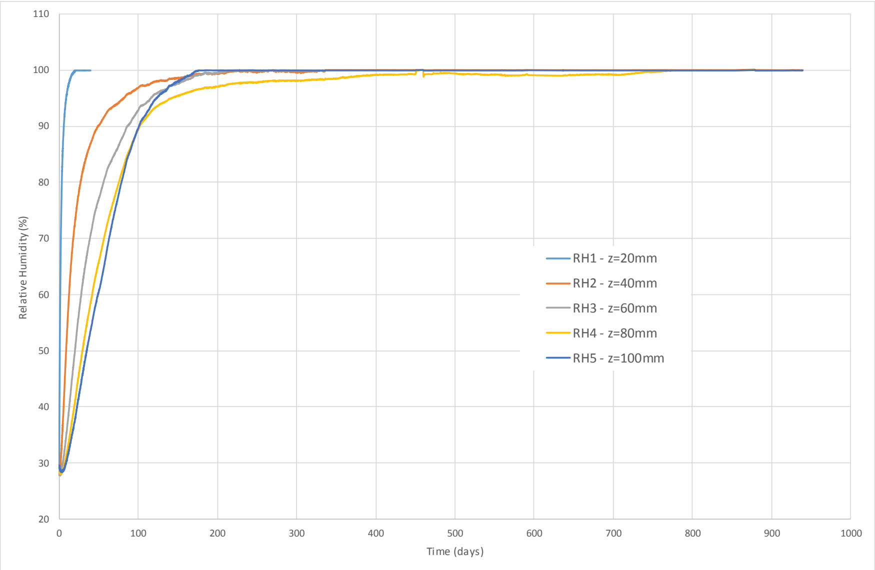

Figure 4-7 Relative humidity measured at four levels

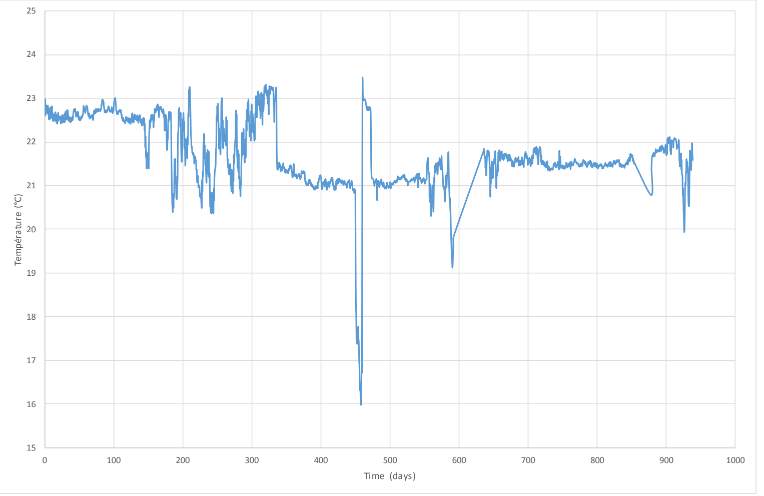

Figure 4-8 Evolution of temperature

Water uptake by the bentonite sample is monitored. The curve is given on Figure 4-9. Estimation of water necessary to reach full water saturation is also indicated on the graph. Results seem to show a slight lost of water certainly due to evaporation.

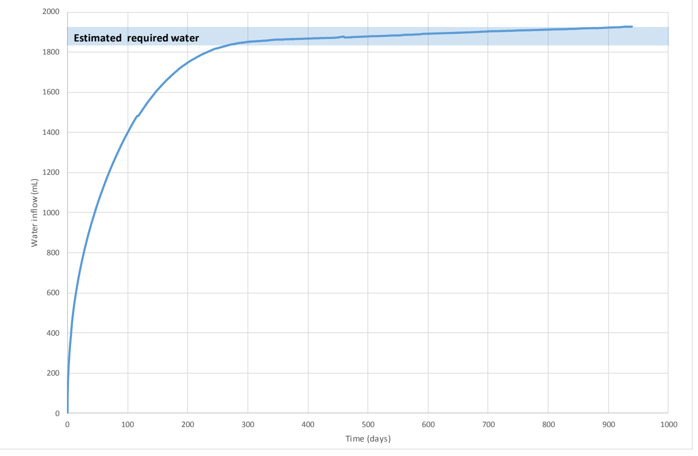

Figure 4-9 Water inflow during the test

On Figure 4-10, the swelling pressure in function of dry density for FSS type mixture is presented. The values obtained for this mixture are comparable to these measured on compacted blocks. This can be seen on Figure 3-13.

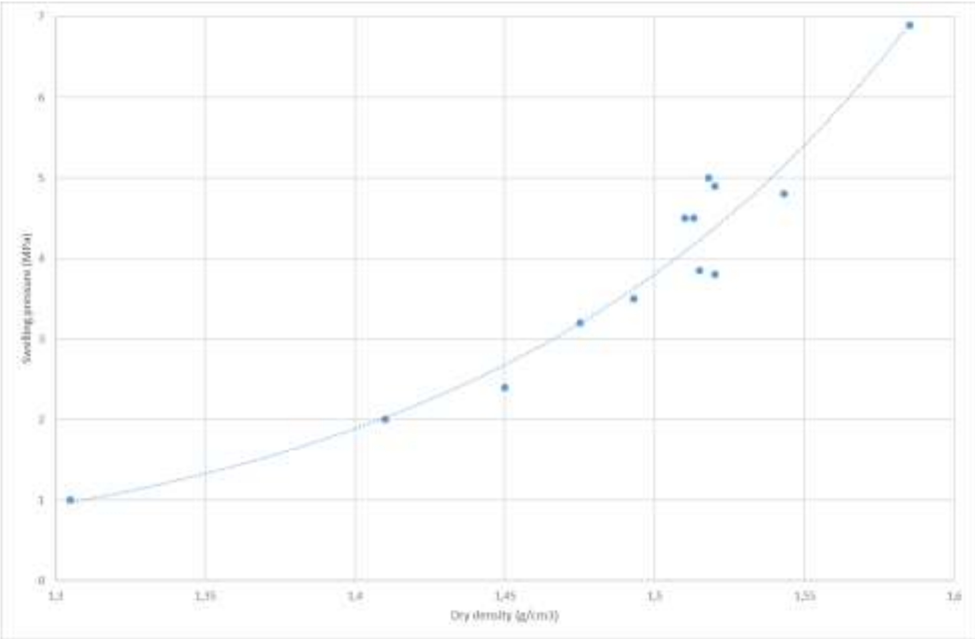

Figure 4-10 Swelling pressure in function of dry density for FSS mixture type

4.5 Requested outputs

Requested outputs for each test are of two different natures:

- Brief description of the model and the parameter used. How the model is calibrated for this specific test
- Results from the test at several locations and for a predefined list of time. To facilitate the comparison of results, an Excel form will be provided to be filled by the participants.

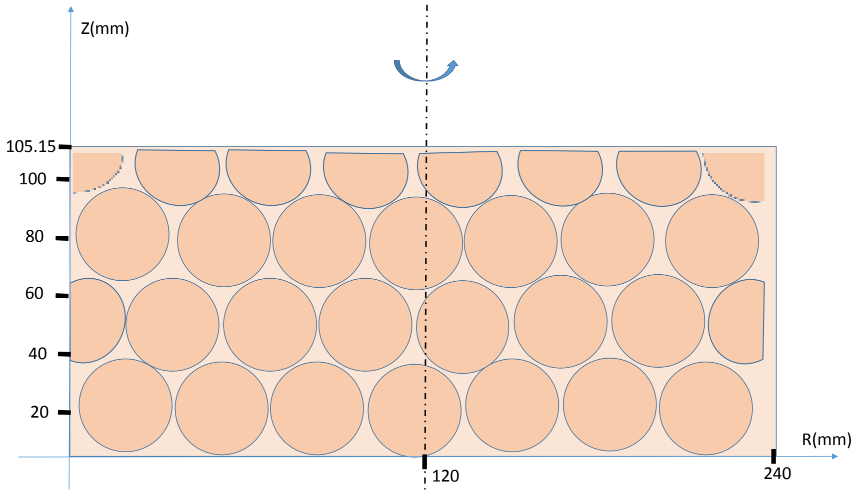

Figure 4-11 Schematic 2D-representation of the bentonite mixture

The requested outputs from this test are:

- Total axial stress function of time on the top of the cell at z=105.15
- total radial stress function of time at z=20, z=40, z=60, z=80, z=100 mm on cell wall

- void ratio and water content function of time at (R=120mm, z=10, 30, 50, 70, 100mm)
- Water saturation function of time at for five positions (R, Z): (40, 20), (70, 40), (100, 60), (70, 80), (40, 100).
- Void ratio and water content profile at z=20 and z= 60mm for several times including t=50days, 100d, 200d, 300d, 400d.
- Contour plots at different times including t=50days, 100d, 200d, 300d, 400d, 900d
  - void ratio and water content
  - total axial stress and total radial stress

5. Test 1c- Swelling pressure test for block and pellets mixture

This test has been developed by POSIVA (Finland) to study buffer swelling and homogenization evolution. In a constant volume cell, a pellets mixture is placed on the top of a compacted block sample.

5.1 Equipment

Test were performed in a constant-volume cell with a 100 mm diameter and a height of 100 mm, equipped with two axial pistons at the top and bottom, and two radial pistons at the midpoints of the block and pellet zones (see Figure 5-1). Water is supplied on the top of the sample via a porous disc at the interface with the pellets zone.

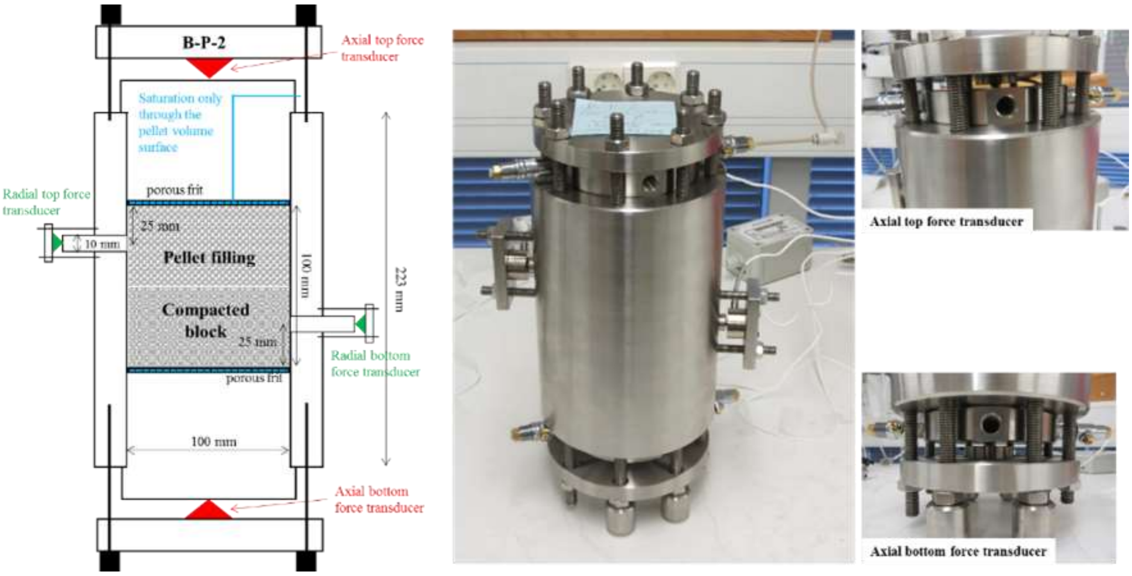

Figure 5-1 ***Schematic illustration and pictures of the block-pellet test system.***

Any surfaces inside cell were not pretreated. Radial pistons are located at the midpoints of the block and pellet zones, 25 and 75 mm from the bottom of the sample, respectively.

5.2 Preparation of specimens

The MX-80 pellets have a pillow shape. Main characteristics for the pellets are given in Table 5-1. Prior to sample preparation all pellet materials were sieved down to a minimum pellet size of 8 mm. However, unseparated doublets and triplets (two or three connected pellets) were frequently observed in the pellet batches (see Figure 2-1) and therefore pellets dimensions varied in length, width and thickness as follows 11.8-26.2, 10.3-14.7 and 5.4-5.9 mm, respectively.

Figure 5-2 Picture of MX-80 pillow-shaped pellets as received before sieving.

Table 5-1 Pellet dimensions and bulk density

	Length 1 (mm)	Length 2 (mm)	Height (mm)	Bulk density (paraffin method) (g/cm^3)
n	80	80	80	25
Minimum	11.8	10.3	5.4	2.08
Average	17.8	12.6	5.6	2.10
Maximum	26.2	14.7	5.9	2.12

Bentonite block sample was compacted directly into the cell on the top of bottom porous metal filter under compaction force of 180 kN (22.9 MPa) to dry density value of 1808 kg/m^3 (back-calculated from estimated block dimensions and used bulk mass). Estimated dimensions after compaction were 100 x 48.5 mm in diameter and height, respectively. Averaged initial water content level was 16.3% over the block zone.

Pellets mixture is poured into the cell on the top of the compacted block without external compaction. The height of the layer is 51.5 mm (based on estimation after pellets installation) (see Figure 5-3).

Radial top piston was not in direct contact with pellet component at the beginning of the saturation process, i.e., the surface of piston was at the same level with the wall of the test cell. Before the top axial piston was installed, a porous frit was placed on top of the pellet zone. Both axial pistons were pushed all the way down so that the "hat" of the piston was in contact with the body piece of the cell. Initial height of total sample was approximately 100 mm (48.5 + 51.5 mm). Air was evacuated from the test cell and all force transducers were attached. Pre-stress loads of approximately 10% of expected swelling pressures were established on each force transducer for 40 hours prior to saturation.

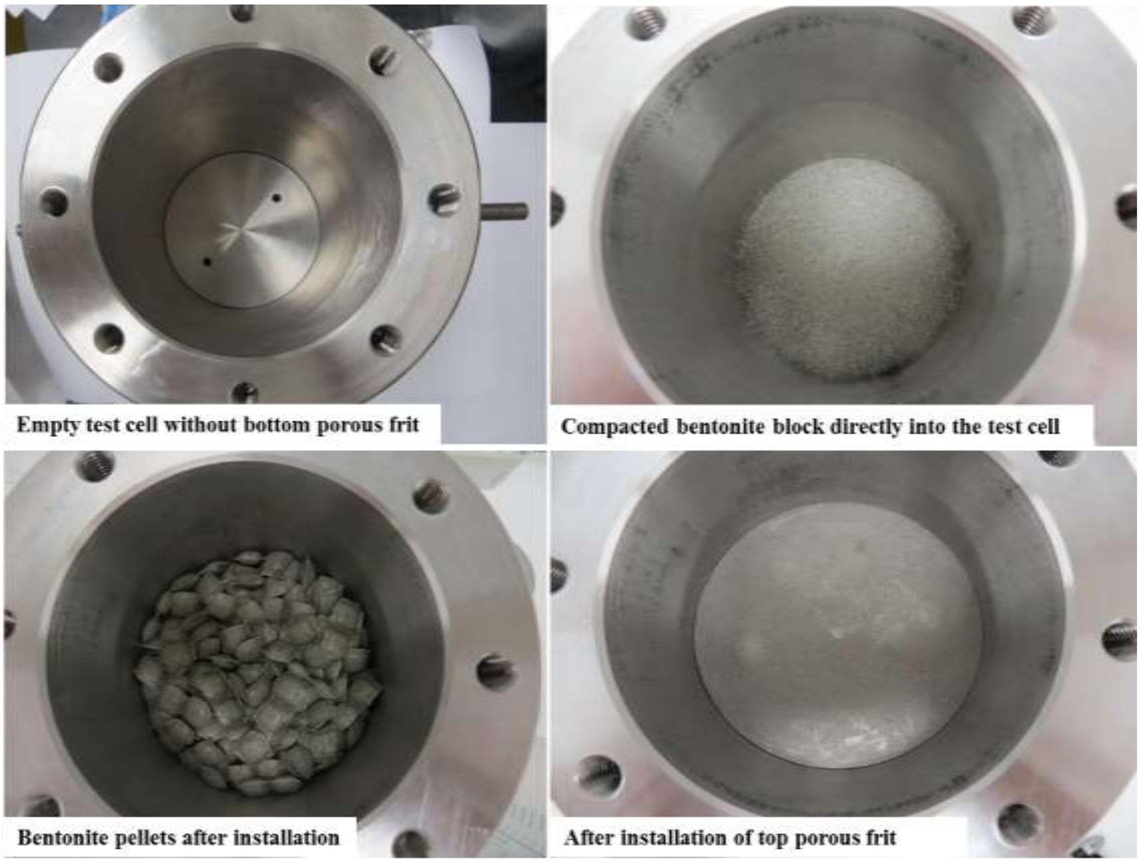

Figure 5-3 **Pictures of the installation of the block-pellet test**

Table 5-2 ***Initial properties for block and pellets zone***

	Initial w (%)	Initial ρ_d (kg/m³)	Constant Radius (mm)	Initial height (mm)
Block	16.3	1808	100	48.5
Pellets	15.3	904	100	51.5

5.3 Test procedure

All samples were saturated against reference groundwater solution. Reference groundwater simulant (TDS = 10 g/L, Ca^{2+}/Na^{+} mass ratio = 0.5), was prepared from deionised water and technical grade $CaCl_2$ and NaCl salts. In all tests the saturating solution was de-aired.

The saturating solution was allowed to flow into the test cell only through the top wetting circuit of the cell under constant head of 10 kPa. One bottom circuit port of the cell was open to atmosphere over the saturation period.

Test was terminated after 672 days. Although the stability of the pressure in both directions (axial and radial) was reached, the test continued over a period of about 1 year.

5.4 Results of test 1c

Swelling pressure have been measured on 672-days and is presented in Figure 5-4. Approximately after 6000 hours (312.5 days) all measured stresses were relatively stabilized. However, the test was continued until 16 122 hours. The measured stresses were systematically higher at the block zone than at the pellets zone. In consequences, axial stresses measured on the top (pellets side) and on the bottom (block side) stayed different all along the test with values at the end of 869 and 1428kPa respectively.

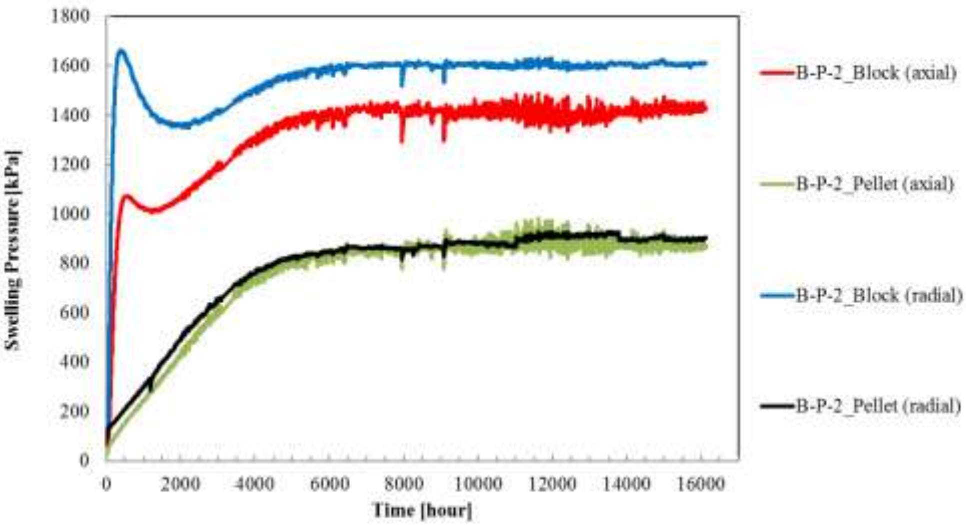

Figure 5-4 Swelling pressure in radial and axial directions function of time

Post-mortem analysis was performed in the axial and radial directions according to the sectioning layout indicates in Figure 5-5.

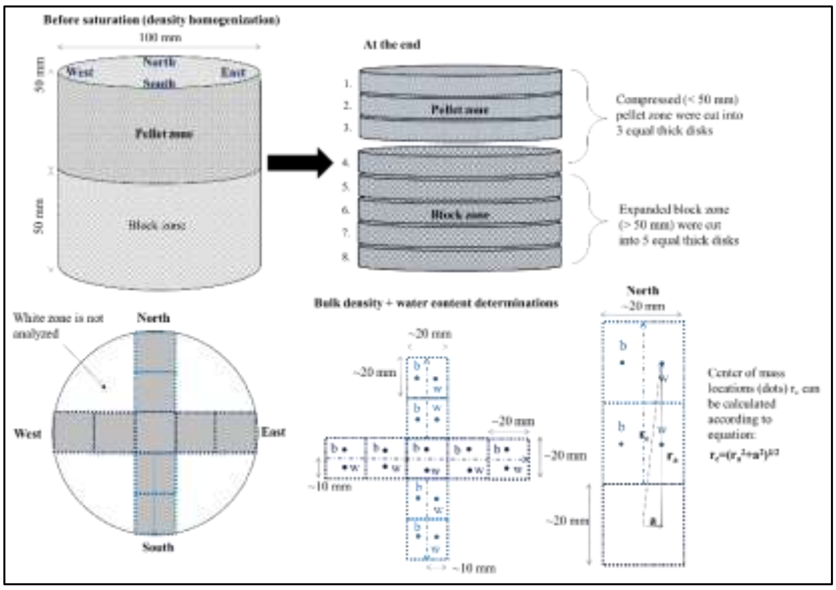

***Figure 5-5** Post-mortem sectioning layouts for water content and bulk density determinations. Block and pellets zones were cut into eight equal thick disks, each disk was cut into nine squares (center + 2 squares per north, east, south and west directions) and each square was cut into halves for bulk density (b) and water content (w) determinations.*

On Figure 5-6, the initial and final dry density over the height of the sample are presented. Density was decreasing from block volume (bottom) to pellet volume (top). The dry density of the pellet zone increased due to block expansion and the dry density of the block decreased.

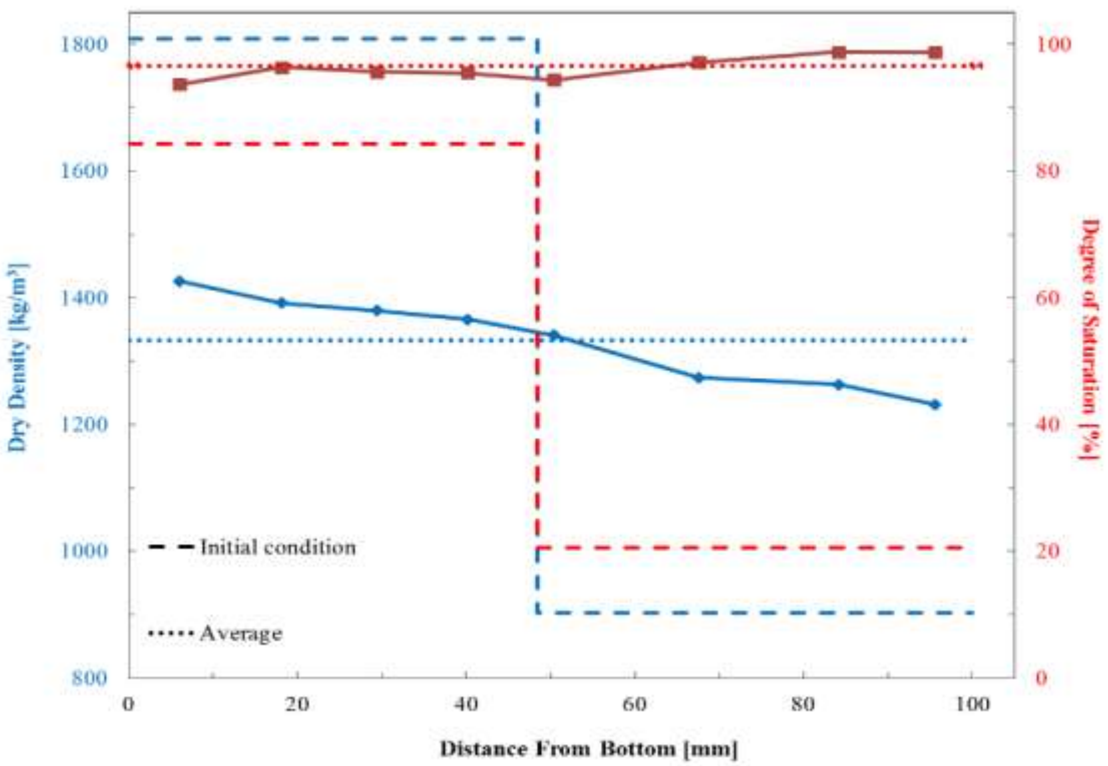

Figure 5-6 Dry density and degree of saturation distributions over the height of block-pellet sample at the end of the test (after 672 days). Blue diamonds and red squares represent averaged dry density and degree of saturation values, respectively on each height at the end of the test. Dashed and dotted lines represent initial, unsaturated condition and average values over sample volume at the end test, respectively.

On Figure 5-7, water content profiles along the vertical is presented. Low water content is found at the bottom in the block zone compared to the top in the pellets zone. It is interesting to see that at a same level water content is homogeneous. The main difference is located in the center in the block zone where water content seems to be higher.

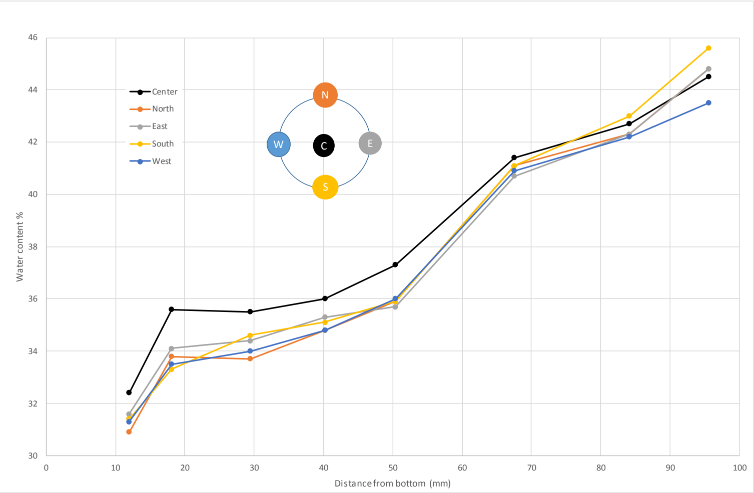

Figure 5-7 *Water content along the vertical at different locations*

On Figure 5-8, dry density distributions are presented according to the conventions presented on Figure 5-5. In the block zone, dry density is mainly lower in the center than close to the wall. A special trend on the pellets zone is not observed.

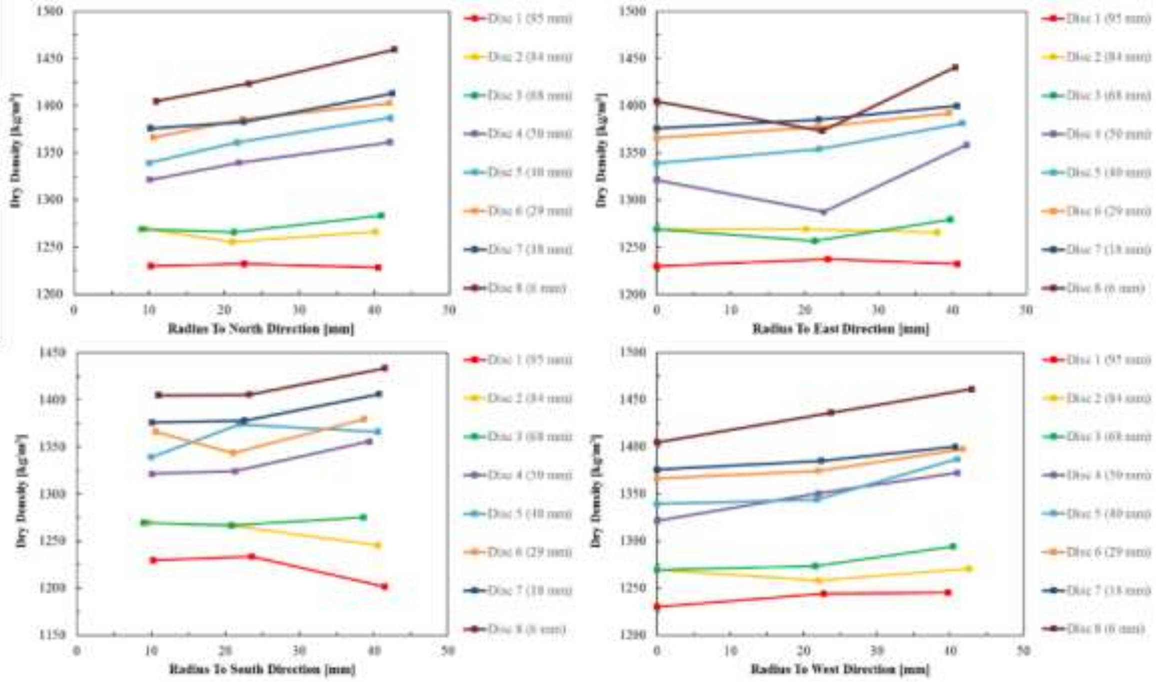

Figure 5-8 **Dry density distributions in the radial directions for block-pellet sample at the end of the test (after 672 days).**

Theoretical calculated and post-mortem determined densities over height of the sample after saturation are presented in
Table 5-3. Theoretical dry density of sample was 10 kg/m³ higher than measured value at the end of test. The relative error was less than 1%.

Table 5-3 Initial dimensions, initial dry density, measured swelling pressures, final dimension, and final dry density for block-pellet sample B-P-2 after 672 days under saturation

Initial Block/Pellet Height[1] [mm]	Initial Dry Density[2] [kg/m³]	Axial $P_{a,block}$[3] [kPa]	Axial $P_{a,pellet}$[3] [kPa]	Radial $P_{r,block}$[3] [kPa]	Radial $P_{r,pellet}$[3] [kPa]	Final Block/ Pellet Height[4] [mm]	Determined Dry Density[5] [kg/m³]
48.5/51.5	1342 (904+1808)	1428	869	1609	900	63.7/37.4	1332

[1]Estimated value
[2]Calculation is based on estimated sample volume and weighed initial masses
[3]Averaged over last 3 days of signal measurements
[4]Measured value
[5]Calculation based on water content and bulk density determinations over the height of the sample

5.5 Requested outputs

Requested outputs for each test are of two different natures:

- Brief description of the model and the parameter used. How the model is calibrated for this specific test
- Results from the test at several locations and for a predefined list of time. To facilitate the comparison of results, an Excel form will be provided to be filled by the participants.

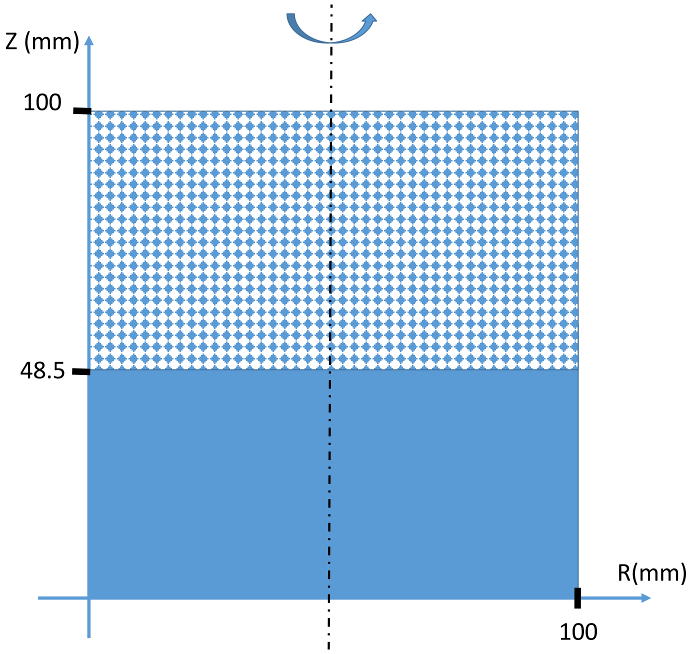

Figure 5-9 Schematic 2D-representation of the set up

The requested outputs from this test are:

- Total axial stress function of time on the top and on the bottom of the cell at z=0 and z=100mm
- Total radial stress function of time at z=25, z=50, z=75, z=95 mm on cell wall

- Dry density and water content function of time at (R=50mm, z=12, 30, 50, 67, 95mm)
- Dry density and water content function of time at (R=90mm, z=12, 30, 50, 67, 95mm)
- Dry density and water content profiles at z=12, z=30, z=50, z=67 and z= 95mm for several times including t=50days, 100d, 200d, 300d, 400d, 670d.
- Dry density and water content profiles at R=90 and R=50mm for several times including t=50days, 100d, 200d, 300d, 400d, 670d.

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