DOPAS WP3 Deliverable D3.7

"Test report on FSS metric clayish material emplacement tests with clayish material definition and laboratory work on its performance"

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CO	Confidential, only for DOPAS partners	

Important Note:

The **three** following DOPAS WP3 Deliverables (as identified below according to the initial DOPAS Description of Work), all related to the FSS experiment, have been merged in **one single document**:

- DOPAS Deliverable D3.3: “Report on clayish material definition for FSS”,
- DOPAS Deliverable D3.5: “Lab test report on the performance of the FSS clayish material”,
- DOPAS Deliverable D3.7: “Test report on FSS clayish material metric core emplacement”.

The **new global document** is titled:

- DOPAS WP3 Deliverable D3.7: “Test report on FSS metric clayish material emplacement tests with clayish material definition and laboratory work on its performance”.

Scope	Deliverable n°D3.7 (WP3)	Version:	A
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REVIEW/OTHER COMMENTS:

The report was internally reviewed by Andra and later submitted in version A for approval by the DOPAS Coordinator (Johanna Hansen for POSIVA).

APPROVED FOR SUBMISSION:

Johanna Hansen (POSIVA) ***9.12.2016***

Executive Summary

In DOPAS, Work Package 3 (WP3) is related to the construction of large scale demonstrators of seals and plugs. FSS (Full-scale Seal) is the "seal industrial demonstrator" (prototype) designed and built by Andra with the scientific help of NAGRA, while other WMO's (i.e. the DOPAS partners) are building or have built or will build their own prototypes (namely DOMPLU, POPLU, EPSP, ELSA).

This report DOPAS WP3 Deliverable D3.7 first gives an overview of the laboratory work, carried out in order to define the most suited clayish (bentonitic) material for the needs of Andra's FSS experiment, i.e. building a swelling clay core inside a test box (drift model), with the relevant "emplaced dry density" value and the adequate permeability performance and the most suited swelling pressure. The material used is a mix of WH2 (a bentonite brand equivalent to MX80) based pellets and powder (made of crushed pellets). It is also tested in the REM Experiment (a 10-30 year long hydration test in a metric test cell), coming as a complement to FSS, in order to assess the material performance at a scale which is ten times that of the tests carried out in lab (at a decimetric scale, over a few months) and provide data to further modelling.

The document includes an overview of the main experimental phases (illustrated by photos, graphs and tables) implemented to determine the right formulation of WH2 bentonite pellets and powder admixture, first used for the bentonite material emplacement tests at a metric scale, preceding the full scale swelling clay core construction activities.

The formulation selected is described and its characterization provided. The metric emplacement tests are also presented with their outcomes. They have an impact on the final bentonitic material specification effectively considered for the FSS swelling clay core construction, as well as on the design of the full-scale backfilling machine to be used in FSS.

Links to previous and future Andra's FSS specific (or more general DOPAS) deliverables are given. The global FSS construction and investigation timeline is summarized in the table below:

Period	Activity
August 2012	Beginning of studies
November 2012 – June 2013	Drift model (aka "Test Box") construction
August 2012 – July 2013	Low-pH SCC concrete and shotcrete mix development
August 2012 – April 2014	Development of bentonitic materials and methodology to emplace the swelling clay core mix
July 2013	Low-pH SCC "upstream" containment wall construction
August 2014	Swelling clay core construction
September 2014	Low-pH shotcrete " downstream" containment wall construction
October 2014 – July 2015	Scientific investigations
August 2015 – December 2015	"Investigation Dismantling" followed by a complete deconstruction of FSS and release of test site to landlord

List of Acronyms – Abbreviations

This list of acronyms is generic. It concerns entities, activities, concepts, equipment and materials; some of which are Andra specific in the context of the FSS experiment.

ASN:	Autorité de Sûreté Nucléaire (French Nuclear Authority).
CIGEO:	Centre Industriel de Stockage Géologique (Industrial Geological Repository, AKA Cigéo).
CNE:	Commission nationale d’évaluation (National Assessment Board).
CP:	Crushed Pellets (bentonite powder made of)
DGR:	Deep Geological Repository (see also GDF)
DOPAS:	Full-scale Demonstration of Plugs and Seals (Name of EC Project on Seals).
EBS:	Engineered Barrier System.
EC:	European Commission.
EDZ:	Excavation damaged zone.
ESDRED:	Engineering Studies and Demonstration of Repository Designs (name of a previous EC supported Project).
FSS:	Full-scale Seal.
GDF:	Geological Disposal Facility (see also DGR).
GME:	Groupement momentané d’entreprises (FSS General Contractor, Consortium of companies).
HLW:	High-level Waste.
IAEA:	International Atomic Energy Agency.
ID:	Internal diameter.
ILW:	(Long Live) Intermediate-level Waste (also LL-ILW).
IRSN:	Institut de Recherche sur la Sûreté Nucléaire (Expert Organization and technical support to ASN).
LECBA:	Laboratoire d’études et caractérisation des bétons et argiles (Laboratory for study and characterization of concrete and clay materials) – member of GME.
LLW:	Low-level Waste.
MPC:	Member of GME – vendor of bentonite based products.
OD:	Outside diameter.
R&D:	Research and Development.
SCC:	Self-compacting concrete.
URL:	Underground research laboratory (Bure is the French URL).
WMO:	Waste Management Organization.
WP:	Work Package.

List of DOPAS Project Partners

The 14 partners from 8 different countries in the DOPAS Project are listed below. In the remainder of this report each partner is referred to as indicated:

Posiva	Posiva Oy	Finland
Andra	Agence nationale pour la gestion des déchets radioactifs	France
DBETEC	DBE TECHNOLOGY GmbH	Germany
GRS GmbH	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

Glossary of scientific formulations/equations

Term	Definition	Formula in French
M (g)	Mass of mixture	
M_d (g)	Mass of dry mixture	
M_W (g)	Mass of water in mixture	
P_C (MPa)	Compacting pressure	
P_S (MPa)	Swelling pressure	
RH (%)	Relative Humidity (measured)	Humidité relative (HR)
k (m/s)	Permeability of saturated material or hydraulic conductivity	
Taux de vide	Percentage of voids between grains, pellets or powder	$= \frac{\text{volume vides inter grains}}{\text{Volume total}}$
W (%)	Water content (measured at 105°C)	$W = \frac{\text{masse eau}}{\text{masse matériau sec}}$
ρ_w (g/cm^3)	Water density (specific gravity)	1.0 g/cm^3
ρ (g/cm^3)	Bulk density (specific gravity)	$\rho = \frac{\text{masse totale}}{\text{volume total}}$
ρ_d (g/cm^3)	Dry density (dry specific gravity)	$\rho_d = \frac{\text{masse sèche matériau}}{\text{volume total matériau}} = \rho \times \frac{1}{1+W}$
ρ_{red} (g/cm^3)	Emplaced dry density (with volume increase)	$\rho_{red} = \frac{\text{masse sèche matériaux}}{\text{volume final}} = \rho_d \times \frac{1}{1+\frac{\Delta V}{V}}$
ρ_s (g/cm^3)	Dry density of solids in clay	2,78 g/cm^3 for WH2
η (%)	Porosity	$\eta = \frac{\text{volume pores}}{\text{volume total}} = 1 - \frac{\rho_d}{\rho_s}$
S_r (%)	Saturation rate	$S_r = \frac{W \times \rho \times \rho_s}{[\rho_s \times (W+1) - \rho] \times \rho_w} \approx \frac{W}{\left(\frac{1}{\rho_d} - \frac{1}{\rho_s}\right)}$

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1. National Context for the FSS Experiment

In France, the repository host rock is the 155-million-year-old Callovo-Oxfordian indurated clayish formation, which lies in the east of the Parisian Basin. The repository project is referred to as Cigéo. The disposal reference inventory includes Long-Lived Intermediate-level waste (LL-ILW or ILW) from operation, maintenance and decommissioning of nuclear facilities and HLW from spent fuel reprocessing. The waste will be disposed of in physically separated disposal zones: one for ILW and one for HLW. The repository's primary function is to isolate the waste from human activities at the surface and its second function is to confine radioactive substance and control the transfer pathways which may in the long term bring radionuclides into contact with humans and the environment (ANDRA, 2013). The principal contribution of the seals in Andra's concept is to provide the second function.

The ILW disposal zone includes several tens of large-diameter disposal vaults, each about 500m long. Vault concrete lining and disposal containers provide a cementitious (buffer) environment for the ILW waste. The gaps and voids between waste packages and vault lining could be left empty or backfilled with cementitious material or neutral filler (e.g. sand).

In the French concept, seals are defined as hydraulic components for closure of large diameter (several meters) underground installations and infrastructure components such as shafts, ramps, drifts1 and ILW disposal vaults. Each seal consists of a swelling clay core (EBS) and concrete containment walls. The conceptual design of drift and ILW disposal vault seals is the same. The location of seals in the planned Cigéo repository is shown in Figure 1.1.

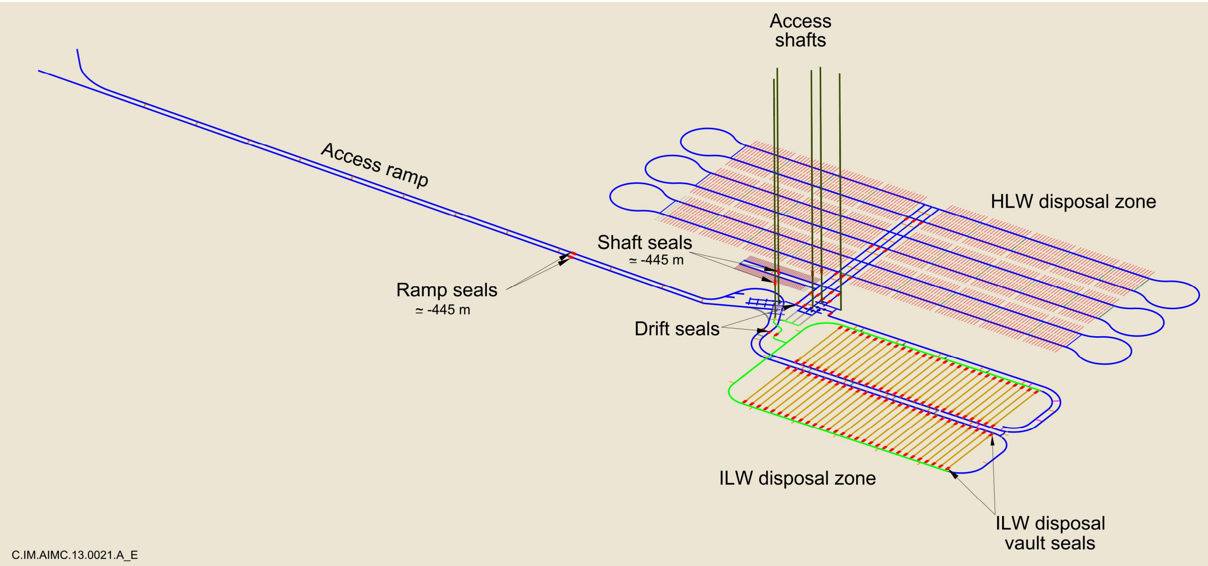


Figure 1.1: Location of the seals (red dots) in the Cigéo concept

[1] Drifts are horizontal tunnels, whereas ramps are inclined tunnels, also called declines.

2. FSS Design Basis and Link to the Cigéo Reference Design Basis

The FSS experiment is a full-scale technical demonstration of construction feasibility for a drift and ILW disposal vault seal, being carried out in a warehouse in Saint- Dizier, which is close to the French URL at Bure.

The FSS test calls for a large excavation, with a significant length and a considerable amount of equipment and materials mobilized and emplaced. The Bure URL is essentially a qualification facility, in which the logistical means are somehow limited (transport means, number of people admitted underground, geometry restrictions for large pieces of equipment,…). Moreover the Bure URL is busy with various other experiments which cannot be conducted concurrently with large scale experiments such as FSS.

For that reason, and for standalone reasons, like global experimental costs, global schedule constraints and needs for "investigation" dismantling and observations, it was decided to go for a surface facility, instead of working underground. The Saint-Dizier site was proposed by the Contractor (GME) in charge of the FSS test, and accepted by Andra, since the vicinity of Bure (30km), the height of warehouse (more than 10m of free gap under the roof frame), and the possibility of air parameters control were in line with the experiment technical specifications.

2.1 FSS Design basis

The FSS test is part of a wide-ranging programme of R&D and demonstrator experiments that was established by Andra in response to the discussions with ASN and the French National Assessment Board (CNE) in 2009, during which it has been noted that seals, and in particular drift and ILW disposal vault seals, required some type of industrial and scientific demonstration in order to achieve licensing authorisation.

As a result, R&D studies and demonstration tests have been launched to assess the technical feasibility and to develop the post-closure requirements of seals in the repository. Those tests cover the performance and constructability issues. FSS belongs to this last category.

The main objective of the FSS test is to develop confidence in, and to demonstrate, the technical feasibility of constructing a full-scale drift (or ILW disposal vault) seal. Technical feasibility includes demonstrating the ability of the approach used to emplace the clay to be suitable for filling recesses (breakouts) in the clay host rock, and also the capacity to build large low pH concrete containment walls with satisfactory mechanical properties (shotcrete and SCC technologies are tested and compared).

The FSS test is focused on the "construction only" of the seal, and the swelling clay will not be saturated or otherwise pressurised. The "REM test" which is a saturation test at a metric scale over some 10 to 30 years, will provide valuable information on the way the bentonitic mix developed in FSS will behave with its progressive saturation and enable a better modelling of a seal behaviour at large scale (cf. DOPAS Deliverable D4.2 "Report on bentonite saturation test", Conil *et al.2015).*

The FSS design basis is described more detailed in different Deliverables of DOPAS WP2. The respective Cigéo seal design basis and that of the FSS experiment are compared and justified in the DOPAS WP2 Deliverable D2.1 "Design Bases and Criteria" (White *et al.2014*), and summarized in D2.4 WP2 "Final Report" (DOPAS, 2016).

The conceptual design of the FSS experiment is otherwise illustrated in Figure 2.1 below.

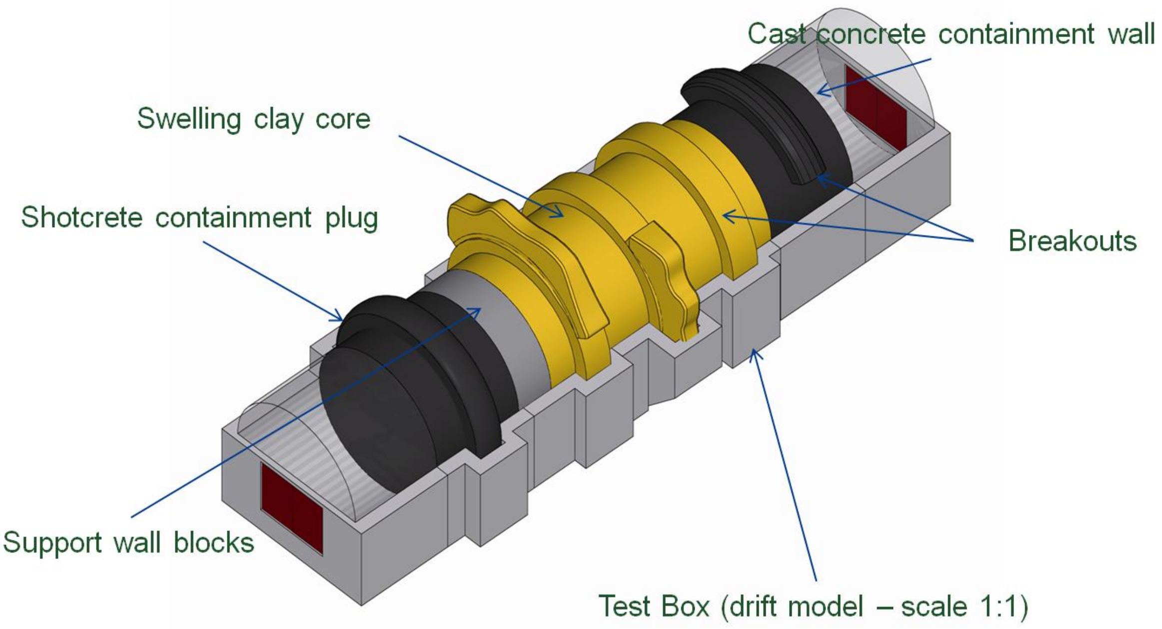


Figure 2.1: Conceptual design of the ANDRA FSS test.

The main difference between the Cigéo reference and FSS design bases for the Andra drift seal is the length of the seal. The real seal underground (in fact, each component: swelling core or containment walls) will be longer than the seal considered in the FSS experiment. The diameter(s) should stay close to what is effectively implemented in FSS.

The FSS test box (cf. Figure 2.2) is some 7.6m ID and 36m long. The drift concrete liner (70cm thick) and the formation break outs (recesses) likely to be generated by the drift lining deposition (up to 1m depth at the liner extrados) are simulated in the construction of the drift model.

Representative underground ambient conditions (temperature around 18-30 °C, hygrometry between 50% and 75%), have to be maintained within the drift model.

Low pH cast-concrete/shotcrete 5m long containment walls close the volume of the swelling core, on both sides. The bentonite swelling core length is some 14m.

2.2 FSS Test Box Design and construction

The FSS Test Box design was elaborated between July and October 2012. The Test Box workshop drawings were also supplied during that period on the basis of the FSS Test Box concept (as specified by Andra), and (following finite element modelling and dimensioning) derived from the schematic presented in Figure 2.2.

The test box design is documented in the DOPAS WP3 Deliverable D3.2 “FSS Tunnel model design report” (Bosgiraud *et al.2013*).

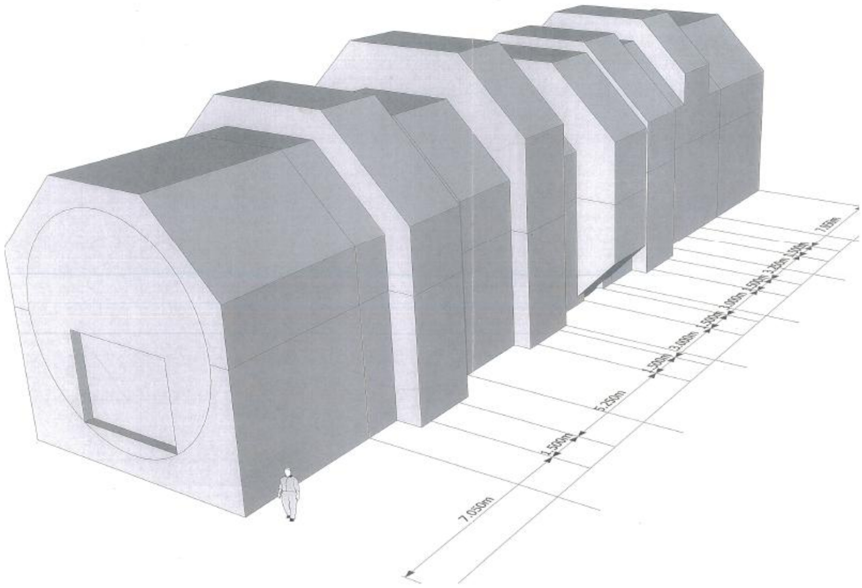


Figure 2.2: 3D schematic of the FSS test box

The construction of the FSS Test Box followed. It was started in October 2012 and was completed in May 2013. The Figure 2.3 shows the Test Box (drift model), commissioned in June 2013, as “experiment ready”. The FSS Test Box construction story is documented in the DOPAS WP3 Deliverable D3.10 “FSS Drift Model Construction Report” (Bosgiraud *et al.2014*).

The construction in July 2013 of the upstream low pH SCC containment wall was then made possible (the wall construction story is detailed in the DOPAS WP3 Deliverable D3.11 “Report on FSS cast concrete plug construction”, Bosgiraud *et al.2014*). The completion of the low pH SCC containment wall was an operational prerequisite of the swelling clay core construction.

Additionally outcomes of the metric clay core emplacement tests were needed, while they had an impact on the design of the full-scale bentonitic mix emplacement machine.

Figure 2.3**:** The FSS Test Box ready for seal construction

3. Work methodology used for the FSS clayish material definition

3.1 Context

The swelling clay core is the most critical component of the seal construction works. The clayish material constitutive of the core must comply with the following criteria (cf. Deliverable D2.1 “Design Bases and Criteria”):

- The swelling pressure must be sufficient to progressively fill the technical voids between the granular material (powder and pellets),
- The swelling pressure must be sufficient to provide an efficient and permanent hydraulic contact with the drift walls (concrete liner or argillites), to reduce or minimize the EDZ (by facilitating self-sealing), without exceeding the natural geological constraints prevailing in the host formation. Ideally, the bentonitic material swelling pressure value should be as close as possible to (but not exceeding) 7 MPa.
- The saturated material permeability value should not exceed 10^{-11}m/s.

The low pH concrete containment walls erected at both ends of the core are necessary to contain the bentonite mix during its swelling phase and keep the swelling pressure at its peak.

The use of low pH concrete helps to (i) reduce the thermal load generated by the concrete hydration, (ii) limit the effect of the alkaline plume generated by the cementitious water (leachate produced at time of the progressive host rock resaturation, following closure of the underground openings) on the swelling clay and the surrounding argillites, and (iii) increase the concrete durability in the underground environment.

3.2 Specifications

The bentonite specifications contained in Andra’s FSS “Scope of Work” (i.e. the technical and contractual document executed by Andra and the GME) are explicit:

- The bentonitic material must be a “Wyoming type sodic Montmorillonite”, under the brand MX80 or WH2,
- The swelling core must be made of a granular admixture of pulverulent materials (such as pellets and powder),
- The swelling core must be emplaced in the test box with industrial means similar to those likely to be employed in a Cigéo drift, at a 500m depth, at time of seal construction (drift or disposal vault closure),
- Similarly, the swelling core commissioning must be implemented with means and methods transposable to Cigéo at time of seal construction activities. These means and methods must then be qualified,
- The performances expected from the emplaced material (at saturation state) are to be fulfilled everywhere in the core: swelling pressure equal (or as close as possible) to 7 MPa, permeability equal to (or less than) 10^{-11} m/s.

All these specifications were integrated in the bentonitic material definition and characterization process described here after.

3.3 Discussion

The return of experience (from previous experiments and laboratories tests) shows that the most challenging parameter to fulfill is the swelling pressure value, set as close as possible to 7 MPa. This swelling pressure value is corresponding to a pre-established specific gravity (dry emplaced density of the swelling material) value. This value is empirically determined and is specific of the clayish (bentonitic) material concerned.

Data available show that, for a “Wyoming type” bentonite, this density is around 1.56 g/cm^3 for pre-compacted blocks swelling in a quasi-constant volume. For a granular material, with a higher porosity, the effective emplaced dry specific gravity is higher, near 1.60 g/cm^3. The inter-pellets voids/spaces are critical to reach such a value; hence various pulverulent admixtures (formulations) must be studied to minimize those voids (the purpose is to obtain the best possible compacity at time of admixture emplacement).

The other specifications are easier to reach. Experience shows that a sodic “Montmorillonite” such as the WH2 type has a permeability value (at saturation state) around 10^{-13} m/s, for an effective emplaced density of 1.60 g/cm^3 coherent with a 7 MPa swelling pressure.

The selection of the bentonite materials for the swelling clay core was undertaken in the following steps:

- First, a decision was made to adopt a pellet-based admixture rather than use of pre-compacted bentonite blocks. This choice is motivated by Andra’s belief that the use of pre-compacted blocks (bricks) is not a choice technically commensurate with the need for emplacing very large volumes of swelling clay in Cigéo in an industrial way.
- Second, laboratory testing of bentonite pellet and powder mixtures was undertaken in parallel with manufacturing tests to identify the appropriate pellet and powder mixture, and initial water content.
- Third, mock-up testing (at a metric scale) and desk-based design work was used to test and develop the design of the bentonite emplacement method.

Note about Adoption of a Pellet-based System:

Andra selected a pellet-based system instead of pre-compacted bentonite blocks because this solution is considered by Andra to be a more efficient industrial method of implementation for significant quantities of material. The method is similar to that proposed by NAGRA for emplacement of bentonite buffer materials in its FE experiment at Mont-Terri (cf. EC funded FP7 Project LUCOEX). In the case of FSS (and of the large seals envisaged by Andra for the Cigéo repository), the pellets/powder can be emplaced by conveyor systems while the blocks are to be positioned by human action or robots at a much lower emplacement speed. Furthermore, the erection of a wall of blocks also raises the issue of its stability, since the blocks are not assembled with a mortar.

3.4 Methodology

The methodology which was implemented for the definition and characterization of the best possible bentonitic mixture is defined in a **10 step process** described below:

Step 1: Supply of material studied and characterized

- It was decided that the supply of bentonite (under the brand name "WH2") would be ordered at a single Wyoming mine site and delivered in one single batch (some 1500 metric tons), in order to work with the most homogeneous material possible in terms of smectite content. The composition of the admixture was also pre-determined by experience with a decision to dry mix WH2 bentonite powder and pellets.
- The conditioning could be in pellets OD 32 mm, or/and in pellets OD 7 mm, and in powder (made or not of crushed pellets) with grains sized between 0.1 and 2 mm/5 mm.
- Supply of steel balls (simulating the different pellets sizes and arrangements) was also ordered.

Step 2: Manufacturing of test equipment

- Some preliminary pellet manufacturing tests (with an existing compacting machine) were carried out to optimize the compacting pressure and other production parameters needed to design and later manufacture the final pellet production machine,
- A polycarbonate test cell (ID 390mm, H 500 mm) was ordered, to be used later for the visualizing and weighing of the various pellets and powder assemblies (Figure 3.1),
- A test cell (ID 120 mm) for the measurement of the bentonitic material swelling pressure and permeability was also ordered and delivered (Figure 3.2).

Step 3: Characterization of the admixture components

The following physical measurements were carried out:

- Geometry of pellets,
- Bulk density (specific gravity),
- Water content,
- Emplaced density,
- Powder granulometry.

Step 4: Sampling of polycarbonate test cell (ID 390mm, H 500 mm)

The following physical measurements were carried out:

- Geometry and weight of test cell (empty),
- Weighing of cell filled with steel balls,
- Weighing of cell filled with preliminary pellets.

Step 5: Study of various admixture combinations in the polycarbonate cell

The following work plan was carried out (in order to obtain the best possible compacity, hence the best possible emplaced dry density):

- Optimizing of binary mixes,
- Optimizing of ternary mixes,
- Tests of admixtures with more than 3 components.

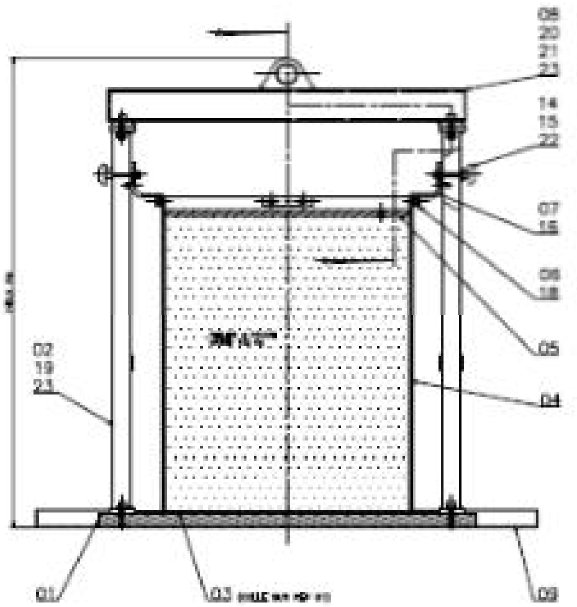


Figure 3.1: Polycarbonate test cell (ID 390mm, H 500 mm) used for the visualizing and weighing of the various pellets and powder assemblies

Figure 3.2: Test Cell (ID 120 mm) for measurement of swelling pressure and permeability

Step 6: Study of various storing, handling, mixing and conditioning methods

Several empiric tests were implemented to optimize the homogeneity and reproducibility of the various admixtures considered (with a view on their transposition to an industrial scale). The storage, segregation, dehydration and attrition issues were also studied.

Step 7: Study of emplacement methods

Various means of emplacing some powder in a pre-mix of pellets were tested, having again in mind their transposition to an industrial scale.

Step 8: Optimizing of mixture components

Two manufacturing processes (tracks) were followed: substitution of an ordinary bentonite powder by either a powder obtained (after screening) from 7mm OD crushed pellets or from 32 mm OD crushed pellets.

Step 9: Selection of 3 admixture formulations for the metric scale emplacement tests

At the end of all this empiric testing campaign, 3 admixture formulations were deemed in line with the requirements and were selected for their eligibility to metric scale emplacement tests (preceding the full scale emplacement test).

Step 10: Editing of a final report related to an admixture formulation adapted to FSS

The above testing steps paved the way to a definition of an admixture formulation (to be first tested and validated at a metric scale) adapted to the construction of the FSS swelling clay core (at scale 1:1).

Note:

All the iterations related to this methodology are not detailed in the document. The main outcomes only are summarized.

4. Preparatory work for the FSS clayish material definition

4.1 Materials used in the lab tests

The following materials were supplied for the purpose of lab testing:

- Bentonite powder WH2, brand name "GELCLAY WH2",
- Pellets 7 mm OD, brand name "EXPANGEL 7",
- Pellets 28 mm OD, brand name "EXPANGEL 28",
- Powder made of crushed pellets 7 mm OD, called hereafter "CP".

Note:

The use of some 28mm OD pellets instead of 32mm OD pellets was justified by the non-availability of the 32mm OD pellets compacting machine (which was still a prototype under development at time of lab test campaign start-up). The 28mm OD pellets were produced with the same WH2 powder (dried at 5 % of water content) as that used for the final 32 mm OD pellet production.

All the materials and components were delivered in 25 liter buckets (watertight and stored at ambient lab temperature) as detailed in Table 4.1.

Table 4.4.11 : Summary of materials used in lab tests

Designation LECBA	Reference LECBA	Date of receipt	Quantity (kg)
Powder WH2 standard	RE12-012	30/08/2012	200
Pellets 7 mm OD	RE12-013	30/08/2012	200
Pellets 28 mm OD	RE12-015	28/09/2012	400
CP (Crushed pellets powder)	RE12-016	11/10/2012	23

4.2 Initial characterization of materials

4.2.1 Water content

The measured water content of each material is given in Table 2. All measures were made by dry heating the material concerned at 105°C during 24 hours.

Table 4.2 : Water content of materials

Material	Water content (%)
Powder WH2 standard	2.3
Pellets 28 mm OD	5.1
Pellets 7 mm OD	4.9
CP (Crushed pellets powder)	4.9

4.2.2 Density

The “bulk density” was measured (by weighing a predetermined volume of pellets or powder or CP) thanks to the polycarbonate cell (Figure 4.1), while the “(apparent) dry density” was measured thanks to the “wax method”. Table 3 summarizes the results.

Figure 4.1: Measurement of bulk density with 28 mm OD pellets

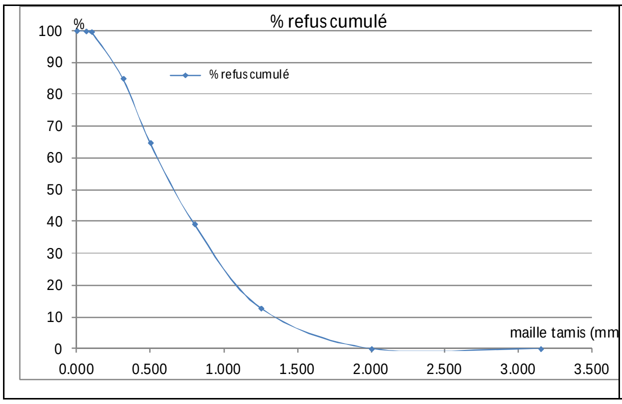
Table 4.3: Density of materials tested

Material	Bulk Density (Mg/m^3)	Dry Bulk Density (Mg/m^3)	Average Mass (g)	Density (Mg/m^3)	Dry Density (Mg/m^3)
Powder WH2 standard	1.084	1.060	-	-	-
Pellets OD 28mm	1.182	1.124	26.329	2.061	1.961
Pellets OD 7 mm	1.268	1.209	0.461	2.096	1.998
CP (Crushed pellets powder)	1.326	1.264	-	-	-

Note: For the WH2 powder, the grain density equaled 2.78 Mg/m^3.

4.2.3 Granulometry

A granulometry spectrum curve was plotted on the WH2 powder (reference LECBA RE12-012). The corresponding results are illustrated in Figure 4.2, confirming pretty well the WH2 characteristics furnished by the vendor (LAVIOSA MPC, another member of the GME).



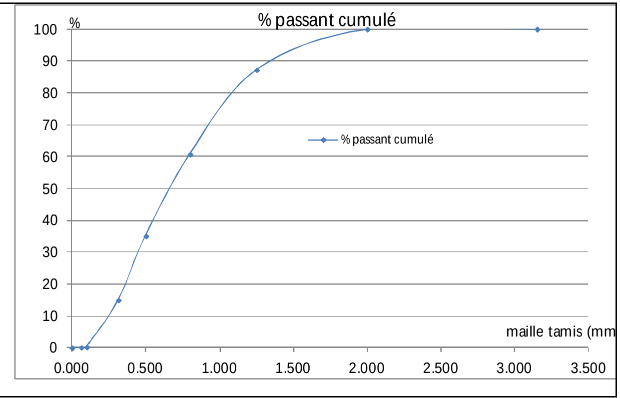


Figure 4.2 : Granulometry of bentonite WH2 powder - Reference LECBA RE12-012

4.3 Description of test equipment

4.3.1 Polycarbonate test cell

The polycarbonate test cell (ID 390mm, H 500 mm) was fabricated (Figure 4.3 shows the polycarbonate cell “as built”) in order to:

- Accurately measure the masses and volumes concerned by the tests,
- Reduce as much as possible the « side effects » by providing a significant test volume (the cell ID is some 12 times the pellet diameter),
- Visualize how the materials behave during filling operations and how the “piling” and “bridging” structures are formed in the mix emplacement,
- Take photos,
- Benefit from an easy assembly and dismantling device, considering the numerous tests implemented.

Figure 4.3 : Photo of polycarbonate cell during its commissioning

For the mass measurement, the cell was disposed on a 160 kg capacity scale with an accuracy of some ±50 g (0.03%). For the volume measurement, a 10 mmm thick aluminum lid was horizontally positioned on the top of the materials: the remaining height between the upper part of the cell and the lower part of the lid was measured with an accuracy of some 1/20 mm.

4.3.2 Mixer and bucket

The mixer used for the tests was a concrete mixer equipped with a fiber glass tank, a speed variator and a removable lid (used to prevent dust spill).

Following the mixing of the bentonite components, the admixture was poured into the polycarbonate cell, thanks to a tilting bucket. Figure 4.4 shows the mixer and the bucket.

Figure 4.4: View of mixer, polycarbonate cell and tilting bucket used

4.3.3 Steel balls

In the waiting of the first experimental bentonite pellets (28 mm OD), an assortment of steel balls, in various diameters was supplied, in order to evaluate the side effects, the piling structure and the compacity of the ball arrangement inside the polycarbonate cell. Table 4.4 presents the data (an average of 10 measures) related to the steel balls as well as the “inter-ball” void ratio. Figure 4.5 shows the evolution of the “inter-ball” void/space ratio as a function of the ball diameter.

Table 4.4 : Steel ball characteristics vs inter-ball void/space ratio

Steel ball OD (mm)	**25**	**31.75**	**34.925**	**39**	**44.45**
Mass (g)	63.797	130.200	174.324	234.424	358.173
Volume (cm3)	8.181	16.758	22.305	31.059	45.985
Density (g/cm^3)	7.798	7.769	7.815	7.837	7.789
Average void ratio (%)	41.86	42.63	43.93	45.37	45.57

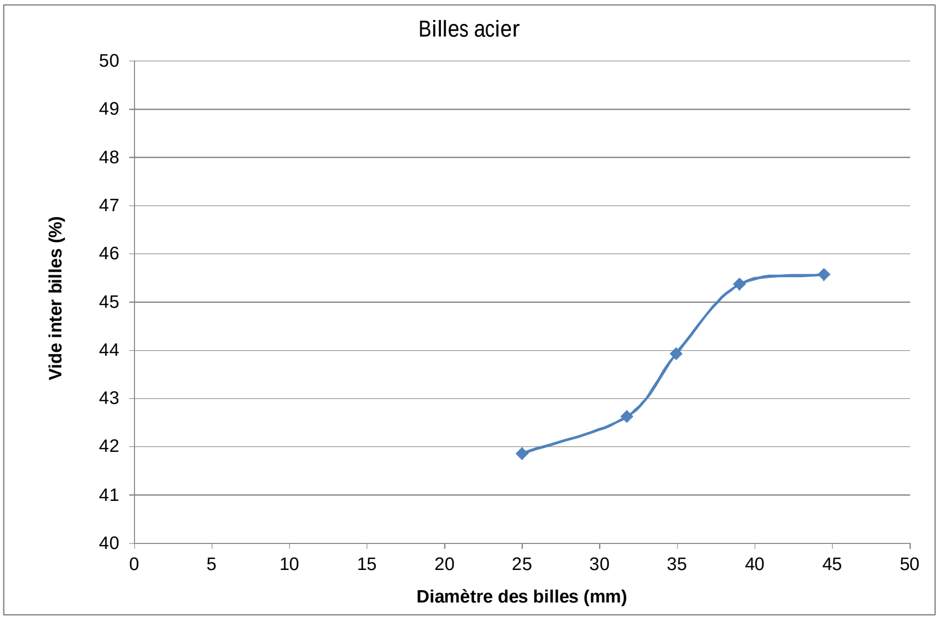


Figure 4.5: Evolution of the “inter-ball” space ratio as a function of the ball diameter

4.4 Tests with bentonite pellets only

The tests were carried out with 28mm OD pellets and 7mm OD pellets (cf. Figure 4.6) to determine the effective “inter-ball” ratio with the real material. Figure 4.7 shows the comparison obtained at the end of the tests.

Figure 4.6: Emplacement tests with 28mm (left) and 7 mm (right) OD pellets

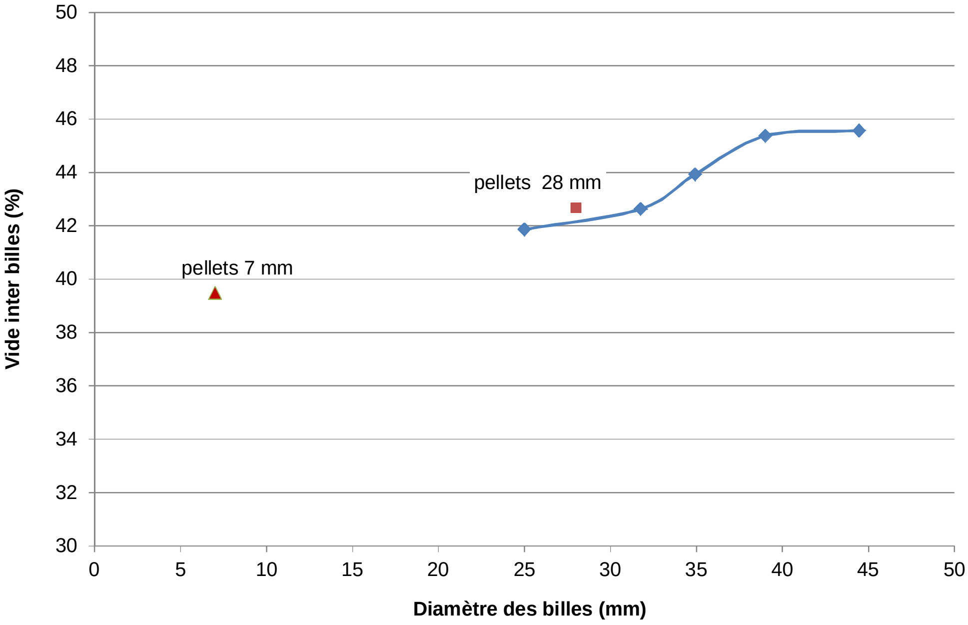


Figure 4.7: Comparison of the inter-pellets void as a function of the pellet diameter

4.5 Tests with binary mixtures

Five binary mixtures were tested, with the following (28mm OD) pellet / (standard WH2) powder ratios: 60/40, 65/35, 70/30, 75/25, 80/20 (the ratios are calculated on the basis of dry mass of each component), as shown in Figure 4.8. The tests were then repeated with a bentonite powder made of crushed pellets (CP).

Figure 4.8: Emplacement tests with binary mixtures

The comparison of the results obtained showed (cf. Table 4.5) that the most relevant mixture was that formulated with a ratio 70/30 and a powder made from crushed pellets (CP 0-5 mm) inserted in 10 layers in the inter-pellets voids.

It was inferred that with an effective 32 mm OD pellet, the emplaced density could be easily achieved and that the relevant mixture was the one identified during these definition tests, provided the pellet diameter change (from 28mm to 32mm) was made effective.

Table 4.5: Results obtained on binary mixture with 28mm OD pellets and crushed powder

Test	Mass of pellets (g)	Mass of powder (g)	% pellets	% powder	Total mass (g)	Height (mm)	Volume (cm^3)	ρ emplaced (g/cm^3)	ρ dry emplaced (g/cm^3)	Volume of void (cm^3)	% void	Total porosity (%)
Pellets 28 mm OD + crushed powder in 10 layers	38960	17380	68,59	31,41	56340	293,64	34796	1,619	1,555	2790	8,02	44,08

4.6 Tests with the real components

Once the production of 32mm OD pellets started, it was possible to repeat the series of tests with the real components and to make the necessary fine tuning formulation adaptation in order to reach the optimum method.

The following materials (cf. Figure 4.9) were delivered to LECBA for the purpose:

- Some 120 kg of pellets 32 mm Expangel SP32, referred at LECBA as n° RE13-005,
- Some 100 kg of crushed powder 0-2 mm, referred at LECBA as n° RE13-006,
- Some 100 kg of crushed powder 0-5 mm, referred at LECBA as n° RE13-007.

The granulometry curve of crushed powder RE13-007 is provided in Figure 4.10.

Figure 4.9 : Pellets RE13-005 – Crushed powder RE13-006 and RE13-007

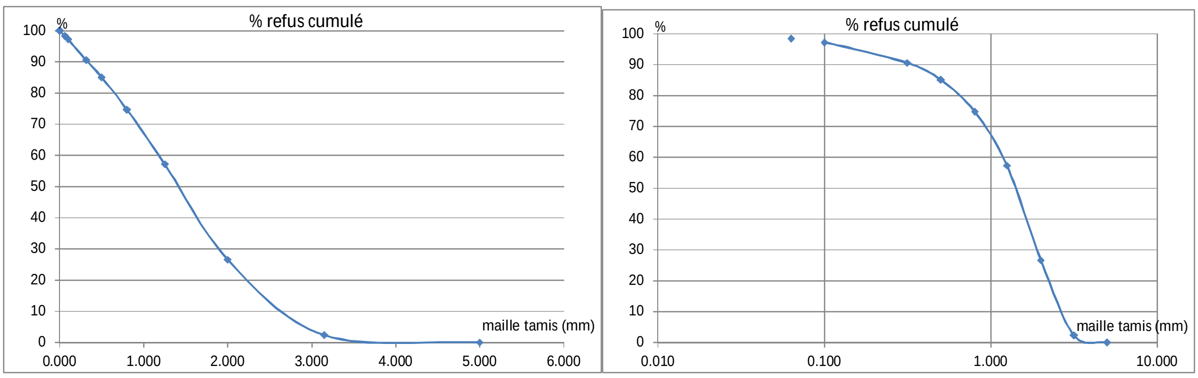


Figure 4.10 : Granumometry of crushed powder RE13-007

Figure 4.11 shows an example of one of a series of tests where the pellets are first introduced, and later the crushed powder is inserted. The Table 4.6 summarizes the best results obtained with 3 formulation combinations.

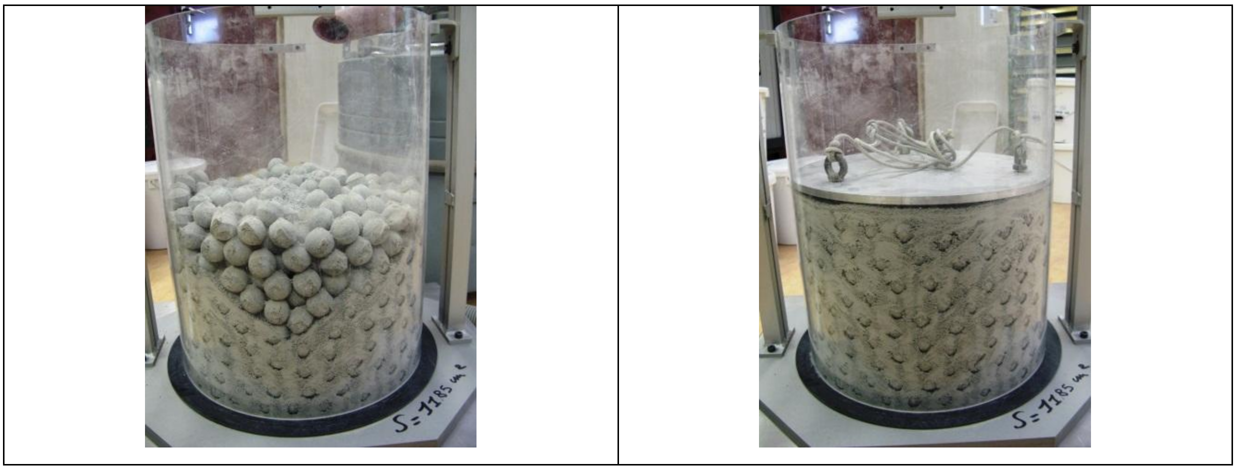


Figure 4.11: Backfilling test with 32mm OD pellets and crushed powder RE13-007

Table 4.6: Results obtained with the best binary mixtures (32mm OD pellets & CP)

Test	% pellets	% powder	ρ emplaced (g/cm³)	ρ dry emplaced (g/cm³)	Void rate (%)	Total Porosity (%)
Pellets 32 - 4 x 3 layers + crushed powder 0-2	68.2	31.8	1.663	1.599	5.04	42.50
Pellets 32 - 10 layers + crushed powder 0-2	70.3	29.7	1.631	1.569	7.85	43.57
Pellets 32 4 x 3 layers + crushed powder 0-5	68. 9	31.1	**1.644**	1.581	4.77	43.14

4.7 Selection of the bentonite formulation

Other iterations of tests were carried out with the above formulations, taking into account, other criteria such as industrial feasibility (homogeneity), logistics (packing, transport, and conservation), use (integrity, production of dust).

The water content of the raw material and the compaction pressure of the pellet manufacturing machine were also adjusted to find the best possible compromise.

At the end, it was decided that bentonitic admixtures with 70% of 32 mm pellets mixed *one layer at a time* with some 30% of crushed powder CP 0-5mm would be the optimum solution, but that the emplacement method had to be first reproduced/adapted at a metric scale before implementing the full scale (1:1) backfilling test in the FSS drift model.

5. Mock-up testing and emplacement machine design

5.1 Introduction

In parallel with the laboratory studies, a mock-up metric-scale set-up was developed for testing the selected bentonite admixtures and the backfilling device concept. It was deemed “necessary and careful” to test first at an intermediate scale (metric), the behaviour of the bentonitic mixes selected, before later going at full scale (decametric), since the manual emplacement methods carried out at a decimetric scale in lab could not be easily transposed (“from scratch”) to an industrial application at a decametric scale.

The test mock-up set-up is illustrated in Figure 5.1. The emplacement device is based on the use of two hoppers (one for pellets, one for CP) and two conveying augers for the respective conveying of pellets and powder (

Figure 5.21).

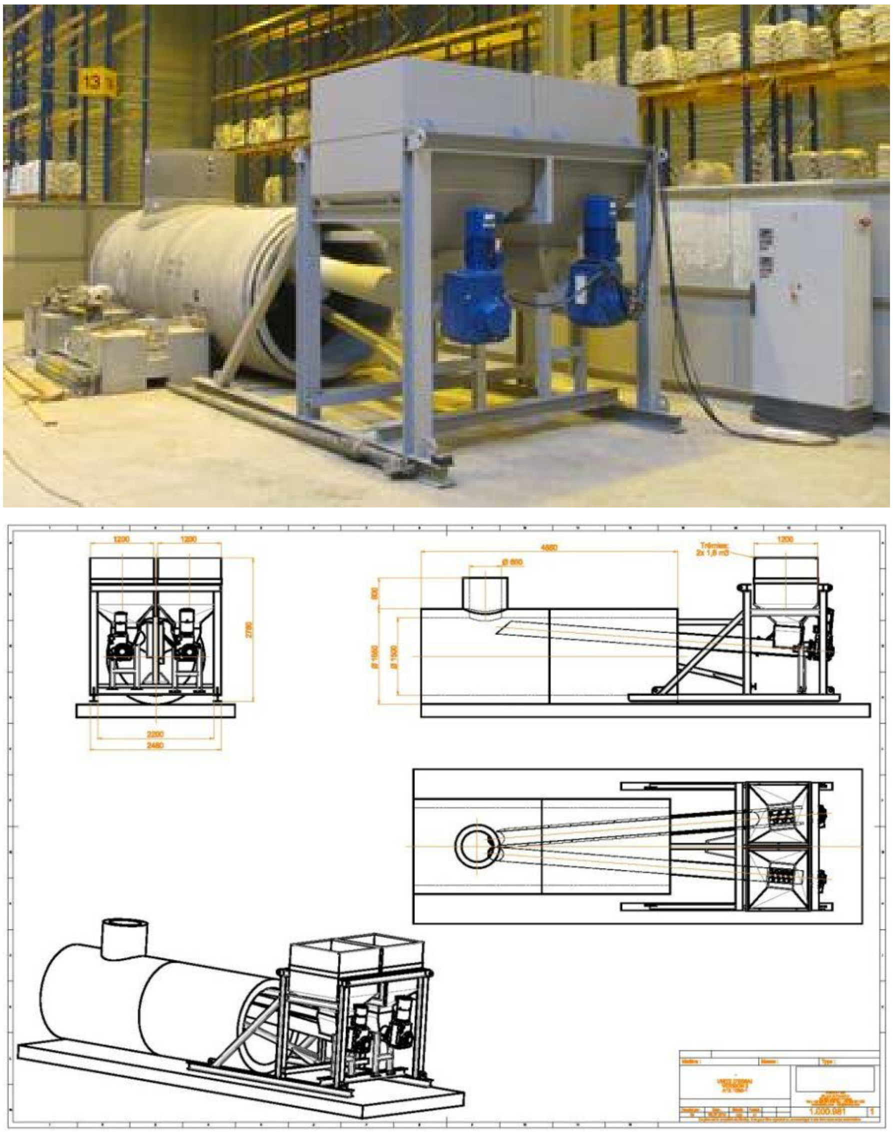


Figure 5.1: Metric emplacement test set-up

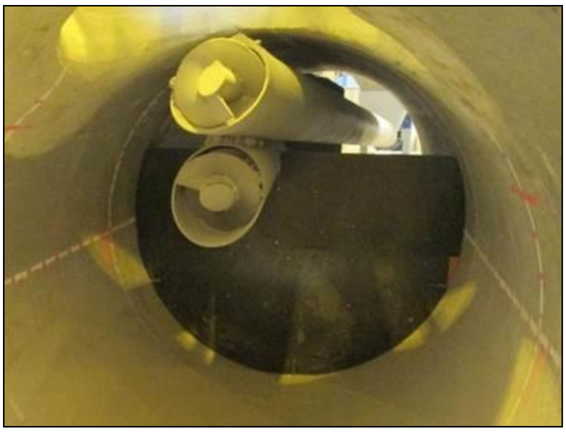


Figure 5.2**:** Mock-up tests of the bentonite pellet-powder mix using conveying augers

5.2 Outcomes

Globally, the use of the mechanical emplacement device selected turned out to be relevant.

The conveying augers managed to efficiently backfill the mock-up concrete pipe (cf. Figures 5.2 & 5.3) with the bentonitic mix and could also provide some “backfill pressure” high enough to fill the drift model summital voids (as simulated in Figure 5.4).

However, the obtained bentonite density was less than the specified value of 1620 kg/m^3 which was manually obtained in laboratory. The best values of the obtained density in this mock-up test were 1510 kg/m^3 with the powder auger above the pellets auger and 1470 kg/m^3 with the two augers side by side. Besides, the second position (side by side) turned out to me the most adapted one to exert an efficient backfilling pressure. This second position was also the one creating the most segregation between the emplaced components.

The main reason for these lower density values was deemed to be the breakage of some pellets during the handling process resulting in closure of inter-pellet spaces and preventing the powder from accessing some voids. As a result, mechanical resistance tests were introduced to measure the “hardness” of the pellets (resistance to erosion or breakage due to a compacting effort as envisaged inside the screw conveyor pipe) at the pellet production workshop and (as a measure of quality control) at the FSS site before emplacement.

A conveyor belt was also added to minimize the length of the passage of pellets inside the conveying augers, thus minimizing pellet erosion/attrition and breakage (cf. Figure 5.5). This solution was effective and incorporated in the design of the full scale emplacement machine for the backfilling of the swelling clay core in the drift model.

Figure 5.3 : Progressive backfilling of the mock-up pipe

Figure 5.4 : Backfilling pressure enabled to fill the summital voids

Figure 5.5 : Incorporation into the emplacement test set-up of a pellet conveying belt

Besides, an evaluation of the relationship between dry density and swelling pressure for WH2 undertaken in parallel with the metric emplacement tests described above showed that with a dry density of 1500 kg/m^3 only the swelling pressure obtained at saturation of material would be around 4 MPa.

This pressure was finally considered by Andra to be sufficient (as far as the permeability target was still preserved and the (host formation/argillite) EDZ self-sealing was still effective), and the FSS swelling clay core construction specifications were accordingly modified so that the required average dry density in the clay core would be 1500 kg/m^3 instead of 1620 kg/m^3 (as originally specified).

6. Characterization of the bentonite mix

6.1 Introduction

Even if the relation between the emplaced density value of the selected bentonitic mix and the swelling pressure was first established by experience (i.e. by extrapolating data from scientific literature on bentonite MX80), it was necessary to confirm that the selected bentonitic material formulation effectively reached the specified swelling pressure, i.e. some 4 MPa as defined at the end of the metric emplacement tests.

This aspect was explored in 2 phases and at 2 different scales:

- First, an oedometric test was carried out in lab on the FSS admixture in a test cell (at a decimetric scale), over a few months; this part is reported below.
- Then the REM test, carried out at the Bure/Saudron Technical Center (at a metric test), with the same FSS admixture, over a few decades (20-30 years). This experiment is ongoing and described in Conil et al. (2015) - DOPAS Work Package 4, Deliverable D4.2 (“Report on Bentonite Saturation Test (REM)”).

6.2 Experimental protocol and results

The FSS mix sample (composition is shown in Table 6.1) was placed inside a specially manufactured oedometric cell (cf. Figure 6.1) and progressively saturated. Saturation took some 181 days and maximum swelling pressure was reached after that lapse of time.

The experiment was then dismantled. The saturated bentonitic material appeared as thoroughly homogenized, without possible visual distinction between the pellets and the crushed powder (cf. Figure 6.2).

Table 6.1: Characteristics of FSS mix sample submitted to oedometric test.

<table>
<tr><th></th><th>Mass (g)</th><th>Dry Mass (g)</th><th>Proportion (%)</th><th>Height(mm)</th><th>Volume (cm³)</th><th>ρ emplaced (g/cm³)</th><th>ρ dry emplaced (g/cm³)</th><th>Pore Volume (cm³)</th><th>Total Porosity (%)</th><th>Sr (%)</th></tr>
<tr><td>Pellets RE14-002</td><td>3258.6</td><td>3121.0</td><td>69.,6</td><td rowspan="3">65.65</td><td rowspan="3">2970</td><td rowspan="3">1.577</td><td rowspan="3">1.510</td><td rowspan="3">1356.3</td><td rowspan="3">45.67</td><td rowspan="3">14.63</td></tr>
<tr><td>CP RE14-003</td><td>1425.6</td><td>1364.9</td><td>30.,4</td></tr>
<tr><td>Total</td><td>4684.2</td><td>4485.8</td><td>100</td></tr>
</table>

The measured pressure obtained after complete saturation was 3.88 MPa, i.e. slightly below the 4 MPa target. This value was however deemed acceptable to proceed with:

- The backfilling of the FSS swelling clay core inside the drift model,
- The launching of the REM experiment.

Figure 6.2.1: Illustration of oedometric test cell backfilling with the FSS mix

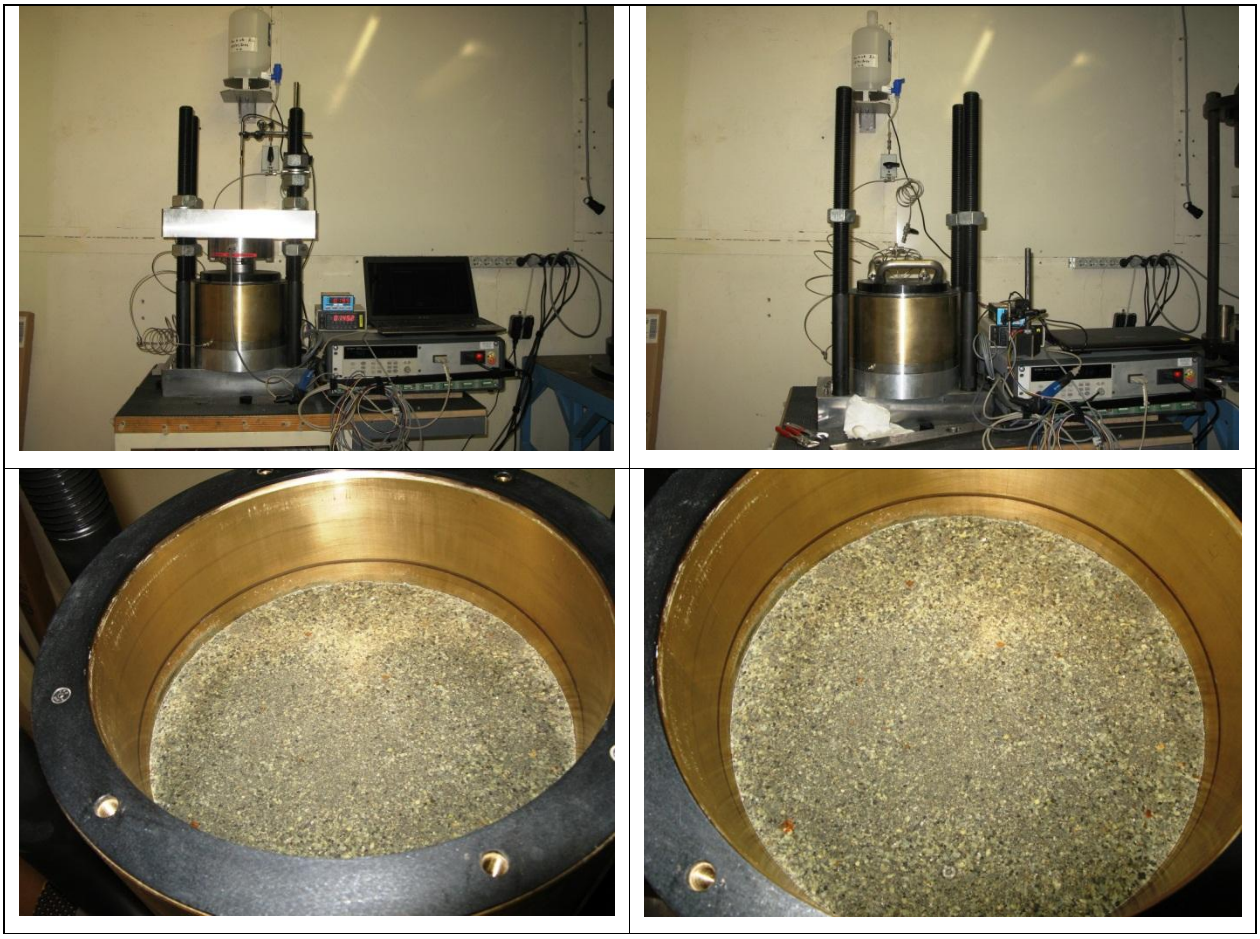


Figure 6.2.2 : Dismantling of test cell and view of saturated/homogenized FSS mix

7. Conclusion

At the end of the swelling clay core definition, metric emplacement tests and characterization, it was concluded that:

- The mix recipe was robust, and that the fabrication of the material manufacturing for FSS could be launched;
- The swelling pressure measured in lab was close enough to the 4 MPa target to initialize the REM experiment;
- The design of the FSS backfilling machine could be frozen and its fabrication ordered (incorporating the pellet conveying belt).

The subsequent swelling clay core construction is reported in Bosgiraud *et al.* (2016) - DOPAS Work Package 3, Deliverable D3.12 ("Report on construction of FSS swelling clay core").

8. References

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- Bosgiraud *et al*. (2013) - DOPAS Work Package 3, Deliverable D3.2 ("FSS tunnel model design report").
- Bosgiraud *et al*. (2016) - DOPAS Work Package 3, Deliverable D3.3 ("Report on clayish material definition for FSS") – combined with D3.7.
- Bosgiraud *et al*. (2016) - DOPAS Work Package 3, Deliverable D3.4 ("Report on low pH concrete formulas for FSS") – combined with D3.8.
- Bosgiraud *et al*. (2016) - DOPAS Work Package 3, Deliverable D3.5 ("Lab test Report on the performance of the clayish material for FSS") – combined with D3.7.
- Bosgiraud *et al*. (2016) - DOPAS Work Package 3, Deliverable D3.6 ("Lab test Report on the performance of low pH concrete for FSS") – combined with D3.8.
- Bosgiraud *et al*. (2016) - DOPAS Work Package 3, Deliverable D3.7 ("Test report on FSS metric core emplacement, with clayish materials definition for FSS and Laboratory work on the performance of clayish materials for FSS").
- Bosgiraud *et al*. (2013) - DOPAS Work Package 3, Deliverable D3.8 ("Test report on FSS cast in box concrete with low pH concrete formulas for FSS and Laboratory work on the performance of low pH concrete for FSS").
- Bosgiraud *et al*. (2016) - DOPAS Work Package 3, Deliverable D3.9 ("Test report on FSS test panel for shotcrete").
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- Bosgiraud *et al*. (2014) - DOPAS Work Package 3, Deliverable D3.11 ("FSS cast concrete plug construction report").
- Bosgiraud *et al*. (2016) - DOPAS Work Package 3, Deliverable D3.12 ("Report on construction of FSS swelling clay core").
- Bosgiraud *et al*. (2016) - DOPAS Work Package 3, Deliverable D3.13 ("Report on shotcrete plug construction").
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