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"Full Scale Demonstration of Plugs and Seals"
DOPAS - Work Package 3

Deliverable D3.11: "Report on FSS cast concrete plug construction"

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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 demonstrator at scale 1:1, designed and built by Andra with the scientific help of NAGRA, while other WMO's (DOPAS partners) are building or have built their own plug or seal prototypes.

This report D3.11 gives an overview of the work implemented at FSS test site (Saint-Dizier) to construct the low pH self-compacting concrete (aka SCC) plug (the first component of the FSS experiment), i.e. the upstream concrete containment wall which was erected in July 2013.

The document includes an overview of the field activities (methodology and tools, timing, outcomes), illustrated by photos, c/w practical details and comments.

Links to previous and future Andra's FSS specific (or DOPAS more general) deliverable reports are also given.

List of Acronyms

This generic list of acronyms concerns entities, activities, concepts, equipment and materials which are Andra (or DOPAS Partners) specific in the context of the FSS experiment.

ASN: Autorité de Sûreté Nucléaire (Nuclear Authority).

CIGEO: Centre Industriel de Stockage Géologique (Industrial Repository, AKA Cigéo).

CEA-LECBA: Company contracted for the low pH concrete mixes formulation and qualification (a member of the GMES Consortium)

CNE: Commission nationale d'évaluation (National Assessment Board).

CSH: Calcium Silicate Hydrates.

DGR: Deep Geological Repository (see also GDF)

DOPAS: Full-scale Demonstration of Plugs and Seals (Name of Project on Seals).

EBS: Engineered Barrier System.

EC: European Commission.

EDZ: Excavation damaged zone.

ESDRED: Engineering Studies and Demonstration of Repository Designs.

FSS: Full-Scale Seal.

GDF: Geological Disposal Facility.

GME: Groupement momentané d'entreprises (FSS General Contractor formed as a Consortium of companies).

HLW: High-level Waste.

IAEA: International Atomic Energy Agency.

ILW: Intermediate-level Waste.

IRSN: Institut de Recherche sur la Sûreté Nucléaire (Expert Organisation acting as a support to ASN).

LLW: Low-level Waste.

OPC: Ordinary Portland cement.

RA: Concrete hardening Retarder

R&D: Research and Development.

SCC: Self-compacting concrete or self-consolidating cast concrete.

SP: Concrete Super-Plasticizer.

SMC: Supplementary cementing materials

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 9 countries) involved in the EC supported DOPAS Project are listed below. In the remainder of this report each partner (if mentioned) is referred to as indicated:

Andra:	Agence nationale pour la gestion des déchets radioactifs (France).
B+ Tech:	B+ Tech Oy (Finland).
CTU:	Czech Technical University (Czech Republic).
DBE TEC:	DBE TECHNOLOGY GmbH (Germany).
GSL:	Galson Sciences Limited (United Kingdom).
GRS:	Gesellschaft für Anlagen und Reaktorsicherheit (Germany).
Nagra:	Die Nationale Genossenschaft für die Lagerung Radioaktiver Abfälle (Switzerland).
NDA:	Nuclear Decommissioning Authority (United Kingdom).
NRG:	Nuclear Research and Consultancy Group (The Netherlands).
Posiva:	Posiva Oy (Finland).
SURAO:	The Radioactive Waste Repository Authority (Czech Republic), aka RAWRA.
SKB:	Svensk Kärnbränslehantering AB (Sweden).
UJV:	UJV Řež a.s. (Czech Republic).
VTT:	Teknologian Tutkimuskeskeskus VTT (Finland).

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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 clayish formation, which lies in the east of the Parisian Basin. The industrial repository project is referred to as Cigéo. The disposal reference inventory includes long-lived Intermediate-level waste (ILW) from operation, maintenance and decommissioning of nuclear facilities and high level (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 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, drifts[1] 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.

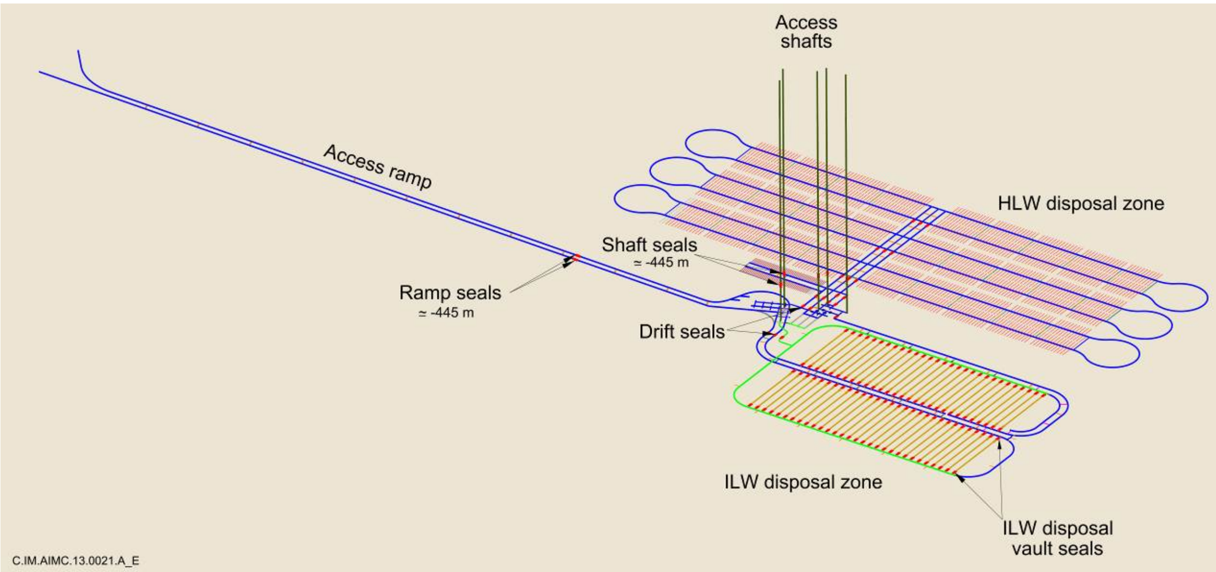

Figure 1: Location of the seals in the French repository concept

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

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 hangar of a surface facility 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, etc.). Moreover the Bure URL is busy with various other experiments which cannot be conducted concurrently with large experiments such as FSS.

For that reason, and for standalone reasons, like global experimental costs, global schedule and needs for "clever" dismantling, 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 hangar (more than 10m of free gap under the roof frame), and the possibility of ambient air parameters control were in line with the experiment technical expectations.

2.1 FSS Design basis

The FSS test is part of a wide-ranging programme of R&D and demonstrator experiments that was established 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 drifts and ILW disposal vault seals, require 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 swelling clay (bentonite) to be suitable for filling recesses (breakouts) in the clay host rock (argillites), and also the capacity to build large low pH concrete* containment walls with satisfactory mechanical properties. The FSS test is focused on the construction of the seal, and the swelling clay will not be saturated or otherwise pressurised. The conceptual design of the FSS test is illustrated in Figure 2.

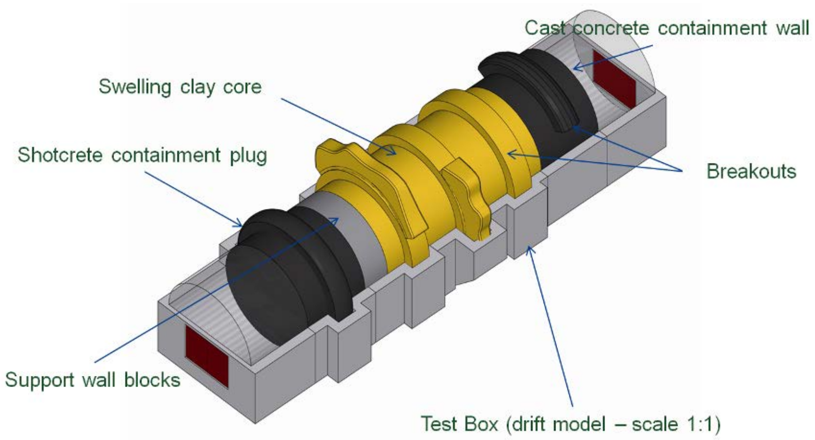

Figure 2: Conceptual design for the ANDRA FSS test

The main difference between the Cigéo reference and FSS design basis for the Andra drift seal is the length of the seal. The real seal underground will be longer than the seal considered in the FSS experiment. The Cigéo seal design basis and that of the FSS test are justified in DOPAS Deliverable D2.1 “Design Bases and Criteria”.

The FSS test box 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.

Representative underground ambient conditions (temperature around 18-30 °C, relative humidity between 50% and 75%, ventilation), 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 is some 14m long.

2.2 FSS Test Box Design

The FSS Test Box design was elaborated between July and October 2012. The workshop drawings were also supplied during that period on the basis of the FSS test box concept (as specified by Andra), and (following modelling and dimensioning) derived from the schematic and general lay-out presented in Figure 3.

The design of the Test Box is documented in DOPAS Deliverable D3.2 “FSS Tunnel model design report”.

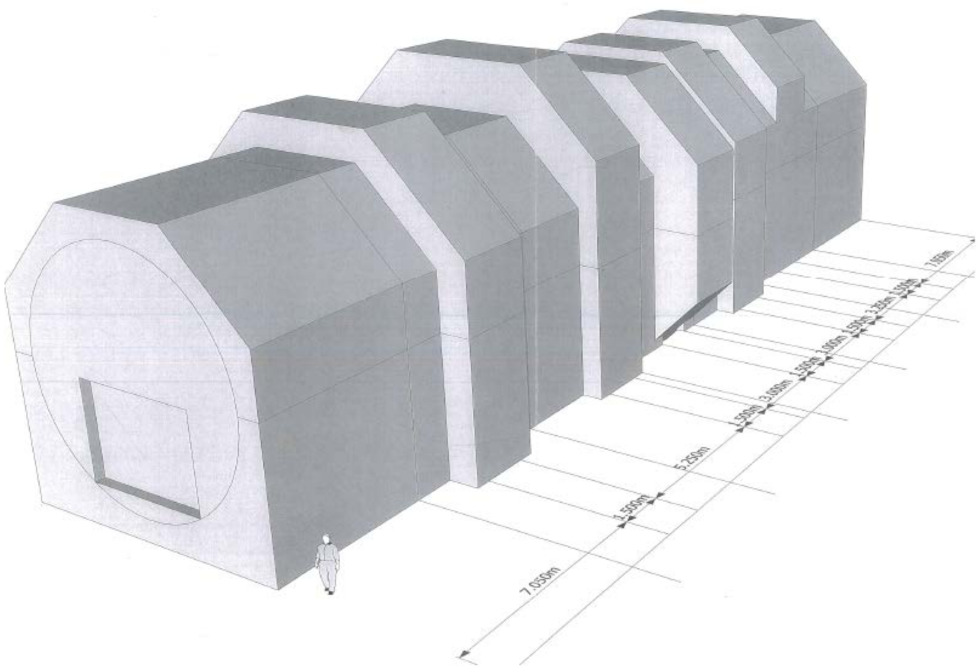

Figure 3: 3D schematic of the FSS test box (drift model)

(*) Low pH concrete is used to mitigate the effects of the alkaline plume on the hydraulic properties of the argillites (host formation) and of the bentonite constituting the swelling clay core.

3. The Construction of the Test Box

Turning the first sod for the FSS construction took place on October 29th, 2012, with a partial cutting and dismantling of the hangar concrete slab. On December 10th, 2012, the lower part of the concrete box framework was started. Before that a concrete foundation base had been poured on the newly created platform.

The reinforced concrete box structure was then built with the casting of 7 lower blocks followed by 7 upper blocks (each 5m long). Nine weeks were necessary to build the lower part of the box, while 13 weeks were necessary to build the upper part. The last block concrete casting phase took place on May 2013.

The access to the top of the test box was made possible thanks to a set of stairs. In order to see and check the bentonite backfill, 12 observation windows were also created. A local exhaust ventilation system ("mine like") was installed, with a closing door in the front of the box, in order to control the ambient temperature and the average moisture rate. A temperature and hygrometry monitoring device was also installed.

The box could then be commissioned and get the "ready for experiment" status (Figure 4).

The Test Box construction story is documented in DOPAS Deliverable D3.10 "Drift construction report".

Figure 4: The FSS test box ready for seal construction

PS: It can be noted that no special research work was done on the concrete mixt used for the test box construction; it was based on an ordinary Portland cement (OPC) and on common local aggregates.

4. The development of the low pH SCC concrete formulation

4.1 Introduction:

The DOPAS-FSS project involves the fabrication of two low-alkalinity concrete plugs (aka containment walls): one made with shotcrete and the other one with SCC. This chapter briefly addresses the formulation and qualification works related to the low pH SCC, first in lab, then in field at a metric and plurimetric scale.

The FSS low pH SCC concrete requirements were defined as summarized below:

- The pH value of the concrete pore solution must be lower than 11.0 at 28 days (and ideally between 10.5 and 11.0),
- The SCC must be pumpable and useable two hours after mixing (to account for the time needed to transport the concrete from surface down to 500 m underground in Cigéo),
- The compressive strength must be greater than 30 MPa after 28 days and 40 MPa after 90 days respectively,
- The maximal temperature reached within the containment wall (Ø8×5 m) during curing and hardening must be less than 50°C at all times,
- The spreading value must remain between 55cm and 75cm, some 2 hours after initial mixing,
- The shrinkage value (90 days after casting) must be as close as possible to 350µm/m.

The design of a proper concrete formulation (mixture design) was dealt with in four consecutive steps:

- First, different binder compositions were tested in lab and the most efficient ones in reducing the pH were then selected for the second phase,
- The second step consisted in proportioning the SCC mix. The resulting concretes were tested in the laboratory and their properties of interest were measured,
- In a third step, the most promising mixes were tested at a metric scale (in field) using the ready-mix plant selected for the FSS project,
- Finally, the relevancy of the formulation was checked at a metric and then a plurimetric scale in field conditions (final casting test was on a $12m^3$ monolith).

This approach enabled the selection of the best formulation used further for the full scale construction of the SCC upstream containment wall in FSS.

This development work is described in DOPAS Deliverables D3.4: “Report on low pH concrete formulas for FSS”, D3.6: “Lab report on the performance of low pH concrete for FSS” and Deliverable D3.8: “Test report on FSS cast in box concrete”. These 3 reports are compiled in one single document (D3.8).

The final formulation of the SCC mixture is given in the last of these reports.

4.2 Low pH SCC Composition

The FSS containment wall construction being scheduled in mid-July 2013, temperature was deemed to have a big impact on the SCC behavior (rheology) at the fresh state. By reference to the concrete formulation pre-defined at the end of the testing and characterization phases (see Chapter 4.1 above), it was then decided to keep untouched the Superplasticizer (SP) dosage and to adjust the Retarding Agent (RA) content to the effective ambient temperature (especially during daytime, at night the temperature was milder): the higher the temperature, the higher the RA dosage (fine-tuning).

Moreover it was required that the maximal temperature reached should be less than 50°C. Thus, using the results from the semi adiabatic calorimetry measures, the heat emitted during hydration was assessed and later used to estimate the maximal temperature at which the concrete could be poured to meet the requirement (in doing so, all the heat emitted was assumed to participate in the temperature increase). It was found that the maximal temperature increase during curing and hardening was 24°C. In practice, it was then advised not to pour concrete with an ambient temperature greater than 26°C. Those ambient conditions were effectively respected at time of casting operations (this issue could be encountered in Cigéo, since the underground temperature may vary significantly, depending on the date at which a disposal panel is closed). The final low pH SCC recipe used for the casting of the FSS upstream containment wall is given in Table 1.

Table 1: Composition of the concrete mixture as used in FSS for the low pH SCC containment wall construction

Components & Origin	Quantity
Rounded Gravel 5/12 (dry) - CALIN	682.1 kg/m^3
Sand 0/4 (dry) - CALIN	698.7 kg/m^3
Cement CEM III/A 52.5 L CE PM ES CP1 NF (ROMBAS) - CALCIA	130.0 kg/m^3
Silica Fume - CONDENSIL	130.0 kg/m^3
Filler - CARMEUSE?	408.4 kg/m^3
Glenium SKY 537 (SP) - BASF	*2.2%
Prelom 510 (RA) - BASF	*0.1%
Water	204.1 kg/m^3

(*) *Percentage of additives expressed as a ratio of binder (cement + silica + filler) weight*

5. The low pH SCC containment wall story

5.1 Preparation of construction operations

The casting operations took place in July 2013 and were preceded by preparation activities implemented in June 2013. The main issue was to design and erect a proper form:

- As what would be the case underground in Cigéo, a one face form was selected (by contrast with a traditional double form with cross bars),
- To withstand the pressure generated by the water-head appearing at time of pouring the semi-liquid concrete, a proper dimensioning of the form was carried-out and strengthening beams (bracons) were added at the rear of the form (see Figures 5 & 8),
- To provide a leak-tight contact with the test box inner wall, it was decided to fix a support angle bar at the periphery of the box inner wall and to add a foam type flat seal between the face of the form and that of the angle bar,
- To prevent the rising of the "one face" form under buoyancy, an anchoring device was attached to the form thanks to a temporary concrete raft (see Figure 6 & 7).

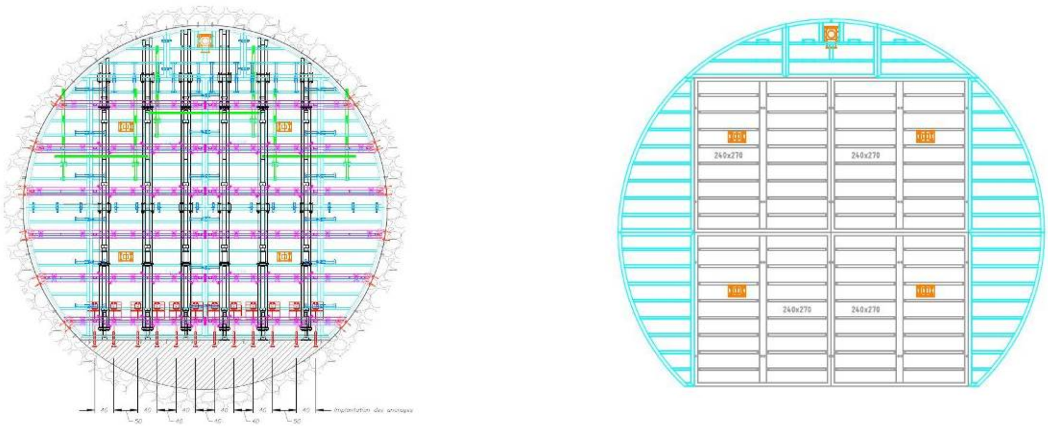

Figure 5: Design of the plug casting form with (left) and without (right) reinforcement

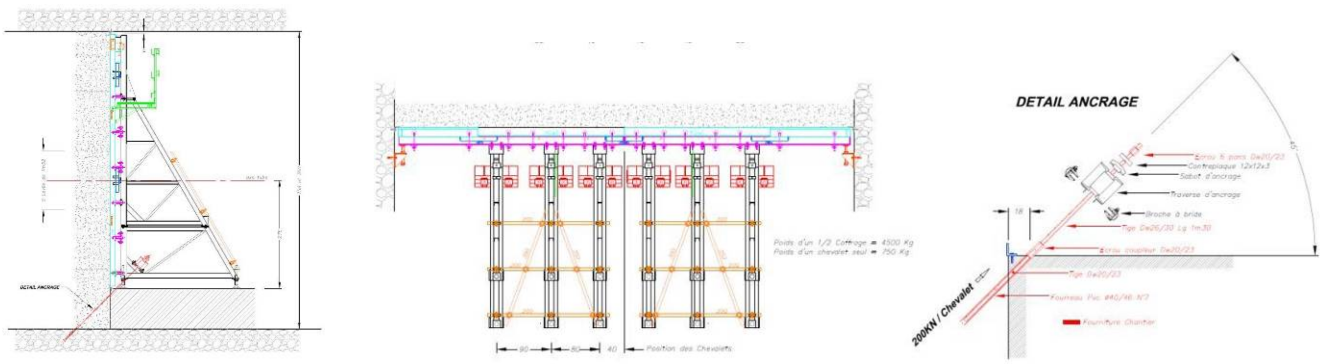

Figure 6: Design of the SCC plug form anchoring device

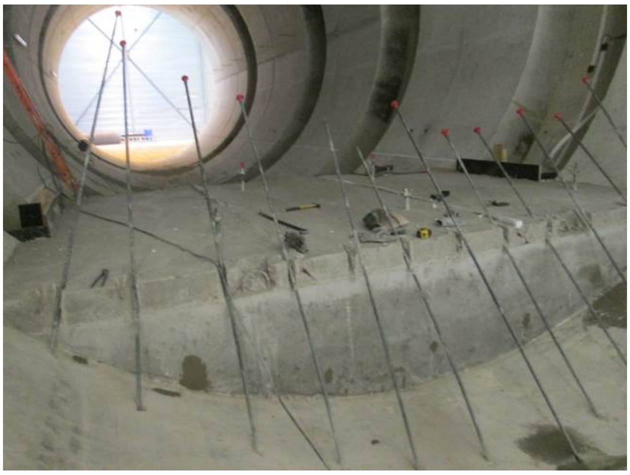

Figure 7: The temporary raft and the form anchoring bars

Figure 8: The one face circular formwork as erected

It was also necessary to install 4 washout vents (tubes): 2 were set to release the air trapped when the concrete rises up into the test box recesses and the 2 others were pre-positioned for the future bonding operations(see Figure 9).

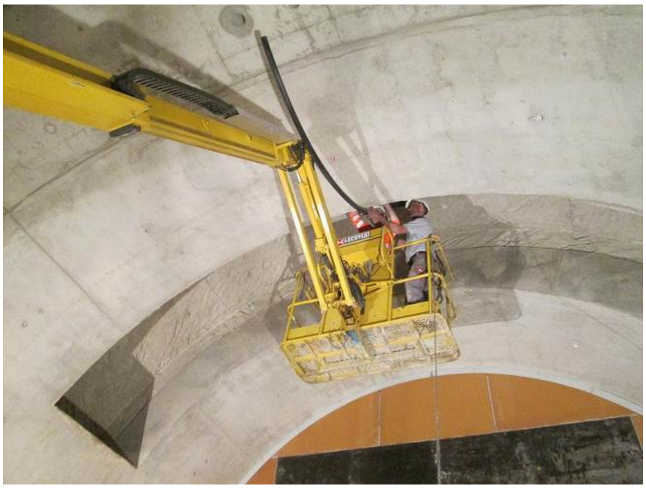

Figure 9: Installation of washout vents in the summital recesses

5.2 The casting operations

The low pH SCC casting operations were carried out with 3 main objectives in mind:

- To realize a monolith type containment wall (~ 250 m^3),
- To abide by a maximum concrete curing temperature criterion of 50°C,
- Try to limit as much as possible concrete shrinkage and cracking.

For that purpose, the following operational choices were made:

- It was decided to pour (mixing truck) batches of $7m^3$ each,
- A stand-by time of 2 hours between two passes of pouring was imposed at the exception of the summital part (when one batch per hour was poured).

The Figure 10 shows how the progressive casting of the containment wall was effectively carried out over time.

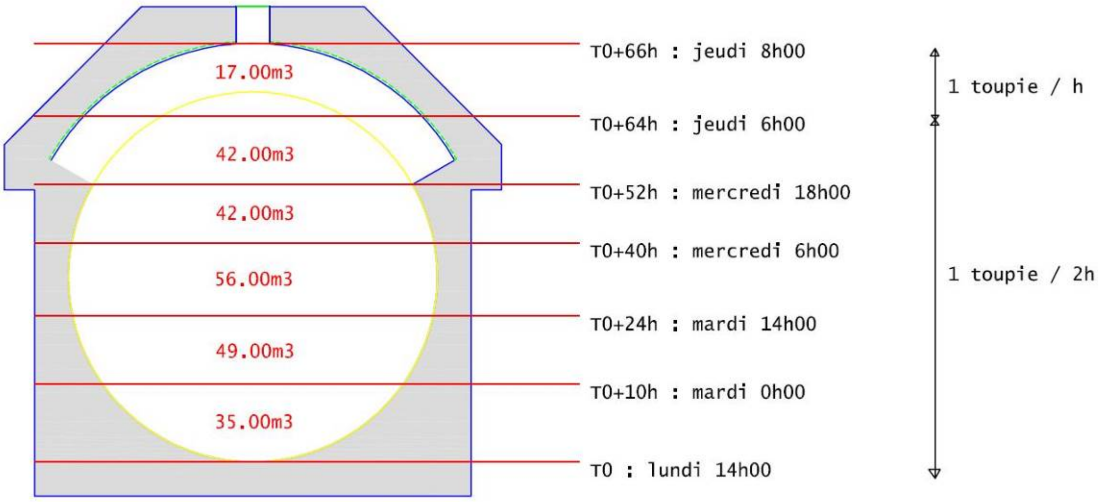

Figure 10: View of the low pH SCC containment wall concreting sequences

From a practical point of view, the fabrication of the low pH concrete batches took place in the concrete mixer plant in Saint-Dizier (some 5 km from the FSS site), the same plant (see Figure 11) as that used for the preliminary test phases, i.e. the concrete formulation and qualification phases.

The concrete was transported by mixer trucks. Each mixer truck batch represented a layer about 15 to 20cm thick in the containment wall construction progress. The pouring speed was some $7m^3$ in 20' followed by 1h 40' in the waiting for the next mixer truck.

All the mixer truck $7m^3$ batches passed a qualifying flow test before proceeding with the pouring of the concrete (see Figures 11 & 12). The spreading value was logged concurrently with the ambient temperature.

Figure 11: Preparation of concrete at the Saint-Dizier mixing plant (left) and concrete sampling at the FSS site (right)

Figure 12: Concrete slump flow test - Abrams values remained between 55cm & 75cm

The casting operations for which a concrete pumping truck was mobilized went very well with the low pH concrete rising progressively inside the box, with a smooth and regular emplacement (see Figure 13).

To finish the operation, it was necessary to totally close the one face formwork and the concrete was injected in blind thanks to concrete placing booms (see Figure 14).

Figure 13: Pouring and even emplacement of SCC inside the test box

Figure 14: Emplacement of SCC close to the recess (left) and in the recess (right)

5.3 The Bonding Grout Injection Operation

After its casting, the SCC containment plug was left for preliminary curing for about 1 week, and then the stripping of the form took place with no particular difficulties. The temporary raft was dismantled.

Some 28 days of hardening later, the injection of low pH slurry (grout) was started to bond the containment wall extrados with the test box concrete liner intrados (see Figure 15). The quantity of injected slurry turned out to be very small (a few tens liters).

It was inferred that in this experimentation, there was little vacuum remaining or/and that the bonding had already taken place (this deduction will be checked during the containment wall coring and dismantling operations planned at the end of FSS – cf. Chapter 7).

Figure 15: Injection of bonding grout at the summital contact between plug and box

5.4 The FSS Upstream Containment wall product after form stripping and bonding

At the end of the casting and bonding operations, the form stripping enabled to watch a very homogeneous monolith without traces so far of cracks or fractures. The contacts between the plug and the concrete liner look also excellent. Few air bubbles are trapped in the matrix.

The only surface particularities are the "ripples" due to the rheological behavior of concrete at time of casting. It was previously checked (by coring the plurimetric monolith cast during the qualification tests) that those ripples were only positioned on surface, without penetration into the matrix.

The first visual impression (see Figure 16) is quite positive, but, as already mentioned, the coring and dismantling operations only will enable to confirm the thoroughness of contacts, the homogeneity of this large monolith and the absence of internal cracks.

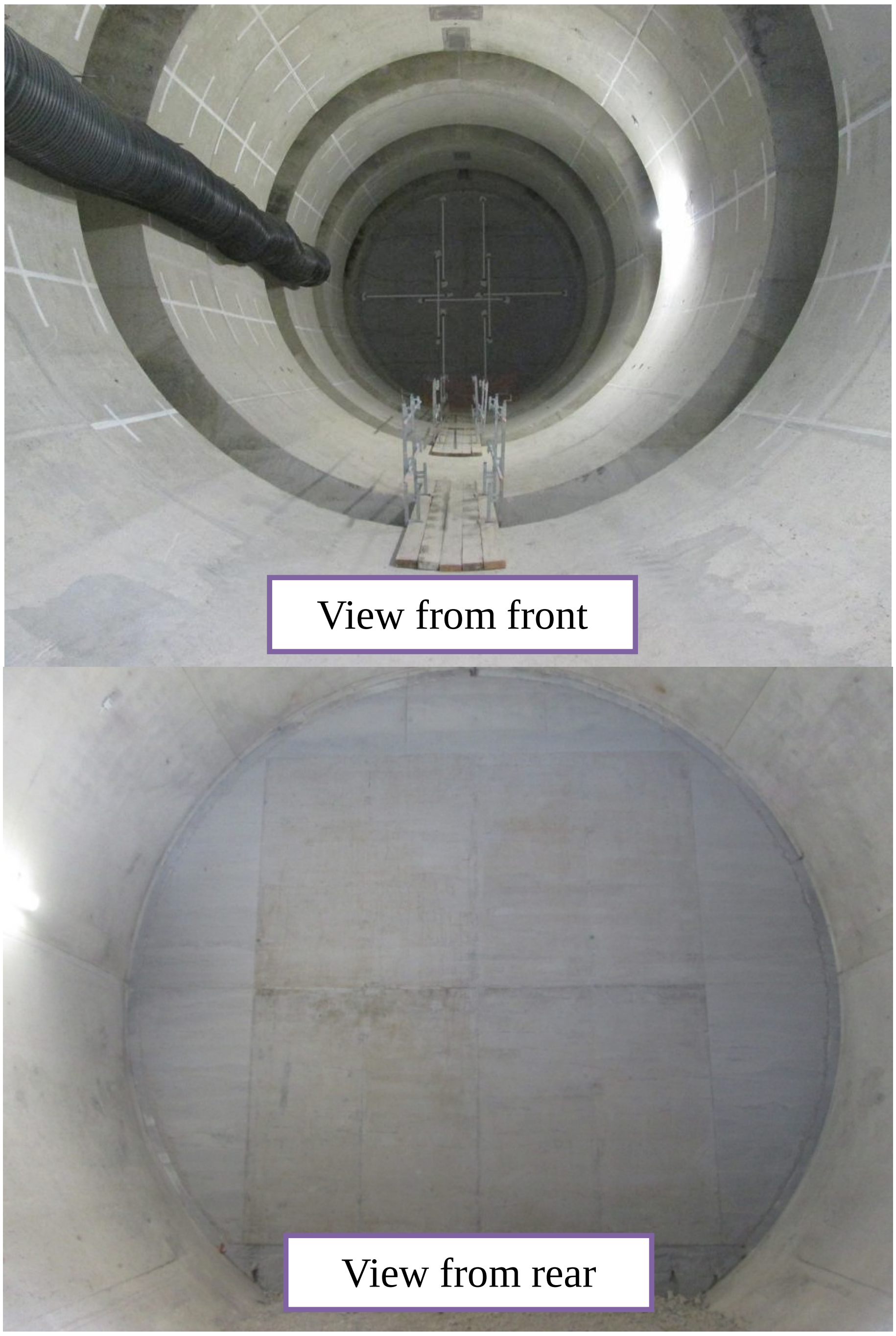

Figure 16: The SCC upstream containment wall as an end product

6. Monitoring of operations and first results

6.1 Compressive strength and rheology

Some 241 $m^3$of low pH SCC were poured in 3 days (3 shifts - 72 hours nonstop) without incidents. The samples taken from each batch gave favorable results in terms of compressive strength (Rc) results (requirement were 30MPa at 28 days and 40 MPa at 90 days) and Abrams spreading values also compliant with the contractual requirements, i.e. between 55cm and 75cm. (cf. Table 2).

Table 2: Measures of the concrete mixture characteristics as used in FSS for the low pH SCC containment wall construction

Sample taken from mixer truck N°	Compressive strength (Rc) at 28days (MPa)	Spreading value at T0+2h (cm)	Concrete temperature at T0+2h (°C)
2	43.2	55	26.7
10	44.5	66	21.9
18	43.6	60	27.0
26	40	59	28.8
34	44.5	70	26.1

Note: The temperature variation between day and night (hence from one batch to the other) justified the somehow wide range of spreading values (RA content was adapted). This had no direct impact on the compressive strength values.

6.2 Results of low pH SCC containment wall monitoring

In order to monitor the evolution of concrete temperature and shrinkage, some probes and sensors were pre-installed in the test box (see Figure 17). They provided some worthy information during casting operations and during the curing and hardening phases to check the SCC behavior compliance.

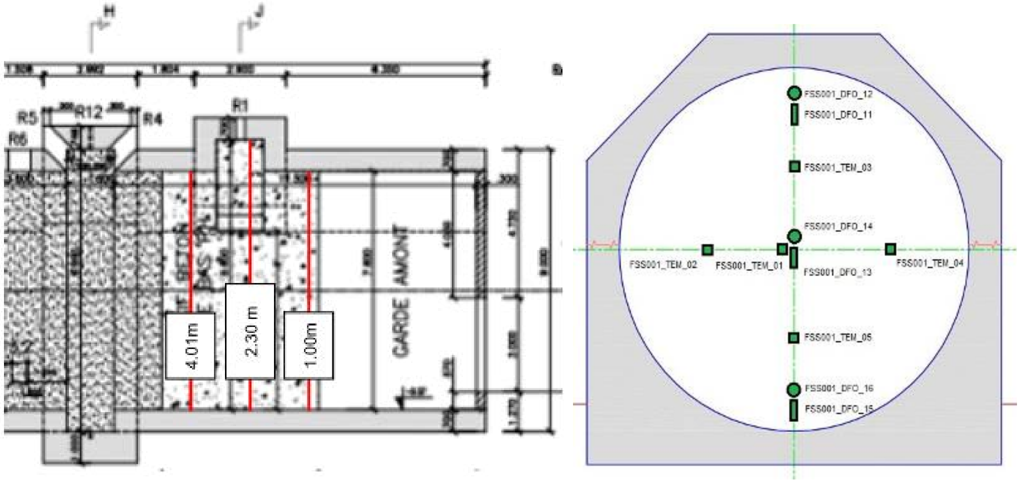

Figure 17: Positioning of temperature probes and shrinkage sensors inside the test box

The maximum curing temperature reached was 47°C, i.e. lower than the 50°C requirement (see Figure 18)

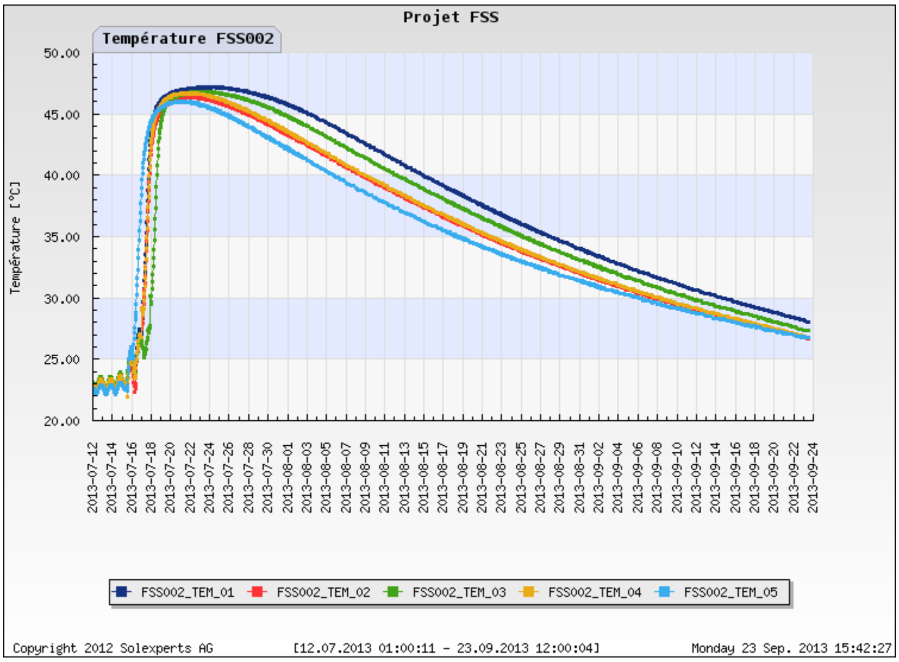

Figure 18: Curves showing the evolution of SCC temperature with time

Shrinkage values were also quite satisfactory (see Figure 19) since they remained under the contractual specification and under the statistical values encountered with a classical OPC formulation (some 500µm/m at 28 days).

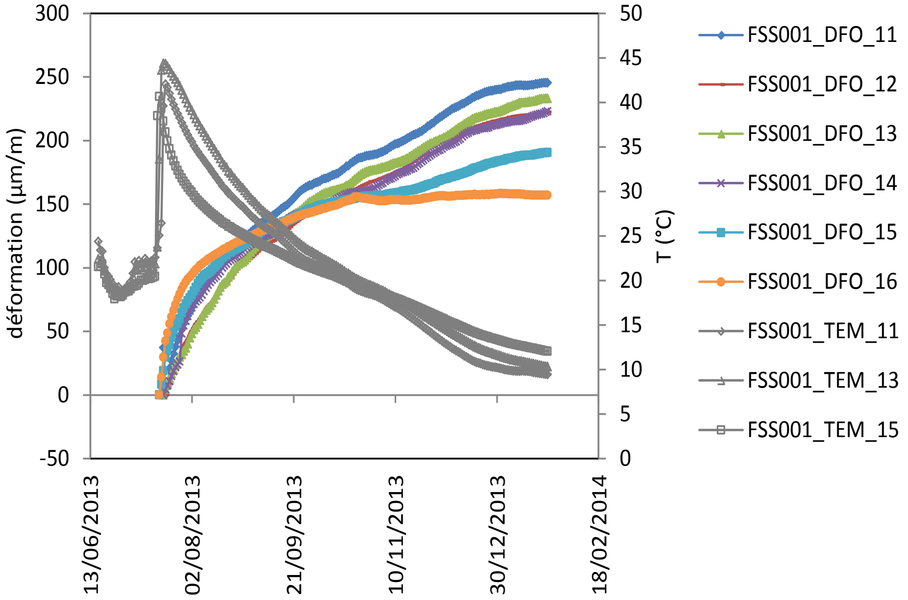

Figure 19: Curves showing the evolution of shrinkage (left scale) & temperature (right scale) with time

7. Conclusions

The main outcomes of the FSS low pH SCC upstream containment wall construction test are listed below:

- The low pH self-compacting concrete formulation is well suited to pumping and pouring of the monolith, as demonstrated by the easiness of casting, the absence of visible cracks and the rare entrapped air bubbles,
- This test is a “first of a kind” in terms of volume and dimensions for low pH concrete works in general and containments walls/plugs in particular,
- The concrete pH values (~ 10.5) and mechanical properties (Rc ~ 40MPa) are commensurate with (or better than) the pre-determined specifications,
- The shrinkage values and curing temperature measurements are also compliant,
- The operational cycle (241m3 cast in 72 hours – 3 shifts) and the operational tools and methods used are compatible with “Cigéo” underground conditions,
- “Clever dismantling” will help in confirming the relevancy of the industrial concept & method tested (the containment walls of FSS will be cored in 2014 and later wire sawed for further evaluation in 2015),
- So far, SCC containment wall construction feasibility is proven with classical civil work & mining equipment.

The operational green light to proceed with the swelling clay core backfilling activities was given in October 2013.

Note 1: Following coring and wire sawing of the low pH SCC containment wall, the cores and concrete samples will be photographed and sent to various laboratories for complementary analysis (porosity, pH, compressive strength, gas and water permeability …). The results available will be presented in the DOPAS Deliverable D4.8 “FSS Experiment Summary Report”, at the end of the DOPAS Project.

Note 2: A video of the FSS low pH SCC containment wall concreting operations can be watched by getting connected to the DOPAS Portal (Web site: http://www.posiva.fi/dopas).

8. References

- Andra 2005 - Dossier 2005 Argile: "Safety evaluation of a geological repository".
- Andra 2012 - Cahier des charges FSS1: "Etude et réalisation du démonstrateur technologique de scellement à pleine échelle (Full Scale Seal)" – (Andra reference CG.TE.F.CDC.AMOA.GC0.2000.12.0014).
- DOPAS Deliverable D2.1 "Design Bases and Criteria".
- DOPAS Deliverable D3.2 "FSS Tunnel model design report".
- DOPAS Deliverable D3.10 "FSS Drift model construction report".
- DOPAS Deliverable D3.4*: "Report on low pH concrete formulas for FSS",
- DOPAS Deliverable D3.6*: "Lab report on the performance of low pH concrete for FSS",
- DOPAS Deliverable D3.8*: "Test report on FSS cast in box concrete" (assembled in one single document)
- DOPAS Deliverable D4.8 "FSS Experiment Summary Report" to be published in 2016.

P.S: (*) Deliverables D3.4, D3.6 and D3.8 are presented and collated in one single report D3.8.