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

Deliverable D3.13: “Report on FSS shotcrete plug construction”

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Executive Summary

In DOPAS, Work Package 3 (WP3) is related to the construction of four large scale demonstrators of seals and plugs, including the FSS experiment.

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 (the DOPAS partners) have built their own plug or seal prototypes.

This report D3.13 gives an overview of the work implemented at the FSS test site (in Saint-Dizier) to construct the low pH shotcrete plug (one of the 3 components forming the FSS seal), i.e. the "downstream" concrete containment wall, which was erected in September 2014.

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

The FSS experiment explores two types of low-pH containment walls, one using self-compacting concrete (SCC) and the other using shotcrete (sprayed concrete), to allow the preferred method to be selected and incorporated into the Cigéo seal reference concept.

Design and selection of the shotcrete mix (formulation) followed a multi-step process, and various parameters were used in a global multi-criteria analysis. The preferred solution was a binary mix, with the selection particularly affected by the pH and compressive strength of the mix (these activities are described in other separate and specific WP3 FSS related reports).

While the casting of the low-pH SCC containment was totally successful, some problems were encountered with the low pH shotcrete plug, notably the management of rebounds and the formation of bonding discontinuities between layers. Furthermore, the low pH shotcrete formulation was difficult to mix at plant and its behaviour (once applied as a layer) was very sensitive to the amount of activator incorporated in the mix at gun level. Locally, the hardening temperature reached inside the concrete monolith was above the specified requirement.

Ways for improvements are identified in this report concerning the formulation and use of low pH shotcrete, even if the use of low pH SCC appears, at time of writing, as the reference solution for building plugs in the future Cigéo. The use of low pH shotcrete would be most likely limited to "small preparation works", such as physically separating the drift ordinary backfill (when closing the geological repository, the drifts will be backfilled with argillite) from the SCC containment wall.

The document D3.13 includes an overview of the field activities (methodology and tools, timing, outcomes) implemented for the shotcrete plug erection, illustrated by photos, c/w practical details and comments.

Links to other Andra's FSS specific (or DOPAS more general) Deliverables (reports) are also given in the document.

List of Acronyms - Abbreviations

This generic list of acronyms concerns entities, activities, concepts, equipment and materials which are Andra (or DOPAS Partners) specific

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.
LL-ILW:	Long-Lived Intermediate-level Waste, aka ILW.
IRSN:	Institut de Recherche sur la Sûreté Nucléaire (Expert Organisation acting as a technical 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 8 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 Tutkimuskeskus VTT Oy.

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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 (LL-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 below in Figure 1.1.

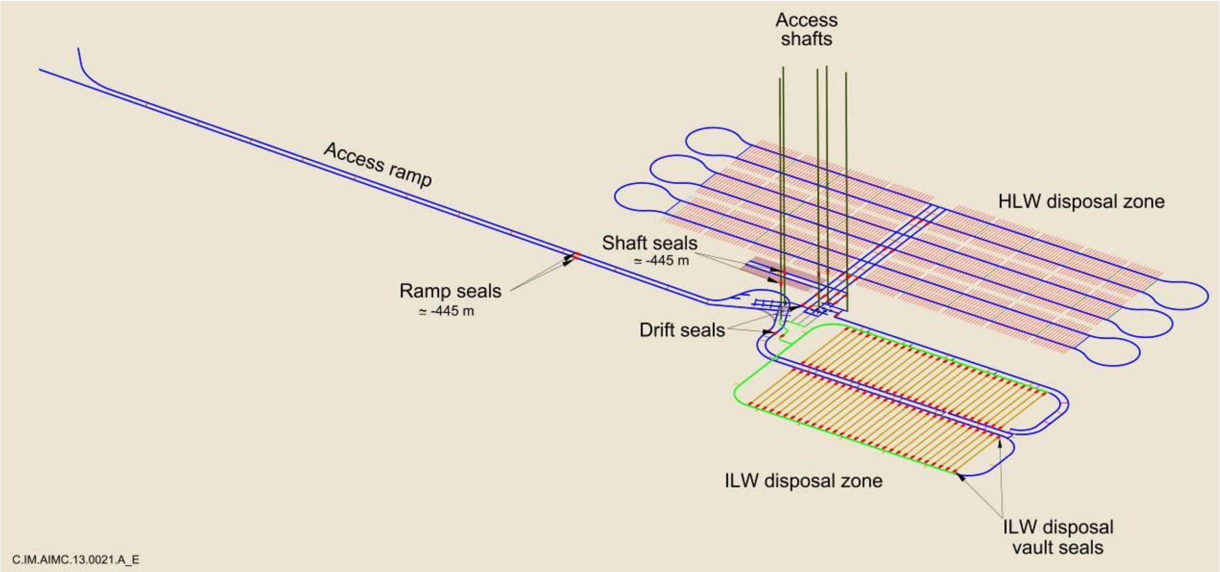

Figure 1.1: Location of the seals in the French repository concept

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[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 horizontal drift or/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 (scientific or technical) 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 "investigation" 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 Andra specified 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 (plugs) with satisfactory mechanical properties.

The FSS test per se is focused on the construction of the sea components, and the swelling clay will not be saturated or otherwise pressurised. This issue is dealt with in a separate test called REM, which is also a part of DOPAS (cf. Report D4.2, Conil et al., 2015).

Besides, the investigation of the components "as built" is also carried out (to evaluate their compliance with the construction specifications) and reported in a specific WP4 report (cf. Report D4.8, Bosgiraud et al., 2016). Thus the description of the outcomes from the shotcrete containment wall activities is limited to the erection and "monitoring while curing" periods.

The conceptual design of the FSS test is illustrated in Figure 2.1. 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.

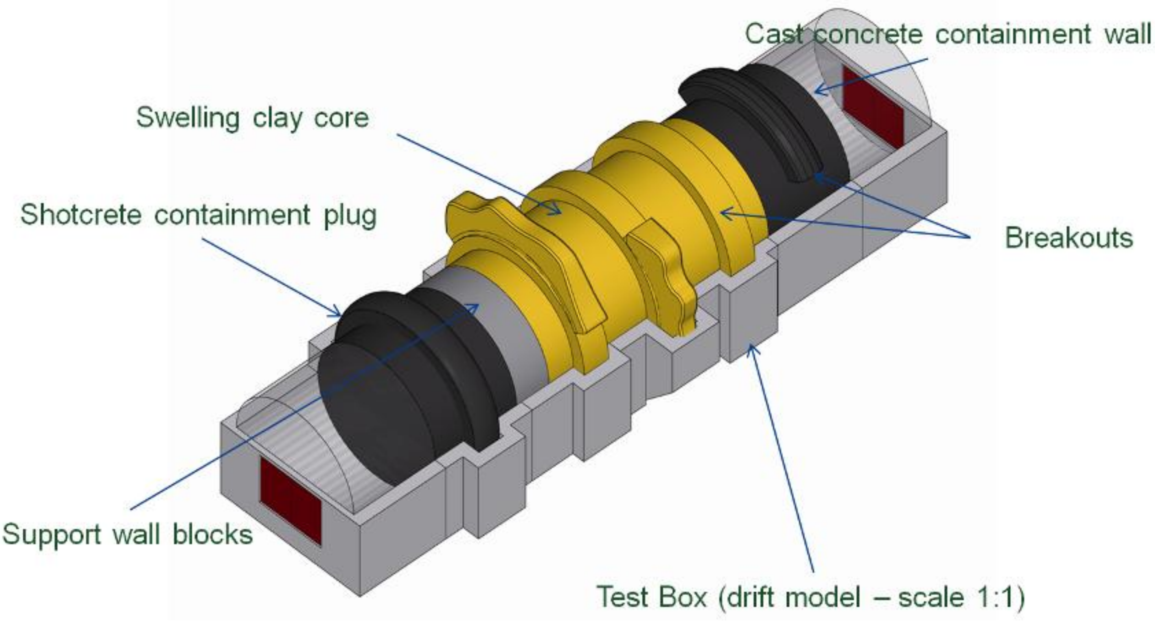

Figure 2.1: Conceptual design for the ANDRA FSS test

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" (White et al. 2014).

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.

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

2.2 FSS Test Box Design and construction

2.2.1 General

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 2.2.

Following its construction, the test box was 3D scanned in order to know the exact volumes of materials necessary for the upstream containment wall, the swelling clay core and the downstream clay core (cf. Figure 2.3).

The design and construction of the Test Box are respectively documented in DOPAS Deliverable D3.2 "FSS Tunnel model design report" and DOPAS Deliverable D3.10 "FSS Drift Model construction report".

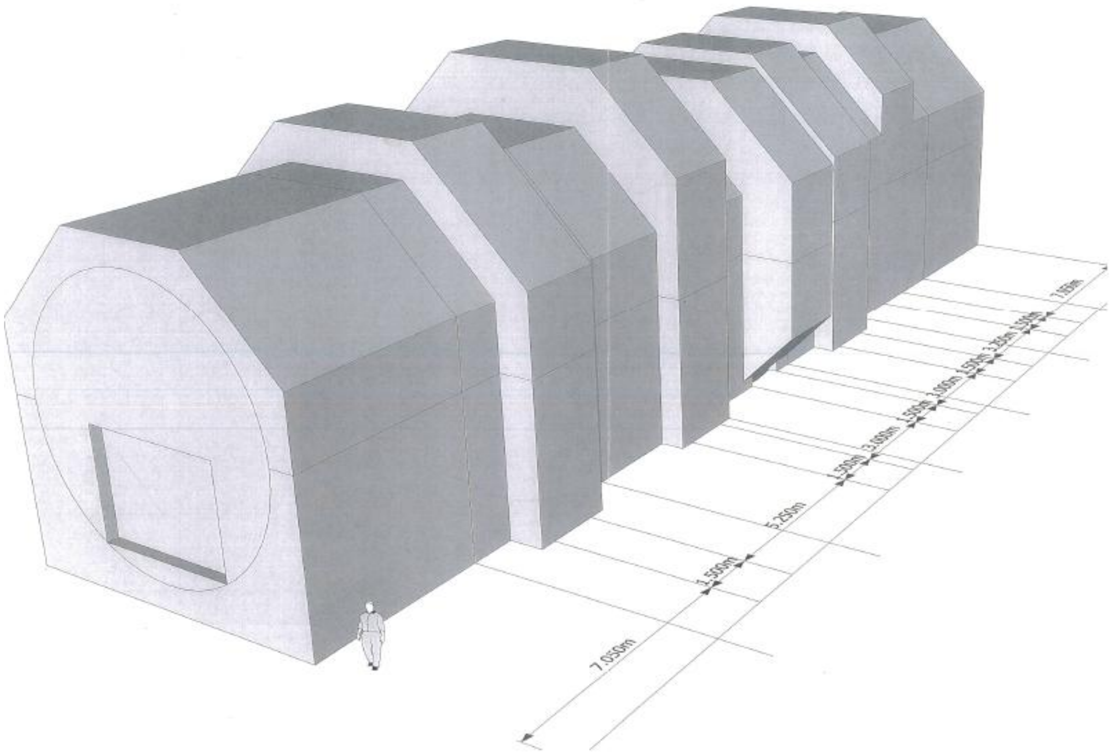

Figure 2.2: 3D schematic of the FSS test box (drift model)

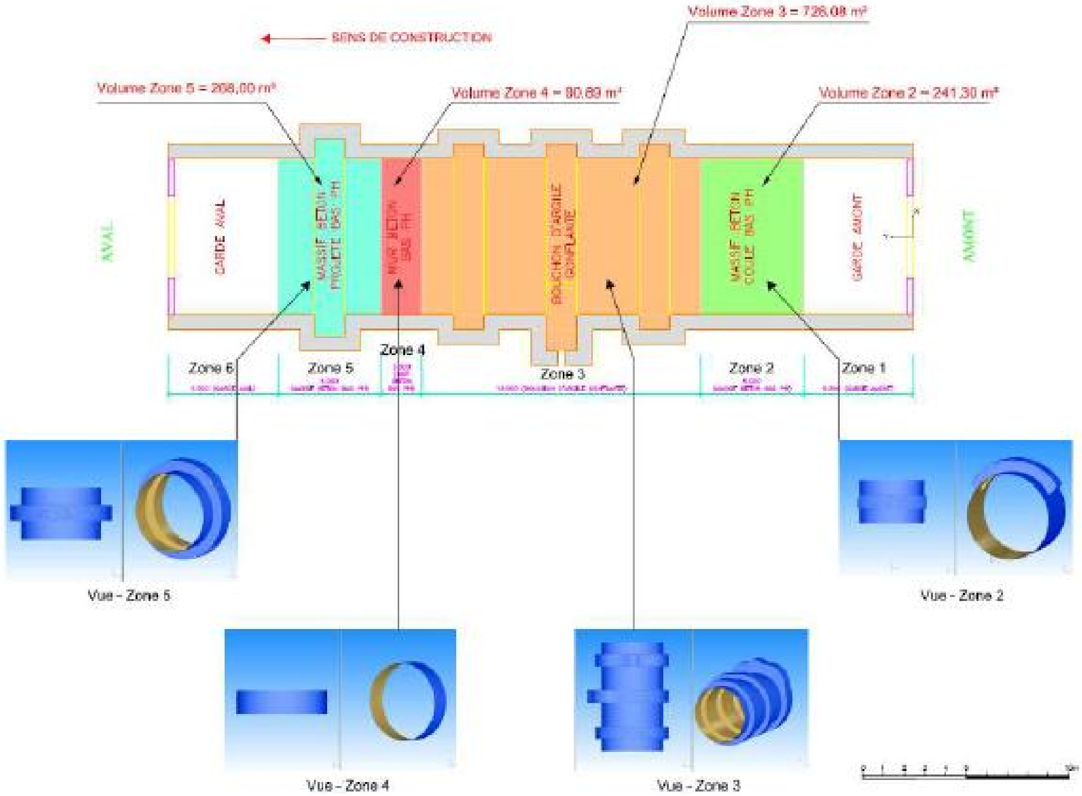

Figure 2.3: Scan 3D - Schematic of the FSS test box inside volumes

2.2.2 Test Box Construction story

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 2.4).

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

Figure 2.4: 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.

3. The development of the low pH shotcrete concrete formulation

3.1 Introduction:

The DOPAS-FSS project involved 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 shotcrete, first in lab, then in field at a metric scale.

The FSS low pH shotcrete requirements were defined as summarized below:

- The pH value of the shotcrete pore solution must be lower than 11.0 at 28 days (and ideally between 10.5 and 11.0 at 90 days),
- The shotcrete must be 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 25 MPa after 28 days and 35 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 shrinkage value (90 days after shotcreting) must be as close as possible to 350µm/m.

The design of a proper concrete formulation (mix 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 step,
- The second step consisted in proportioning the shotcrete 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.

This approach enabled the selection of the best formulation used further for the full scale construction of the low pH downstream shotcrete containment wall in FSS.

This development work is described in DOPAS Deliverables D3.9 (“Report on FSS test panel for shotcrete”, Bosgiraud *et al.*, 2016), where the final formulation of the shotcrete mixture (B 50 CEM 1 52.5 Le Teil with 100% silica fume) is justified in more details.

3.2 Low pH Shotcrete Composition

The FSS (low pH shotcrete) downstream containment wall construction was implemented in September 2014. By reference to the shotcrete formulation pre-defined at the end of the testing and characterization phases (see Chapter 3.1 above), it was decided to change the Superplasticizer (SP) and use that developed for SCC (namely Master Glenium Sky 537) and to adjust the effective activator content to the effective ambient temperature and the effective behaviour of each layer of concrete sprayed (it was “fine-tuning learning” while spraying).

The formulation effectively employed is summarized in the Table 3.1 below.

Table 3.1: Formulation of low pH shotcrete used for the FSS downstream containment wall

Components	**Quantity (kg/m^3)**	**Tolerances (±)**
Gravel 4/8 (dry)	408	10 kg
Sand 0/4 (dry)	1347	10 kg
CEM1 52.5 Le Teil	190	2 kg
Silica fume	190	1 kg
Master Glenium Sky 537	13.5 kg (3.7% of binder mass)	100 g
Master Roc HCA 101	2.7 kg (0.7% of binder mass)	50 g
Total water	200	1 kg

The low pH shotcrete was prepared and delivered to the construction site by the same (Paul Calin) Saint-Dizier mixing plant. The batches were transported in mixing trucks same as those which were used for the preliminary shotcrete formulation preparation tests. This plant (and the mixing trucks) was more generally used for all the operations concerning the low pH and shotcrete SCC.

4. The low pH shotcrete containment wall construction story

4.1 Preparation of construction operations

4.1.1 Equipment

The shotcrete was "wet" sprayed using a spraying machine "Aliva 263" (cf. Figure 4.1), an air compressor (with a nominal capacity of 20 000 l/min) and a dosing pump "AL 403.3" for incorporating the activator (at gun level).

Figure 4.1: Spraying machine "Aliva 263"

The main operator (i.e. the person applying the shotcrete layers) was positioned on a cherry picker (at this experimental stage, no remote operated gun system was considered since it was a first-of-a-kind test, but in Cigéo such a solution would be most likely preferred). Figure 4.2 shows the fixing of the spraying gun on the cherry picker platform.

Figure 4.2: Fixing of spraying gun on platform

The operations were organized in 2 shifts (20/24 per day), 6 working days a week. During all the concreting operations, the main operator was assisted by a team composed of:

- One worker dedicated to “fine tuning” the spraying machine and the dosing pump,
- Three workers assigned to general support and rebound purging, including cleaning between two layers.

4.1.2 Spraying principles

The main challenge was to spray the shotcrete in a “geometrically” homogeneous way (the concrete monolith must sustain the considerable forces exerted by the swelling clay core at time of saturation). For that purpose an “onion shape” (dome) layer was selected as the most suited solution to minimize the effects of potential discontinuities between two layers. The Figure 4.3 illustrates the “spraying pattern” concerned.

The “waiting time” between two layers was fixed at a minimum of 2 hours of hardening (for a minimum of strength) and a maximum of 4 hours (beyond this lapse of time, bonding becomes too difficult or requires additional action).

During stopover periods (e.g. on weekends), water was sprayed on the concrete layer surface (before leaving the site and as an early starter when resuming operations), to improve the bonding effect.

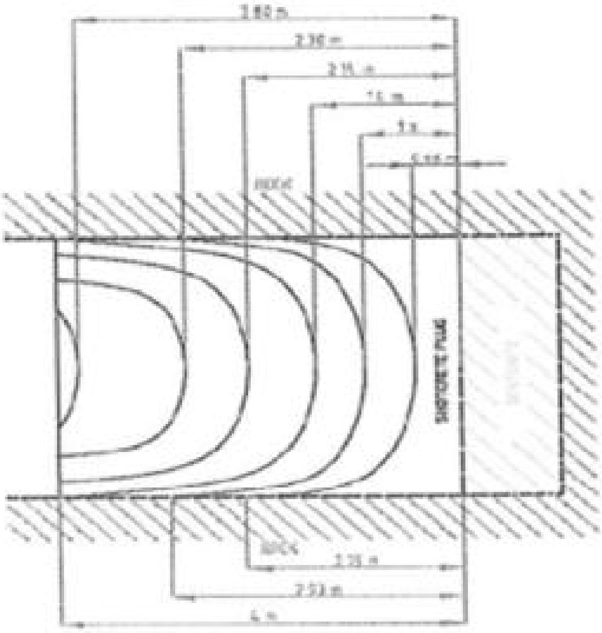

Figure 4.3: Spraying pattern principle

4.2 Shotcrete containment wall construction

The downstream low-pH shotcrete containment wall was constructed after emplacement of a mortar to close the joints in the supporting wall that would separate the swelling clay core from the shotcrete wall (cf. Figure 4.4). The mortar was emplaced between blocks and at the contact with the test box wall.

The low-pH shotcrete containment wall (Figure 4.4) was finished in September 2014 after solving initial challenges with fabrication of the shotcrete, such as:

- The rheology of the prepared shotcrete was initially found to be highly variable; some batches of shotcrete were found to be too stiff and some too soft. This difficulty was solved by increasing the time of mixing (at plant) from 30 seconds to two minutes so as to have a better incorporation of silicate fume. After making three batches (with a volume of 3 m^3), a check was then carried out to adjust the amount of additives for the last four batches to get the expected final consistency.
- The rebound rate was around 10 to 12% and the difficulty was to thoroughly remove it after each mixer-truck emplacement to prevent its incorporation into the wall. The rebound was stored and evacuated in big bags (cf. Figure 4.5).

Figure 4.4: Installing the second containment wall made of low pH shotcrete in FSS.

Figure 4.5: Shotcrete rebound storage in the waiting for evacuation.

5. Monitoring of operations and first results

5.1 Results of low pH shotcrete 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 5.1). They provided some worthy information during spraying operations and during the curing and hardening phases to check the shotcrete behavior and its compliance with requirements.

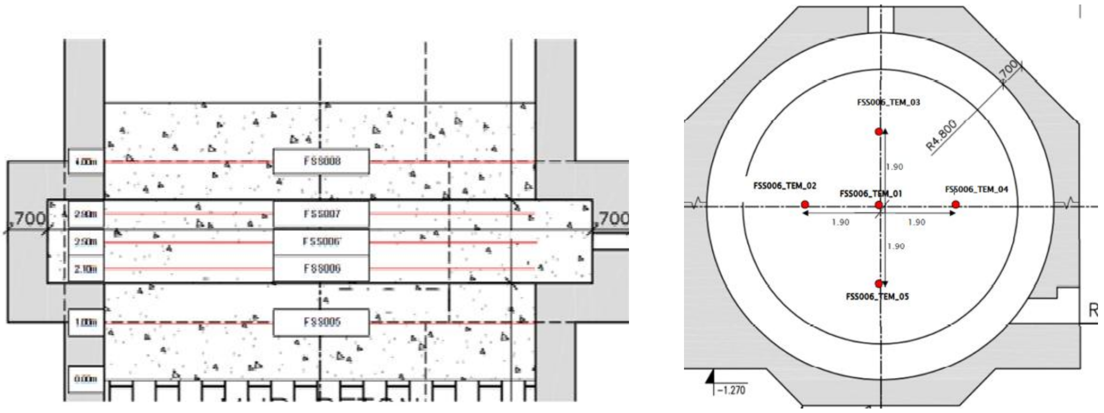

Figure 5.1: Temperature probes and shrinkage sensors installed inside the

Test Box (downstream low pH shotcrete containment wall sections)

The maximum curing temperature reached was 67°C, i.e. above the 50°C requirement (see Figure 5.2). The choice of cement selected (CEM 1, a very reactive material by nature) and the (probably) excessive dosage of activator (at spraying gun level) are deemed the main explanations of such a deviation.

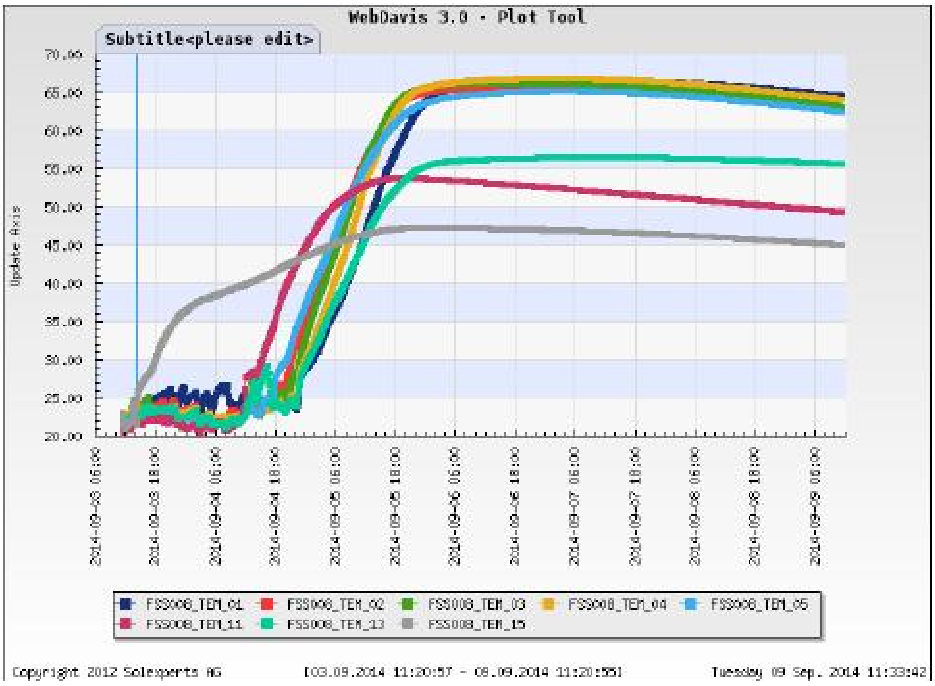

Figure 5.2: Curves showing the evolution of low pH Shotcrete temperature with time

Unfortunately, no shrinkage values could be measured, which is a significant loss of knowledge. It was not determined if this situation was due to a general failure (damage) of sensors generated during the shotcreting operations or to a poor connection between the sensors and the DAS (Data acquisition system) at time of wiring them.

Figure 5.3 shows the downstream face of the low pH shotcrete after completion of shotcreting operations and general cleaning of the site.

Figure 5.3**:** The low pH Shotcrete wall completed

5.2 Compressive strength of low pH shotcrete

Samples of fresh concrete were taken from each batch of concrete on delivery at test site, and sent to a laboratory for measurement of the compressive strength: the results were varying between 55.5 MPa and 76.9 MPa at 28 days. Cores were also taken from the sprayed concrete and sent for analysis. The results were varying between 41.5 MPa and 49.1 MPa at 28 days.

The obtained values are above the specified requirements.

5.3 Alkalinity of low pH shotcrete

The pH value measured in lab on a core taken from the containment wall turned out to be 10.4 at 90 days.

The obtained value is compliant with the specified requirement.

6. Conclusions

6.1 Outcomes

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

- This test is a “first of a kind” in terms of volume and dimensions for low pH shotcrete works in general and containment walls/plugs in particular,
- The concrete pH values (~ 10.4) and mechanical properties (Rc ~ 45MPa) are commensurate with (or better than) the pre-determined specifications,
- The curing temperature measurements obtained are **not** compliant with the requirements,
- The operational cycle (271m^3 sprayed in 167 hours, 2 shifts) and the operational tools and methods used are compatible with “Cigéo” underground conditions,
- The low pH shotcrete formulation used in FSS is not easy to mix at the plant and quite sensitive to the activator dosage at spraying gun level,
- The onion shape (dome) was respected with a good bonding between the drift liner roof and the shotcrete,
- Shotcrete containment wall construction feasibility is proven with classical civil work & mining equipment, but there is room for improvements.

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

6.2 Improvements

The main improvements identified are listed below:

- From a logistical point of view, there is a need for spare equipment at hand. The dosing pump in particular is a quite sensitive item,
- More discipline (and supervision) is needed when purging (cleaning) the rebound, the presence of which is detrimental to a good layer bonding and to even mechanical properties, hence to the monolith general homogeneity,
- Most likely, a binder formulation based on the incorporation of CEM III/type cement would help reducing the hardening temperature (and probably the shrinkage).
- Shrinkage sensors must be either better protected from the effect of spraying or carefully checked at time of wiring.

7. 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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- Conil *et al.* (2015) - DOPAS Work Package 4, Deliverable D4.2 ("Report on Bentonite Saturation Test (REM)").
- Bosgiraud *et al.* (2016) - DOPAS Work Package 4, Deliverable D4.8 ("FSS Experiment Summary Report").
- DOPAS (2016b) - DOPAS Final Project Summary Report. DOPAS Work Package 6, Deliverable D6.4. DOPAS Project Deliverable D6.4.