DOPAS Work Package 3 - Deliverable 3.1
WP3 FSS Construction Summary Report

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Johanna Hansen (POSIVA) ***18.11.2016***

Executive Summary

Report Background

The Full-Scale Demonstration of Plugs and Seals (DOPAS) Project is a European Commission (EC) programme of work jointly funded by the Euratom Seventh Framework Programme and European nuclear waste management organisations (WMOs). The DOPAS Project is running in the period September 2012- August 2016. Fourteen European WMOs and research and consultancy institutions from eight European countries are participating in the DOPAS Project. The Project is coordinated by Posiva (Finland). A set of full-scale experiments, laboratory tests, and performance assessment studies of plugs and seals for geological repositories are being carried out in the course of the project.

The DOPAS Project aims to improve the industrial feasibility of full-scale plugs and seals, the measurement of their characteristics, the control of their behaviour in repository conditions, and their performance with respect to safety objectives. This work does not start from a clean slate, since previous works (at a lower scale) were anteriorly implemented by some of the participants. For example, the works carried out in the FP6 ESDRED and FP7 LUCOEX projects are some of the reference works on which the DOPAS work is partly building on.

The DOPAS Project is being carried out in seven Work Packages (WPs). WP1 includes project management and coordination and is led by Posiva, Finland. WP2, WP3, WP4 and WP5 address, respectively, the design basis, construction, compliance testing, and performance assessment modelling of five full-scale experiments and laboratory tests. WP2, WP3, WP4 and WP5 are led by SKB (Sweden), Andra (France), RWM (United Kingdom), and GRS (Germany), respectively. WP6 and WP7 address cross-cutting activities common to the whole project through review and integration of results, and their dissemination to other interested organisations in Europe and beyond. WP6 and WP7 are led by Posiva.

The DOPAS Project focuses on tunnel, drift, vault and shaft plugs and seals for clay, crystalline and salt host rocks:

- *Clay rocks*: the Full-scale Seal (FSS) experiment, being undertaken by Andra in a surface facility at St Dizier, is an experiment of the construction of a drift seal or/and of an intermediate level waste (ILW) disposal vault seal.
- *Crystalline rocks*: experiments related to plugs in horizontal tunnels, including the Experimental Pressure and Sealing Plug (EPSP) experiment being undertaken by SÚRAO and the Czech Technical University (CTU) at the Josef underground research centre (URC) and underground laboratory in the Czech Republic, the Dome Plug (DOMPLU) experiment being undertaken by SKB and Posiva at the Äspö Hard Rock Laboratory (Äspö HRL) in Sweden, and the Posiva Plug (POPLU) experiment being undertaken by Posiva, SKB, VTT and BTECH at the ONKALO Underground Rock Characterisation Facility (URCF) in Finland, which is also the site of the future Finnish repository.
- *Salt rocks*: tests related to seals in vertical shafts under the banner of the Entwicklung von Schachtverschlusskonzepten (development of shaft closure concepts – ELSA) experiment, being undertaken by DBE TEC together with the Technical University of Freiburg and associated partners, complemented by laboratory testing performed by GRS and co-funded by the German Federal Ministry for Economic Affairs and Energy (BMWi).

Each experiment represents a different stage of development. The Swedish experiment was started prior to the start of the DOPAS Project and was pressurised during the early stages of the Project. The Finnish, Czech and French experiments were designed and constructed during the Project. Initial pressurisation of the Finnish and Czech experiments occurred within the last year of the Project. The French experiment FSS was not pressurised, but “investigation dismantling” of the experiment was undertaken during the Project period. The German tests focused on the early stages of design basis development and on demonstration of the suitability of designs through performance assessment studies and laboratory testing, and will feed into a full-scale experiment of prototype shaft seal components to be carried out after DOPAS.

This report is Deliverable D3.1 in the DOPAS Project and is part of WP3. The objective of this report is to provide an integrated summary of the work undertaken for the design and construction of the scale 1:1 experiment called FSS (Full Scale Seal), carried out by Andra, with the scientific support of NAGRA. A parallel report, DOPAS Deliverable D4.8 in WP4, discusses the performance of the FSS experiment and the feedback to the design basis.

This report aims to summarise the work undertaken and identify the lessons learned from the following aspects of the experimental work:

- The objectives of the FSS experiment as undertaken in the DOPAS Project.
- The preliminary laboratory investigations and *in situ* materials testing that helped in the determination and confirmation of the properties of the materials used in the FSS experiment.
- The approach used to site the FSS experiment, and the reasons for selecting the location chosen.
- The excavation or construction of the experiment location.
- The installation of the experiment (seal) components.

Lessons learned are considered from the perspective of this individual experiment and by cross-comparing the outcomes from the design and construction work undertaken. The lessons learned after dismantling FSS are exposed in WP4 D4.4 and more specifically in D4.8.

Design and Construction of the FSS Experiment

During the course of the DOPAS Project, the design for the FSS experiment has been finalised and the construction experiment has been successfully implemented.

The FSS experiment is a test of the technical feasibility of constructing a drift and/or Intermediate-Level Long Live waste (ILW-LL) disposal vault seal at full scale (i.e. 1:1).

The test box (a Cigéo drift model) has an internal diameter of 7.6 m and is 35.5-m long. The FSS seal per se includes a swelling clay core supported by two low-pH concrete containment walls (plugs). Andra tested two types of low-pH for the containment walls: low-pH self-compacting concrete (SCC) and low-pH shotcrete.

Construction of the FSS experiment test box (a drift model) commenced in November 2012, while materials research was undertaken in the period August 2012-April 2014, and the main components of the experiment were installed (built) between July 2013 and September 2014.

A range of concrete mixes were tested in the laboratory, and in mock-up tests at the metre and several-metre scales, since scale effects are considerable. Design and selection of the SCC mix was undertaken in a three-step process in which the range of options was progressively narrowed. Final selection of the materials considered a global multi-criteria analysis using both technical parameters (compressive strength, shrinkage, organic matter concentration, pH, porosity and permeability, workability) and non-technical parameters (distance of the manufacturer to the test facility and cost). The preferred solution was a binary mix with 50% cement and 50% silica fume.

Design and selection of the shotcrete mix followed a similar multi-step process, and similar parameters were used in the global analysis (the analysis also included the odour of the mixture as a result of sulphur presence in the slag materials). The preferred solution was again a binary mix, with the selection particularly affected by the pH and compressive strength of the mix.

Andra has adopted a bentonitic pellet-based system for installation of the swelling clay core, as the use of pellets is considered by Andra to be an efficient industrial method for implementation of significant quantities of materials (seven hundreds or thousands of m^3 are at stake for each seal in Cigéo). Testing of candidate materials in the laboratory identified a preferred admixture of 32-mm diameter pellets combined with powder (made of crushed pellets). The bentonite used was WH2 bentonite from Wyoming (a material very similar to MX-80, a brand more commonly known). Emplacement of the admixture used a dual auger system, preliminary metric-scale testing of which identified the need to arrange the augers either one-above-the-other or side-by-side, according to the emplacement phase. Although the original target for the pulverulent admixture emplaced dry density was 1620 kg/m^3, evaluation of the dry emplaced density and swelling pressure for WH2 undertaken in parallel with material testing showed that the required swelling pressure (that which would satisfy the need for the host rock EDZ self-sealing) could be achieved with a dry density equal to 1500 kg/m^3 only.

The installation of the FSS components was undertaken according to the plan. Several lessons were learned regarding the method of installation, for example the need to match the SCC retardant dose to the ambient temperature and the need to manage dust produced and control pellet breakages during the emplacement of the bentonite admixture. Although the casting of the low-pH SCC was successful as the concrete rose progressively inside the box, with smooth and regular emplacement, some problems were encountered with the low pH shotcrete, notably the management of rebounds and the formation of bonding discontinuities between layers.

Conclusions

Within WP3 of the DOPAS Project, the FSS experiment has demonstrated that constructing at scale 1:1 a seal for ILW-LL disposal vault or a horizontal drift is feasible, in environmental conditions which are representative of prevailing underground repository conditions. The challenges and complexities of containment walls/ swelling clay core design and construction can be met through technology, methods and procedures currently available.

A specific bentonitic mix was designed and produced; a specifically designed bentonite emplaced machine was designed, constructed and operated. In practice, logistics will be a significant issue for constructing seals underground. There may be other issues associated with manpower and machinery availability (and performance). Therefore, contingency planning, such as the provision of back-ups and spares may be necessary. Contingencies also need to be built into project plans and schedules.

Finally workers' safety (e.g. during concrete liner deposition and subsequent clay excavation) and workers' health (e.g. bentonite generated dust) must also be thoroughly considered in the construction process.

Application of the lessons learned from the FSS experiment and feedback to reference designs are considered in WP4 of the DOPAS Project and reported in Deliverable D4.8 (WP4 FSS Experiment Summary Report) and in D4.4. (WP4 Integrated Report). These 2 last reports also include an analysis of further work required to develop seal designs so that they are ready for implementation in the Cigéo repository in the near future.

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

List of Acronyms – Abbreviations

AECL:	Atomic Energy of Canada Limited
ASN:	Autorité de Sûreté Nucléaire (Nuclear Safety Authority in France)
BMU:	Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit (Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety in Germany)
BMWi:	Bundesministerium für Wirtschaft und Energie (Federal Ministry for Economic Affairs and Energy in Germany)
Cigéo:	Centre Industriel de Stockage Géologique (Industrial Geological Repository in France)
DOMPLU:	Dome Plug
DOPAS:	Full-scale Demonstration of Plugs and Seals
EBS:	Engineered barrier system
EC:	European Commission
EDZ:	Excavation damaged zone
EE:	Expert Elicitation
ELSA:	Entwicklung von Schachtverschlusskonzepten (Development of shaft closure concepts)
EPSP:	Experimental Pressure and Sealing Plug
FSS:	Full-scale Seal (test)
GBT:	Green Break Technology
GPR:	Ground penetrating radar
HRL:	Hard Rock Laboratory
ILW:	Intermediate-level waste
LASA:	**La**ngzeitsicherer **S**chachtverschluß im S**a**linar (Long-term Safe shaft closure in Salt)
LECA®:	Light-weight expanded clay/concrete aggregate
LVDT:	Linear variable differential transformer
OPC:	Ordinary Portland Concrete
PHM:	Physical Hydraulic Model
PIM:	Physical Interaction Model
POPLU:	Posiva Plug
PVDF:	Polyvinylidene fluoride
R&D:	Research and development
RSC:	Rock Suitability Classification
SCC:	Self-compacting concrete
STUK:	The Finnish Nuclear Regulatory Authority

TC-Tests: Triaxial compressions tests

TDR: Time domain reflectometer

THM-Ton: Untersuchung der THM-Prozesse im Nahfeld von Endlagern in Tonformationen (investigation of THM processes in the near field of a repository in clay)

TRL: Technology Readiness Level

TSO: Technical Support Organization

URC: Underground Research Centre

URCF: Underground Rock Characterisation Facility

URL: Underground research laboratory

WMO: Waste management organisation

WP: Work package

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1. Introduction

1.1 Background

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- The excavation or construction of the experiment location.
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Lessons learned are considered from the perspective of this individual experiment and by cross-comparing the outcomes from the design and construction work undertaken.

1.2 Objective

The objective of this report is to provide an integrated summary of the work undertaken and the lessons learned in the DOPAS Project WP3 related to the detailed design and construction of the FSS experiment:

- The objectives of the experiments undertaken in the DOPAS Project.
- The laboratory investigations and *in situ* materials testing that helped in the determination and confirmation of the properties of the materials used in the experiments.
- The approach used to site the full-scale experiments, and the reasons for selecting the location chosen.
- The excavation or construction of the experiment location.
- The installation of the experiment components.

1.3 Scope and Link to other DOPAS Deliverables

The intended audiences of this report D3.1 are technical staff and technical management of WMOs, and the report has been written primarily for this audience. The report is also expected to be of potential interest to regulators and TSO (Technical support organizations).

This WP3 report (D3.1) is part of a series of WP-level summary reports describing the integrated outcomes of the technical work in DOPAS:

- D2.4, the WP2 Final Report (DOPAS, 2016a), describes the design basis for the plugs and seals considered in DOPAS, conceptual and basic designs, and the strategy adopted in programmes for demonstrating compliance with the design basis. The design basis is presented for both the repository reference design and the full-scale experiment design.
- D3.30, the WP3 Final Summary Report (DOPAS, 2016b), summarises the work undertaken and the lessons learned from the detailed design and construction of the various experiments implemented in DOPAS. These include the full-scale demonstrators, laboratory work and its upscaling, and the learning provided by the practical experience in constructing the experiments.
- D4.4, the WP4 Integrated Report (DOPAS 2016c), summarises what has been learnt with respect to the repository reference designs for plugs and seals. The report also considers alternatives to the repository reference designs (e.g. the wedge-type plug investigated by Posiva). It considers what can be concluded from the full-scale experiments conducted in DOPAS with respect to the technical feasibility of installing the reference designs, the performance of the reference designs with respect to the safety functions listed in the design basis, and identifies and summarises achievements of DOPAS WP2, WP3 and WP4 at the time of writing. D4.4 also considers the feedback from the work to the design basis.
- D4.8, the WP4 D4.8 FSS Experiment Summary Report (Bosgiraud et al., 2016), which summarises the outcomes from FSS.
- D5.10, the WP5 Final Integrated Report (DOPAS, 2016d), describes the conceptualisation of plugs and seals in post-closure safety assessments and the expected long-term evolution of plugs and seals. This includes a description of the evidence that the materials used in plugs and seals will maintain their required performance for the period specified in the design basis.

D3.1 is based on information available by the date of data freeze (on 31 December 2015). At this time, all design and installation work had been completed, although some assessment of the work was on-going. Progress in the FSS experiment by this date was as follows:

- For FSS, the upstream containment wall was cast in June 2013, the clay core was emplaced in August 2014 and the downstream shotcrete plug was emplaced in September 2014. Investigations of FSS were undertaken in the period November 2014 to July 2015, followed by “investigation dismantling” between August 2015 and December 2015 (information related to this phase is dealt with in D4.4 and D4.8).

The various technical reports detailing the phases of design and construction of FSS are referred in Chapter 5 of the present D3.1 Report.

1.4 Terminology and abbreviations

Throughout this report consistent terminology has been applied. This has required, in places, changing the terminology used in a specific programme or within a specific country. The key terms that have been changed for consistency are:

- In this report, the term used to describe the combination of materials in a specific concrete is *mix*. In specific cases, this term replaces the use of *formulation* and *recipe*.
- In this report, the term used to describe a test of plug/seal components at a reduced scale is *mock-up*.

In general, in the DOPAS Project it has been agreed that reference to IAEA glossary (2013) is made in the Project to use this glossary for the terms, which are not specifically described in the report or in the list of abbreviations.

1.5 Report Structure

This report is presented in the following sections:

- Chapter 2 provides a summary of the experiences and learning from FSS. For this experiment, the following issues are described:
  - The experiment background and objectives.
  - The development and testing of materials used in the experiment.
  - The structural design, i.e., the work undertaken to select the components in the experiment and their geometrical properties.
  - Siting of the experiment.
  - Excavation of the experiment location or construction of the experiment facility.
  - Construction of the experiment.
  - Lessons learned regarding the design and construction of the specific seal experiment.
- Chapter 3 provides an integrated discussion of the lessons learned and future challenges from the design and construction of the FSS experiment.
- Chapter 4 provides conclusions from the Report.
- Chapter 5 is the list of the main DOPAS and FSS Deliverables which are linked to the present D3.1 Report.

2. FSS Experiment

This chapter provides a summary of the learning from design and construction of the FSS experiment:

- In Section 2.1, the background to the experiment and its objectives are summarised.
- In Section 2.2, the phases of testing and selection of materials prior to FSS full scale implementation are described.
- In Section 2.3, the siting of the FSS experiment is explained.
- In Section 2.4, the construction of the FSS test box (drift model) is described.
- In Section 2.5, the installation of the FSS components is summarised, with particular focus on the novel aspects of the experiment.
- Discussion of the lessons learned regarding the design and installation of the FSS experiment is provided in Section 2.6.

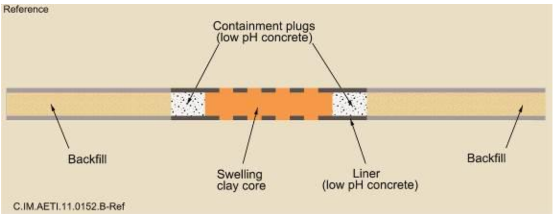
Further outcomes of the design and construction of FSS are available in the FSS Experiment Summary Report (D4.8 - Andra, 2016).

2.1 FSS Experiment Background and Objectives

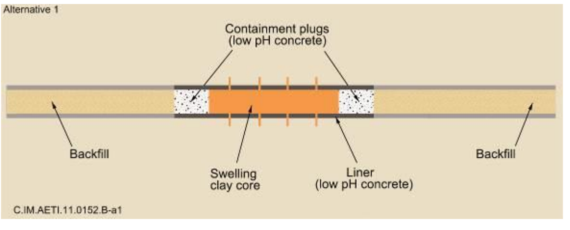
There are potentially up to 130 seals envisaged (at this stage of design) in the French reference repository (aka Cigéo) concept for HLW and ILW. Three types of seals are recognised: (vertical) shaft seals, (inclined) ramp seals, and (horizontal) drift and ILW disposal vault seals. Each category of seal consists of a swelling clay core positioned between two concrete containment walls (plugs). The swelling clay core provides the required long-term hydraulic conductivity performance of the seal, whereas the containment walls are included to mechanically contain the clay core when swelling.

Andra has proposed two different conceptual designs for seals (Figure 2.1):

- A **Reference Solution** in which the concrete drift lining in the swelling clay core section is either totally or partially removed prior to emplacement of the core. Removal of the lining allows direct contact of the swelling clay core with the host rock, and the sealing of any potential flow paths within the lining and along its interfaces with the bentonite and host rock.
- An **Alternative Solution** in which radial hydraulic cut-offs (also known as “grooves”) are sawn from the host rock allowing the excavation damaged zone (EDZ) to be intercepted by the bentonite material in the seal.



Reference Solution



Alternative Solution

Figure 2.1: Conceptual design for seals in Andra’s Cigéo disposal concept.

During the review of Andra's Dossier 2009[1], the nuclear authority (ASN) asked Andra to prove the industrial feasibility of seals by constructing technological demonstrators at scale 1:1.

The FSS experiment was built in response to ASN's request, to prove the technical feasibility of constructing a seal at full scale, and especially to:

- Demonstrate the industrial feasibility of emplacement of large volumes of bentonite and emplacement of low-pH concrete and shotcrete at the scale of a Cigéo seal (approximately ten metres in diameter and several tens of metres in length).
- Define the operational requirements useful to obtain the specified properties, for example the tolerances on the density distribution in the core after emplacement or on the ratio of acceptable residual voids.
- Define and deploy the control means to check the compliance, during construction, with the emplacement requirements.
- Define and deploy the control means to check the compliance, after construction, with the emplacement requirements.

The main difference between the reference and FSS designs for the Andra drift and ILW vault seal is the length of the seal. The real seal underground will be longer than the seal considered in FSS. The FSS experiment investigates two types of low-pH containment wall, one using self-compacting concrete (SCC) and the other using shotcrete, to allow the preferred method to be selected and incorporated into the seal reference concept.

Technical feasibility includes demonstrating the ability of the approach used to emplace the clay core to be suitable for filling recesses in the clay host rock, i.e., any potential breakouts generated during the removal of the concrete support lining. Therefore, the concrete test box includes recesses that mimic breakouts.

As the experiment is focused on the construction and installation of the seal, the materials were not saturated or otherwise pressurised to check the swelling pressure and hydraulic conductivity. Complementary experiments were undertaken in parallel with FSS. These include the REM experiment, which is part of WP4 of the DOPAS Project and consists of an "as close as possible to *in situ* conditions" resaturation test undertaken in a surface laboratory with the same bentonite pellets/powder mixture as used in FSS (cf. Deliverable D4.2).

The conceptual design of the FSS experiment is illustrated in Figure 2.2 and the schedule of activities is summarised in Table 2.1. Further information on the FSS experiment conceptual design and design basis is presented in D2.4, DOPAS (2016a).

[1] The Dossier 2009 presented Andra's operational safety case and developments to the design of the Cigéo repository since Dossier 2005 (Andra, 2005).

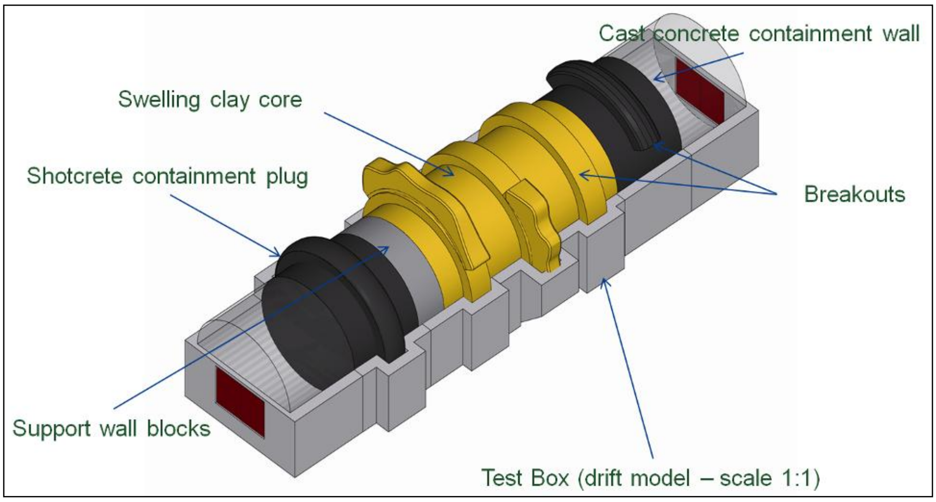


Figure 2.2: Schematic illustration of the FSS experiment design.

Table 2.1: The schedule of activities undertaken in the FSS experiment.

Period	Activity
August 2012	Beginning of studies
November 2012 – June 2013	Mock-up (box) construction
August 2012 – July 2013	Low-pH SCC concrete and shotcrete development
August 2012 – April 2014	Development of bentonite materials and methodology to emplace the core
July 2013	Low-pH SCC containment wall construction
August 2014	Bentonite core construction
September 2014	Low-pH shotcrete containment wall construction
October 2014 – July 2015	Scientific investigations
August 2015 – December 2015	"Investigation Dismantling" followed by complete deconstruction of FSS

2.2 FSS Material Testing and Development

2.2.1 Development and Testing of the SCC Mix

Studies were carried out to develop and test the mix for the low-pH SCC, first in a laboratory, then in tests at the metre and several-metre scales. Further details of the development and testing of the low-pH SCC mix are provided in D3.4, Bosgiraud and Foin (2014).

The design and selection of the concrete mix was undertaken in the following three steps:

1. ***Step 1: Identification of Binder Options:*** The first step in development and testing of the SCC mix was testing of different binder compositions in a laboratory. Eight compositions were studied (Table 2.2) and their impact on pH, compressive strength and curing temperature were measured (Table 2.3). After this investigation, four of the eight binders were selected for further testing based on their potential suitability for application in FSS. The compositions selected for further testing were:
    - B50 CEM I 52.5 Le Teil.
    - T3 (L) Le Teil.
    - B50 CEM III/A 42.5 Héming.
    - B50 CEM III/A 52.5 Rombas.
2. ***Step 2: Laboratory Testing of the SCC Mix Options:*** The four selected binders were tested in concrete mixtures in a laboratory to determine their properties. Slump flow measurements were used to test "flowability". Visual examination gave valuable information on the concrete quality, based on the distribution of aggregates, aggregate/paste separation and bleed water. Laboratory testing also included measurement of the temperature increase due to curing, the compressive strength, the porosity, and the pH of the pore solution. After this testing, it was decided to omit the T3 (L) Le Teil composition from further testing.
3. ***Step 3: Metric-scale Testing of the SCC Mix Options:*** The three remaining mixtures were then tested at the metric scale in field conditions using a ready-mix plant selected for the FSS project (Figure 2.3). For this step, the concrete mixtures were produced using industrial methods and used to fill test boxes with a volume of 1 m^3 (Figure 2.4). After 28 days, cores were extracted for analysis.

Following Step 3, a multi-criteria analysis was carried out in two phases to select the most suitable mix. The first phase was a technical analysis based on the measured compressive strength, the pH value, the porosity and permeability of the samples (Table 2.4). This phase did not allow clear identification of a preferred composition, and, therefore, an additional phase, which included non-technical considerations, was undertaken (referred to as a global multi-criteria analysis). As illustrated in Figure 2.5, five criteria were included in this last step: pH, shrinkage (referred to as "retrait" in Figure 2.5), distance of the manufacturer from the test facility, presence of organic matter and cost (referred to as "coût" in Figure 2.5).

Based on the global multi-criteria analysis, the **B50 CEM III/A 52.5 Rombas** binder was identified as the preferred composition for the low-pH SCC. Further testing of this mix in a test box with a volume of 12 m^3 verified the industrial feasibility of using this mix, based on a consideration of its curing and hardening.

Table 2.2: Binder compositions considered during Step 1.

Component	Binary CEM I		Ternary CEM I		Binary CEM III			
	B40	**B50**	**T1(CV)**	**T3(L)**	**B20**	**B30**	**B40**	**B50**
Cement	60%	50%	37.5%	20%	80%	70%	60%	50%
Silica Fume	40%	50%	32.5%	32.5%	20%	30%	40%	50%
Fly Ashes	-	-	30%	-	-	-	-	-
Slag	-	-	-	47.5%	-	-	-	-
Binder Silica Content	~53%	~61%	~56%	~54%	~42%	~50%	~57%	~64%

Table 2.3: Measured pH, compressive strength and curing temperature for the eight binder compositions considered in Step 1, and their rank order for each parameter - pH and compressive strength were measured after 28 days.

Binder Composition		pH		Compressive Strength		Maximum temperature increase	
		Value (slurry)	**Ran k**	**Value (MPa)**	**Rank**	**(°C)**	**Rank**
Binary CEM I	B50 Le Teil	11.6	4	50.1	2	14.4	5
	B40 Le Havre	11.5	3	41.9	6	10.0	3
Ternary CEM I	T3(L) Le Teil	11.8	5	42.0	5	9.5	1
	T3(L) Le Havre	-	-	42.3	4	-	-
Binary CEM III	B40 III/A Rombas	11.9	6	51.0	1	-	-
	B40 III/A Héming	11.9	6	-	-	-	-
	B50 III/A Rombas	11.3	2	44.3	3	11.5	4
	B50 III/A Héming	11.1	1	39.0	7	9.7	2

(a) Concrete mixer-truck used to carry concrete © Paul Calin

(b) Sample for testing

Figure 2.3: Delivery of concrete for metric-scale testing of concrete mixtures (D3.4, Bosgiraud and Foin, 2014).

Figure 2.4: Test box used for metric-scale testing. In this photograph, the fluidity of the concrete is shown at the outlet of the pump and evidence of self-compaction is provided by the smooth surface produced (no vibration or shocks were applied during the test) (D3.8, Bosgiraud and Foin, 2014).

Table 2.4: Measured compressive strength, pH, porosity and permeability for the 3 mixtures tested at the metric-scale.

Metric Test Blocks Composition	**Compressive Strength (MPa)**			**pH**		**Porosity**	**Permeability m^2**
	Cylinder		**Cores**				
	28 d	**90 d**	**28 d**	**28 d**	**90 d**	**28 d**	**28 d**
B50 CEM III/A 52.5 Rombas	37.8	50.7	34.9	11.8	10.1	19.7%	17.10^{-18}
B50 CEM III/A 42.5 Héming	36.9	49.6	31.3	11,8	10.2	19.,9%	19.10^{-18}
B50 CEM I 52.5 Le Teil	46.7	61.9	46.2	12,2	10.3	17.7%	-

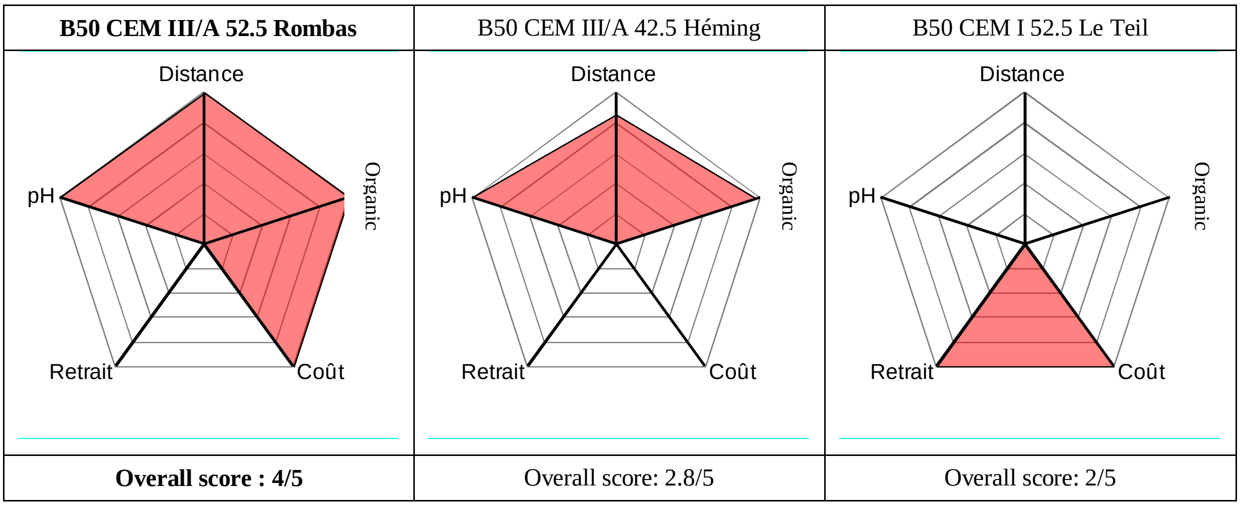


Figure 2.5: Global multi-criteria analysis to identify the preferred option for the low-pH SCC to be used in FSS. The French terms are defined in the text (Bosgiraud and Foin, 2014).

2.2.2 Development and Testing of the Shotcrete Mix

The research to identify the preferred low-pH shotcrete mix for construction of the downstream containment wall used a similar approach to the research used to identify the preferred option for the low-pH SCC. Three candidate mixes were selected for testing:

- B50 CEM III/A 52.5 Rombas.
- B50 CEM I 52.5 Le Teil.
- B50 CEM III/A 52.5 Héming.

After test spraying of metric-scale test panels (Figure 2.6), cores were extracted to measure the same properties as measured for SCC, i.e., compressive strength, pH, porosity and shrinkage (Table 2.5). In addition, the quantity of material experiencing rebound during emplacement was estimated by collection and measurement of material in front of the test panels (Table 2.5).

B50 CEM III/A 52.5 Rombas
(100 % silica fume)

B50 CEM I 52.5 Le Teil
(50% + silica fume + 50% nanosilica)

B50 CEM III/A 52.5 Héming
(100 % silica fume)

Figure 2.6: Photographs of the outcomes from the test spraying of metric test panels.

Table 2.5: Technical results for the three shotcrete mixtures tested at the metric-scale.

Parameter		B50 CEM III/A 52.5 Rombas	B50 CEM I 52.5 Le Teil	B50 CEM III/A 52.5 Héming
Slump (mm)	t_0	200	200	200
	t_0+1h	220	200	210
	t_0+2h	180	90	180
Percentage of rebound		2.2 %	8.0 %	9.1 %
Compressive strength at 28 days (MPa)		11±3	24±3	19±3
pH after 28 days		11.3	11.4	12.3
Water porosity after 28 days		21.1%	22.3%	19.8%
Shrinkage after 28 days (µm/m)	Endogenous	19	12	19
	Total	420	280	500

As for the selection of the low-pH SCC, final selection of the low-pH shotcrete was based on a global analysis (Figure 2.7). In addition to the parameters considered in the low-pH SCC analysis, the global analysis for selection of the preferred low-pH shotcrete mix also considered the odour of the mixture resulting from sulphur present in the slag materials (“odeur” in Figure 2.7) and the compressive strength at 28 days (“résistance” in Figure 2.7). The preferred mixture based on this multi-criterial analysis was identified as being the recipe **B50 CEM I 52.5 Le Teil**, and this mixture was subsequently taken forward for shotcreting of the downstream containment wall.

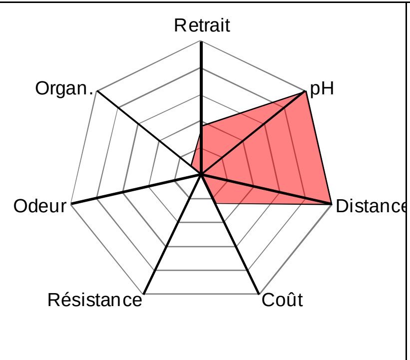
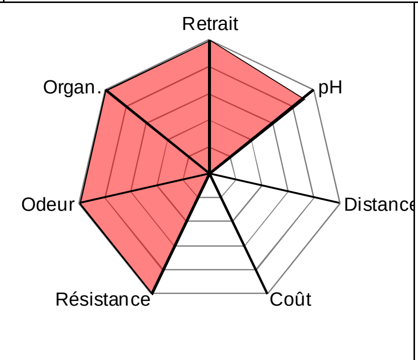
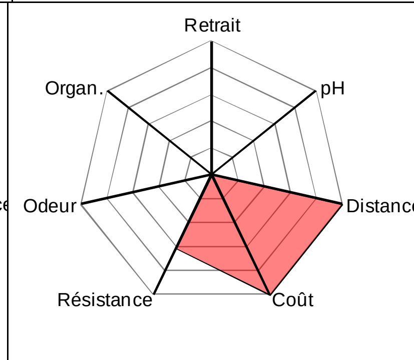
B50 CEM III/A 52.5 Rombas	**B50 CEM I 52.5 Le Teil**	B50 CEM III/A 52.5 Héming
		
Overall score: 1.9/5	**Overall score: 3.5/5**	Overall score: 1.9/5

Figure 2.7: Global multi-criteria analysis to identify the preferred option for the low-pH shotcrete to be used in FSS. The French terms are defined in the text.

Further details of the development and testing of the low-pH shotcrete mix are provided in the report D3.9, Andra (2016) and references therein.

2.2.3 Selection of Bentonite Materials

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 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 and desk-based design work was used to test and develop the design of the bentonite emplacement method.

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 (Kohler *et al.*, 2015). In the case of FSS (and the large seals envisaged by Andra for the Cigéo repository), the pellets can be filled 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 raises the issue of its stability, since the blocks are not assembled with a mortar.

Laboratory Testing and Manufacturing Trials of Pellet and Powder System

Andra specified the use of a pure sodium bentonite, without any other constraints, for the swelling clay core. The contractor chose WH2 bentonite from Wyoming. The raw WH2 material is equivalent to the well-known MX-80, but is provided by a different supplier.

Several studies were carried out to determine the required properties of the bentonite clay core material to be used in FSS. The initial requirements on the swelling clay materials focused on the swelling pressure and hydraulic conductivity; these are 7 MPa and

$1x10^{-11}$ m/s, respectively. During material testing, the dry density value of 1620 kg/m^3, corresponding to a swelling pressure of 7 MPa after hydration, was specified to ensure that the required swelling pressure could be achieved.

Laboratory studies were carried out to determine the preferred pellet size and choice of powder. The objective was to obtain the best possible dry density for the emplaced pellet-powder admixture. The tests showed that the best value for the dry density was obtained using an admixture with the following properties:

- The pellets had a cylindrical-spherical form with dimensions of: 32 mm (height) and 32 mm (diameter), and weight of around 42 g. This size was selected as a compromise between the optimum void between the pellets (to allow for a good emplacement of the powder) and the manufacturing capacity of the pellet producing machine (diameter vs compacting pressure).
- The 32 mm pellets were manufactured with a material composed of 90% WH2 powder and 10% WH2 fine particles with a grain size <160 µm. The dry density of the manufactured pellets was ≥2040 kg/m^3. The water content of bentonite was adjusted to around 4.5% (between 4% and 5%). This water content was the best compromise to obtain a good density of pellets.
- The bulk dry density of the pellets measured in the laboratory is approximately 1.10 kg/m^3, while the bulk dry density of standard WH2 powder is 1060 kg/m^3. Based on geometrical considerations, an optimum density value was observed for a 70% pellet and 30% powder mixture ratio. An addition of 30% of powder to the pellets can provide only an additional 320 kg/m^3 of dry density to the admixture. Therefore, the use of 32-mm pellets and WH2 powder does not provide the dry density of 1620 kg/m^3 required. To achieve the required density, the pellets were mixed with crushed pellets rather than with powder. The ratio of pellets to crushed pellets was 70%-30%. Laboratory measurement of this admixture confirmed that its bulk density was 1620 kg/m^3, i.e., the bulk density of the admixture in the laboratory matched the initial specification.
- The powder made with crushed pellets was controlled by sieving of the material to ensure a maximum grain size of 4 mm. This maximum was imposed to ensure that the powder could fill the voids between the pellets; powder with a grain size >4 mm could stay on the top of the heap (creating a bridging effect) preventing the powder from accessing the inter-pellets voids.

Mock-up Testing and Emplacement Machine Design

In parallel with the laboratory studies, a mock-up metric-scale setup was developed for testing the selected bentonite admixtures and the backfilling device. This device is based on two augers for emplacement of pellets and powder (Figure 2.8).

The metric emplacement tests demonstrated that the auger devices are the best adapted means capable of backfilling the drifts in an industrial way. However, the obtained bentonite density was less than the specified value of 1620 kg/m^3 which was 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. The main reason for these lower 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 production workshop and at the FSS site before emplacement.

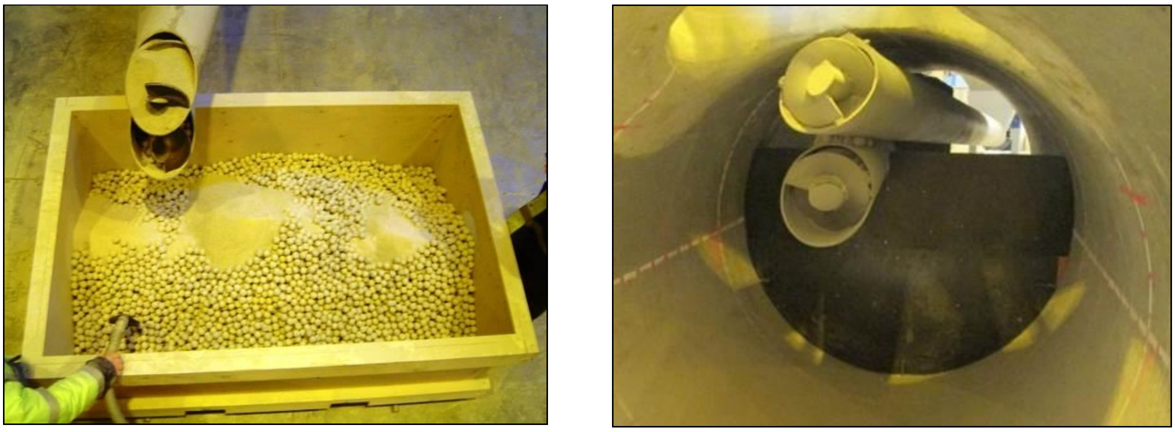


Figure 2.8: Mock-up tests at the metric scale of the bentonite pellet-powder admixture emplacement using augers.

Evaluation of the relationship between dry density and swelling pressure for WH2 undertaken in parallel with the design work described above showed that with a dry density of 1.5 kg/m^3 the swelling pressure would be around 5 MPa. This pressure was finally considered by Andra to be sufficient, and the FSS specifications were modified so that the required average dry density in the clay core would be 1500 kg/m^3 instead of 1620 kg/m^3 specified originally.

Further details of the selection of bentonite materials are provided in the report D3.12, Andra (2016) and references therein.

2.3 Siting of FSS

The FSS experiment was carried out in a warehouse at a surface facility in Saint-Dizier, which is close to the French underground research laboratory (URL) at Bure. The choice of a surface facility was made for the following reasons (D3.2, Bosgiraud and Foin, 2013):

- Carrying out the experiment underground requires a large excavation, with a significant duration, and a considerable amount of equipment and materials to be mobilised and emplaced. The Bure URL is essentially a qualification facility, in which the logistical flexibility to undertake large experiments such as FSS is limited. Logistical limitations include, for example, the means to transport significant quantities of materials, the number of people permitted underground at any one time, and the geometry of the underground tunnels, which limit the ability to use large equipment. A surface facility does not have these logistical limitations, and, in addition, allows investigations of the experiment from the external surfaces of the "test box".
- Several experiments were already planned to be carried out at Bure at the same time as the period in which FSS was to be conducted; this also limited the ability to use Bure for FSS.
- The experimental costs, schedule and requirements on later "investigation dismantling" also favoured the use of a surface facility.

The Saint-Dizier site was proposed by the Contractor in charge of the FSS experiment (GME), and accepted by Andra, for three reasons: the vicinity of Bure (30 km) where many

Andra staff are located, the height of the warehouse (more than 10 m of free gap under the roof frame), and the proposed building was suitable from the perspective of controlling the air humidity and temperature, as it had a double-insulated roof and atmosphere control equipment available.

2.4 Construction of the FSS Test Box

The FSS "test box" (or drift model) design concept was specified by Andra to contain the FSS experiment. Report D3.2 (Bosgiraud and Foin, 2013) provides a detailed description of the test box construction. The test box is made of Ordinary Portland Concrete (OPC) and is shown in Figure 2.9. One of the main requirements on the test box is for it to remain stable during the various construction and filling operations. Displacements and deformations must not exceed 5 mm and must be monitored throughout the whole duration of the FSS test (D3.2, Bosgiraud and Foin, 2013). The results of preliminary geotechnical investigations on the soil of the warehouse concluded that there was a need for replacing the alluvium layer present underneath the facility floor with a substrate (a limestone aggregate) between -2 m and -4 m to reinforce the soil beneath the test box. The construction procedure of the test box is summarised below and is described in more detail in D3.10 (Bosgiraud and Foin,2013).

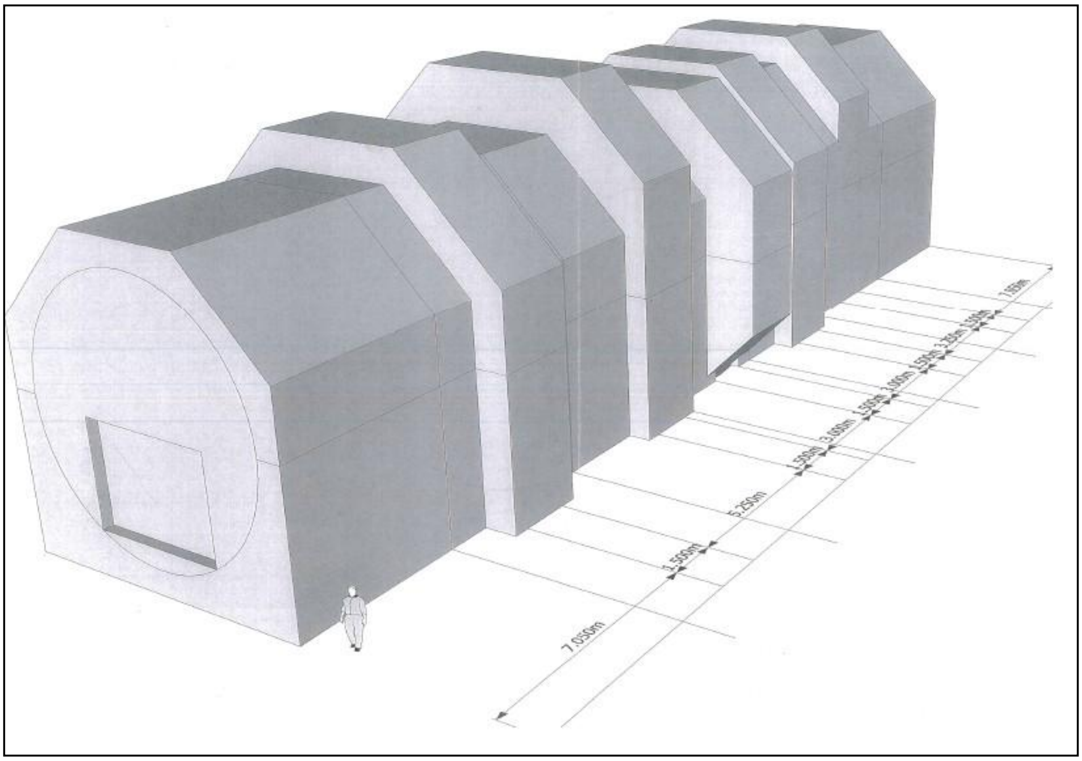


Figure 2.9: 3D schematic of the FSS test box (D3.2, Bosgiraud and Foin, 2013).

The first step in construction of the test box was to pour a concrete foundation slab on the newly created limestone aggregate platform (Figure 2.10a). Construction of the lower part of the concrete box framework commenced in December 2012 and was completed in nine weeks. The box structure was then built with seven lower blocks and seven upper blocks (each 5-m long). A wooden formwork was used to make the circular inner form, while for the outside a classic steel formwork was used (Figure 2.10b).

The concrete lining recesses were shaped by adding wood rings onto the principal inner formwork, and a special folio was pasted onto the rings to simulate the texture of the argillite walls in the breakout zones (Figure 2.10c).

After completion of the lower part of the text box, a layer of sand was laid on the ground inside the box in order to enable working on a flat floor and three steel sheets were used to slide the scaffolding equipment from a given block casting position to the next one (Figure 2.10d).

a) View of the concrete foundation

b) The inner wooden form and steel form

c) the folio pasted on the wood circular inner form to simulate the argillite walls

d) The completed lower part of the test box with a sand layer at the bottom and scaffolding also shown

e) Removal and translation of the wooden formwork between the two phases of the upper block casting

f) The completed test box

Figure 2.10: Different stages in the construction of the FSS test box (D3.10, Bosgiraud and Foin, 2013).

After that, the inner wooden framework was turned upside down and deposited on a shoring system made of a support beam and brackets so that the construction of the upper part of the box could be performed. Two phases of casting were carried out to complete the upper part of the box. Between the two phases of concrete casting, the external framework was totally removed, while the internal framework was slipped on rollers (Figure 2.10e).

It took thirteen weeks to construct the upper part of the box (Figure 2.10f), with construction completed in May 2013. A set of stairs was used to access the top of the test box. Twelve observation windows were installed to enable observation and checking of the bentonite filling operations. A local "mine-like" exhaust ventilation system was also installed, with a closing door in the front of the box, in order to control the ambient temperature (18°C < q < 30°C) and humidity (50% < HR < 75%) inside the box, as required by the experiment specification.

The test box construction was successfully commissioned as "test ready" by mid-June 2013, paving the way for the first step in the seal construction, i.e., installation of the upstream low-pH SCC containment wall.

2.5 Installation of FSS Components

Installation of FSS started with the construction of the first concrete containment wall (Section 2.5.1) followed by bentonite clay core emplacement in parallel with a support wall (Section 2.5.2). The last installed component of FSS was the second containment wall made of shotcrete (Section 2.5.3). The installation of the measurement system was undertaken in parallel with installation of the other components and is described in Section 2.5.4. The installation of the components is described in detail in the report D3.12 (Andra, 2016).

2.5.1 First Containment Wall

The casting operations for the first concrete containment wall took place in July 2013. The low-pH SCC casting operations were carried out with two main objectives (D3.8, Bosgiraud *et al.*, 2014):

- To realise a monolith type containment wall (with a volume of ~250 m^3),
- To minimise (as much as possible) the concrete shrinkage and cracking extent.

To achieve these 2 objectives, it was decided to pour concrete in batches of 7 m^3 at a time, i.e., the maximum capacity of the truck. In order to simulate the expected logistical constraints in a repository, for the majority of the SCC containment wall a period of two hours elapsed between starting one casting operation and starting the next. This period is consistent with the expected time for transport of concrete from the surface to underground emplacement sites in the Cigéo project. However, for the upper part of the wall, one batch per hour was poured to avoid rinsing the concrete pump pipes between two mixer-trucks and to maintain a sufficiently fluid concrete mass in the upper part of the wall to improve bonding.

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 was used for the preliminary test phases. The concrete was transported by mixer trucks. Each mixer truck batch represented a layer about 15-20 cm thick in the containment wall construction progress. Each pour was completed in approximately twenty minutes followed by a pause for approximately one hour and forty minutes before commencement of the next pour. All of the mixer truck 7 m^3 batches passed two qualifying slump flow tests, one just after mixing (i.e. at plant site) and another immediately before emplacement (i.e. at FSS construction site). The slump flow target was 550-750 mm.

The temperature of the concrete and the ambient temperature significantly affected the rheology of the fresh SCC. Therefore, during emplacement of the low-pH SCC containment wall, it was decided to adjust the retarding agent with respect to the ambient temperature; the higher the ambient temperature, the higher the retarding agent dosage. The superplasticiser dosage was kept unchanged. Moreover, it was required that the maximal temperature reached in the concrete during curing should be less than 50°C. Thus, the heat emitted during curing was measured during trials and later used to estimate the maximum temperature at which the concrete could be poured to meet the requirement. It was found that the maximum temperature increase during curing and hardening was 24°C. In practice, it was then decided not to pour concrete with an ambient temperature greater than 26°C. Those ambient conditions were effectively respected at the time of casting operations.

The casting operations were judged to be successful as the low-pH concrete rose progressively inside the box, with smooth and regular emplacement (Figure 2.11). To finish the operation, it was necessary to totally close the formwork before the concrete was injected in the upper part of the containment wall (Figure 2.11).

Figure 2.11: Pouring and even emplacement of SCC inside the test box (left) and emplacement of SCC close to the recess (right) (D3.8, Bosgiraud *et al.*, 2014).

After casting, the SCC containment wall was left for preliminary curing for about one week, and then the formwork was stripped from the concrete with no particular difficulties. Some 28 days of hardening later, the injection of low-pH slurry (grout) commenced in order to bond the containment wall to the test box concrete liner. The grout was emplaced through small pipes installed at the higher part of the cast concrete (two for grouting and two others to serve as air evacuation). The mix for the grout is provided in Table 2.6 and the grouting machine is shown in Figure 2.12. The quantity of injected slurry turned out to be very small (a few tens litres). It was thus inferred that, in FSS, there was only a small gap generated by concrete shrinkage and/or that the bonding had already taken place. This issue was investigated further during the dismantling of FSS, which is reported in D4.4 (DOPAS, 2016c) and D4.8 (Bosgiraud *et al*, 2016).

Table 2.6: The mix for the low-pH grout used for bonding in FSS.

Component	Quantity (kg/m^3)
CEM III/A 52.5 Rombas	311.7
Silica fume	311.7
Very fine sand (“Sablon”)	781.7
Water	438.0
Glenium ®Sky 537	1.9% of (C + SF) : 11.4 L
Rhéomac ®SRA 872	2.0% of (C + SF) : 12.5 L

Figure 2.12: Grouting machine used for bonding in the FSS experiment.

2.5.2 Bentonite Clay Core and Support Wall

The swelling clay core backfilling activities were commenced in October 2013 (after completion of the SCC containment wall).

Before the start of bentonite emplacement, all material was delivered and stored at the warehouse, including 847 tonnes of 32-mm diameter pellets (in 770 octabins) and 368.5 tonnes of crushed pellets powder (in 335 big bags). A specially developed "backfilling" machine for the purpose of bentonite emplacement was constructed (Figure 2.13). The machine comprises a carriage that moves in the *y*-direction into the test box on two rails overlaid by a movable turret in the *x*-direction. This turret incorporates all components used for conveying of materials: a hopper for pellets, a hopper for crushed pellets, and a crane used to move the augers in the *z*-direction as bentonite emplacement progresses.

Figure 2.13: The bentonite mix emplacement machine.

The filling procedure commenced with emptying of the octabins (containing bentonite pellets) and the big bags (containing bentonite powder) into separate movable hoppers (Figure 2.14). The movable hoppers were then lifted by forklift trucks and emptied into fixed hoppers positioned on the filling machine (Figure 2.15). Filling of the lower two thirds of the clay core volume was completed with the two augers (one for the pellets and one for the powder) one above the other to reproduce the laboratory experiments in which the best results were obtained (Figure 2.16). Filling of the upper third was completed with the augers side-by-side to enable the filling of the recesses (reproducing the metric tests).

The process of transferring bentonite powder into hoppers and then to the forklift trucks followed by placement in the concrete test box generated high-levels of dust. Examination of the ventilation system after the first day of use identified non-ideal performance of the mine-type filter, which was then cleaned, resulting in lower levels of dust in the warehouse facility.

Figure 2.14: Emptying of an octabin containing bentonite pellets (left) and a big bag with bentonite powder (right) into hoppers.

Figure 2.15: Transferring the bentonite into the filling machine using forklift trucks (left) and then transfer of pellets through a conveyor belt into the auger (right).

Figure 2.16: Bentonite materials transferred through the augers (left) into the core of the seal (right).

Emplacement of the bentonite materials was facilitated by construction of supporting walls. At first, a supporting wall was partially constructed (at mid-height) to contain the first part of the bentonite core. The supporting wall was then progressively constructed concurrently with the bentonite filling operations. This wall was built with half-cubic-meter low-pH concrete blocks made with the same SCC as that used for the first containment wall. The swelling clay core emplacement was finished in August 2014.

During the filling operations, two problems were encountered and mitigated:

- Too many pellets were found to be broken during the emplacement process, which would have a significant impact on the emplaced density. The augers were inspected and excessive wear of the transport screw was discovered. Subsequently, the screw was replaced, resulting in far less breakages.
- The gear motor of the bentonite powder auger also required replacement.

2.5.3 Second Containment Wall

The second 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. The mortar was emplaced between blocks and at the contact with the test box wall. This containment wall was built by spraying shotcrete in wet conditions in order to test an alternative to the use of low-pH SCC. The low-pH shotcrete containment wall (Figure 2.17) was finished in September 2014 after solving initial challenges with fabrication of the shotcrete:

- The rheology of 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 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 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.

Figure 2.17: Installing the second containment wall made of low pH shotcrete in FSS.

2.5.4 System for Measuring FSS Components Parameters

The main environmental condition parameters measured in the FSS experiment to ensure that they are similar to those expected in Cigéo included, ambient temperature (measured continuously), humidity (measured continuously), and dust in the air (measured randomly as done in a mine). For the concrete and shotcrete containment walls, continuous measurements of the curing temperature and shrinkage were implemented. For the bentonite core, the quality of the material used at each step of fabrication and the quality of the filling and mass balance of the admixture were checked. 3D scans were performed for evaluation of the bentonite backfilled volumes at pre-defined phases. The emplaced bentonite dry density was also evaluated. More information on the measurement system is available in Andra (Report D4.8, Bosgiraud et al. 2016). It is important to mention that the monitoring of FSS was dedicated only for the test run-time of the experiment until its dismantling.

2.6 Lessons Learned from the Design and Installation of FSS

Prior to the commissioning of the FSS experiment, some of the lessons learned concern the need to allow enough time to design the experiment, especially with no previous experience of full-scale tests of plugs and seals. All the experiment specifications need to be individually checked and cross checked to ensure consistency (for example, the temperature and pH values for concrete, type of materials for the bentonite and their density, etc.).

An important lesson for the material specifications is the selection of realistic and achievable targets. This was the case with the bentonite material dry density specification. Initially a high value of the dry density was specified even though a more realistic and lower target was found to be sufficient and more easily achievable. Where feasible, a range of values for material specifications should be provided rather than absolute values as this will facilitate quality control during installation. It furthermore provides "robustness" to the concept.

Besides, for the WH2 admixture, the original target swelling pressure of 7 MPa turned out to be somehow a real "overkill" and was reduced to 5 MPa since this value is compatible with the seal permeability target and the argillites EDZ self-sealing.

For instance, the requirement for the concrete temperature (50°C) was not a requirement given in D2.4, but a decision made by Andra for the input for design and work specifications given to the contractor. The explanation about this is that Andra thought it right to have a safety margin (i.e. 10°C less than the usual 60°C temperature requirement commonly found for curing of concretes). On the other side, for the low-pH SCC, it was found that the temperature at the experiment site impacts on concrete, therefore, this will need to be appropriately managed underground. For the shotcrete, it was concluded that new metric or plurimetric tests would need to be implemented in order to have a better know how of the shotcrete emplacement methods.

Selection of both the SCC and shotcrete mixes used both "technical" (e.g., pH, shrinkage, compressive strength and presence of organic matter) and "non-technical" considerations (e.g. distance from manufacturer and cost). Overall, the shotcrete mixes tested had a lower strength than the SCC mixes.

Similarly, the concrete pH value requirements were changed from the original pH 10.5-11 @28 days to pH 10.5-11 @90 days. The justification is that the original requirement was some type of "overkill", since pH value keeps diminishing with time for these types of concrete.

Development of the bentonite admixture recognised the need to combine pellets with crushed pellets rather than the standard WH2 powder (the crushed pellets are referred to as “powder”) to achieve higher densities, and the need to arrange augers vertically rather than horizontally to achieve the best density. However, emplacing the bentonite near the tunnel ceiling requires the augers to be arranged horizontally.

During experiment installation, one of the main challenges was dealing with the vast amount of dust generated by handling bentonite in the warehouse. The use of a scraper conveyor to transfer material into the filling machine instead of forklift trucks would reduce the dust generated during unloading of bentonitic components (powder in particular) into the forklift truck hoppers and also reduce the transfer time of material. A special hooded vacuum tube with a filter to remove dust could be incorporated into the design of the bentonite emplacement machine.

During construction of the experiment, it was emphasised that the safety and health of staff is paramount, especially with material which can potentially be hazardous (e.g., silica fume, bentonite dust, etc.). Supervisors need to be mobilised all the time during the full-scale test in order to verify that the procedures and regulations are always adhered to.

3. Achievements, Lessons Learned and Future Challenges

This chapter provides an integrated discussion of the achievements of, and the lessons learned from FSS, in relation to the design and construction of full-scale experiments for plugs and seals, and for full-scale experiments in general. Achievements and lessons learned from FSS Project experiments are discussed in seven sections:

- Section 3.1 discusses good practice for successful planning of a full-scale experiment.
- Section 3.2 discusses the strengths and weaknesses of the location used for conducting the full-scale experiment in Saint-Dizier.
- Section 3.3 discusses the achievements and lessons learned with respect to design and installation of the FSS seal low pH concrete containment walls.
- Section 3.4 discusses the achievements and lessons learned with respect to design and installation of bentonite mix forming the FSS swelling clay core.
- Section 3.5 discusses the achievements and lessons learned with respect to excavation of the future seal emplacements in Cigéo.
- Section 3.6 presents some of the challenges encountered during installation of FSS and how these were overcome.
- Section 3.7 summarises logistical issues encountered during the design and construction of FSS.
- Section 3.8 summarises health and safety issues addressed during the design and construction of FSS.

Evaluation of the monitoring and measurement systems used in the DOPAS Project experiments, including their installation, is included in WP4 of the DOPAS Project and reported in Deliverables D4.4 (DOPAS 2016c) and D4.8 (Bosgiraud *et al.,* 2016).

3.1 Good Practice for Successful Experiment Planning

The design and construction of the FSS experiment have been successful, within the timeframe of the DOPAS Project. Success of the design and construction activities has been underpinned, in part, through the use of good planning, through application of systematic design processes, by taking a stepwise approach involving studies at multiple scales, and through a mix of experienced and less-experienced staff.

The FSS experiment had benefitted from the development of comprehensive and detailed design bases, as recorded in the DOPAS Design Basis report D2.1 (White *et al.*, 2014). This experiment had clear objectives, which allowed the Andra team to have a clear and shared vision of how activities related to the global objective:

- The FSS experiment was built to prove the technical feasibility of constructing a seal at full scale,
- It was not saturated or otherwise pressurised to check the swelling pressure and hydraulic conductivity since these processes were examined and implemented in the parallel experiment REM which is part of WP4 of the DOPAS Project (cf. Deliverable D4.2, Report on Bentonite Saturation Test, Conil *et al.,* 2015).

This full-scale experiment was supported by a series of mock-ups undertaken at a range of scales to support the upscaling of the design from the laboratory to the full scale. For example, Andra rearranged the transfer system used to emplace the bentonite pellet and powder mix based on metric-scale testing of the backfilling machine. Mock-up tests may be required by the regulator prior to implementation of a process within an operating repository; the experience from the DOPAS Project (and from FSS) has illustrated the general benefit from undertaking such activities.

Another successful aspect of the organisation of the experiment was the incorporation of experienced staff within the project (including from the Contractor's side) even if some delays were experienced.

The FSS experiment also benefitted from cooperation between staff from Andra and Nagra, the latter one having just completed the FE Experiment, within the frame of the EC financially supported LUCOEX Project. These included lessons related to bentonite mix design and bentonite mix emplacement methods.

3.2 Location of the Demonstrator

At the time of FSS planning, working underground was naturally first considered. The first prospect was the Andra Bure URL, which turned out to be incompatible with the experiment logistical needs and the "full scale" geometrical requirements, while the URL workload was another factor for discarding such a choice. An ordinary underground facility (i.e. out of the argillite formation) was also quickly considered and discarded for legal (unadapted tunnel regulations) and environmental (difficulties to reproduce Cigéo-like conditions) reasons.

Thus, locating the FSS experiment at the surface provided the benefit of flexible access to the test box for both monitoring of the construction and for the ultimate dismantling activities. The additional space in the building meant that it was feasible to store materials and ensure their availability for the filling operations. Although the experiment was not undertaken underground (in Cigéo like conditions), it was feasible to control the ambient temperature and relative humidity so that the conditions were suitably representative.

<u>Note:</u> It is worth mentioning that the fact of not working underground is partly misleading, as far as the drift liner dismantling issues (and clay rock purging) are not dealt with in this experiment, by contrast with other experiments like DOMPLU and POPLU. However, these issues will addressed during the Cigéo Pilot Phase (2025-2034), when "full scale demonstrators" will be built in a ramp and in a drift.

3.3 Design of Concrete Components of Plugs and Seals

A range of low-pH concrete mixes have been developed, tested in FSS. Shotcrete and SCC formulations have been selected and used to build the large concrete monoliths (250m^3 each) forming the containment walls on each side of the swelling clay core. Laboratory testing of these mixtures has demonstrated that they have the required curing temperature, hydraulic conductivity, shrinkage characteristics, strength, water interaction (pH of pore water or leachate) and rheology/segregation characteristics for application in repository plugs and seals.

All of the low-pH concrete mixes used in the DOPAS Project (and in FSS) used a common approach to provision of the low pH. This included the substitution of cement commonly used in high-pH concretes with silica fume and fly ash, with the addition of filler. Aggregates were locally sourced. All of the cement mixes needed to be accounted for the properties of the specific components, such as locally-sourced cements and aggregates, and had to be tailored to the boundary conditions of the experiment.

Amongst the key properties of concrete used in plugs and seals are the values for compressive strength, pH of leachate and maximum curing temperature. High compressive strengths of ~40-60 MPa could be achieved for some of the concrete mixes tested in FSS.

Note: By contrast with the Czech EPSP experiment, Andra decided not to include glass or steel fibres for additional strength, since the phenomenology (corrosion, ageing or chemical interaction) of this type of material is difficult to predict over a significant lapse of time (thousands of years).

Challenges encountered during the emplacement of the concrete mixes have been overcome:

- In FSS, the preparation of concrete mixes at the concrete plant had to be scrutinised and monitored to ensure compliance with the mix specification, for example to check the homogeneity of the dry material mixture.
- However, there is further work to be undertaken on low-pH concrete mixes. Additional work should be done to evaluate the sensitivity of the concrete performances to marginal variations in component percentages and infer, by so doing, how robust a given mix can be. The role of certain additives e.g., plasticisers should also be further explored to see how dependant on the ratio between organic and mineral components a concrete mix composition can be. This is necessary to better assess the robustness of the safety demonstration (i.e. determine the role of complexing organic products in long-term safety). All of the concrete mixes used in FSS are novel materials, and, therefore, are not yet compliant with existing standards.
- Therefore qualification of the concrete mixes is required, and this is discussed further in Deliverables WP4.4 and D4.8 of the DOPAS Project.

3.4 Design of Bentonite System for the Swelling Clay Core

In FSS, a mixed pellet and crushed pellet bentonite system was used to erect the swelling clay core, which has an internal diameter of 7.6 m. Although the original bentonite dry emplaced density requirement was 1620 kg/m^3, evaluation of the “dry density linked” swelling pressure for the bentonite undertaken in parallel with material testing showed that the required swelling pressure could be achieved with a dry emplaced density of 1500 kg/m^3 only.

One of FSS swelling clay core challenges was to manage the heterogeneity in the system, particularly the vertical heterogeneity, which results in a lower density being achieved towards the top of the bentonite layers, i.e. close to the drift roof. In principal, this is achieved by exceeding the design specification in the lower parts of the layer to compensate for lower densities in the upper parts of the layer. In FSS, the overall dry emplaced density of the system meets the design specification. Furthermore, at smaller scales, it was many times observed that homogenisation of the saturated material appears with time.

3.5 Challenges during Excavation and Construction of the Experiment Site

As noted above, in FSS, rock excavation was not carried out as the experiment was located in a surface facility. Partial dismantling of the drift concrete liner in Cigéo will be an issue of its own, for which scale 1:2 tests are planned by Andra in its Bure URL in the years to come.

These tests will provide further information on the potential for break-outs in drift and ILW vault seal locations, and provide a basis for excavation methodology development. This may include further work to develop criteria related to the EDZ at the location of plugs and seals.

3.6 Challenges during Installation

Installation of the FSS experiment was successfully completed within the timeframe of the DOPAS Project. However, there have been challenges associated with installation of materials close to the model drift wall (especially the roof) and with installation of the instrumentation. This was found to be an issue in several DOPAS experiments:

- All of the experiments required modified procedures for emplacement of material close to the roof space. Future design improvements should include better processes for installation of materials in this area.
- FSS was conducted in a surface facility, obviating the need for certain activities, such as removal of the tunnel lining before installation of the swelling clay core. Procedures for removal of the tunnel lining will need to be developed in the future.

In FSS, the main challenge was the pellet breakage which appeared with the progressive wearing of the augers (screws) installed inside the bentonite pellets conveyor pipes: this breakage contributed to a poor effective dry density of the emplaced material (a phenomenon due to the bridging effect created by the broken parts of the pellets preventing the bentonite powder from fillings the voids). This situation led to a change of screw steel characteristics to minimize the wearing effects.

Nonetheless, the FSS experiment demonstrated good application of quality control and construction procedures during the installation of the experiment components.

3.7 Logistics

Although all of the experiments were successfully installed within the course of the DOPAS Project, logistical problems were faced by all experiments. Of particular note were delays associated with machine availability. Delays were encountered, for example, when excavation machines required regular maintenance. Delays in one aspect of installation can have knock-on effects, especially when novel machinery is scheduled to be used elsewhere.

Delays were experienced by the FSS experiment when the screw augers required replacement parts (an electric motor was also replaced), and, during later stages of the project, replacement screws and electric motors were made available.

Logistical issues slowed the construction process down for FSS. Besides, the manufacturer of the FSS bentonite mixture backfilling machine was bankrupted during the project and this caused an additional delay in the experiment construction start-up.

In addition, FSS relied on a specialized contractor to mix concrete, which was appropriate, but delivery was challenging.

3.8 Health and Safety

The experience of the DOPAS Project has shown how health and safety concerns can slow and/or require changes to the installation of experiments. This applies to FSS, since management of dust was an issue. All workers had to wear face masks and the content of dust in the air had to be monitored to follow the workers' exposure. This was caused, in part, because the mining ventilation installed turned out to be insufficient.

4. Conclusions

Within WP3 of the DOPAS Project, four full-scale experiments of plugs and seals have been designed and constructed. These include the FSS experiment in France.

Design and construction of the FSS experiment contribute to the technology readiness level (TRL5, according to Expert judgement, cf. D6.3.2 – Palmu 2016) of seal installation in Cigéo in the future. The completion of the experiment design and construction represents a successful collaboration between Andra and its contractors or consultants.

The design and construction of FSS has demonstrated that seals are more challenging and complex sub-systems of the repository than previously recognised. However it is worth knowing that the challenges and complexities of seal design and construction can be met through available technology, methods and procedures currently available.

Significant work on low-pH concrete, contact grouting and bentonite pellet systems has been undertaken within FSS.

Logistics is a significant issue for concrete containment walls and swelling clay cores. There may be multiple components requiring installation and appropriate time must be allowed for these materials to be installed and evolve prior to installation of the next component. There may be issues associated with manpower and machinery availability (and performance). Therefore, contingency planning, such as the provision of back-ups and spares may be necessary. Contingencies also need to be built into project plans and schedules at time of repository operations.

Application of the lessons learned from the FSS experiment and feedback to reference Cigéo seal design are considered in WP4 of the DOPAS Project and reported in Deliverables D4.4 and D4.8. This includes an analysis of further work required to develop Cigéo seal design so that it is ready (TRL9) for implementation in Cigéo in the future.

5. References

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