FSS (Full Scale Seal) Experiment
Transposition from laboratory tests to full scale emplacement reality
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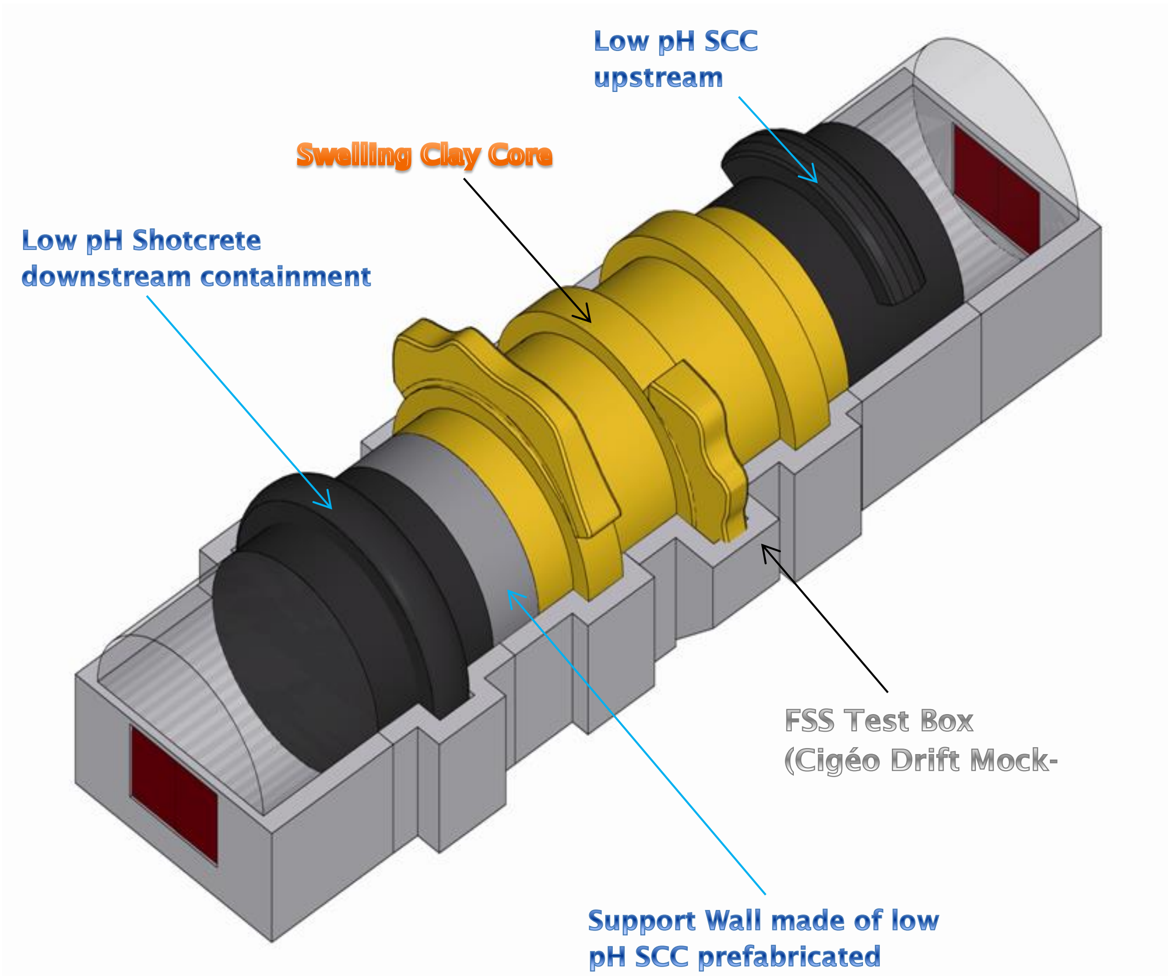
----SUMMARY----

The objectives of this topic is to show the main difficulties encountered by Andra in the FSS experiment to comply with the specified requirements regarding the construction of the swelling clay core and the construction of its 2 containment walls (one with low pH SCC and the other one with low pH shotcrete), in relation with (in particular) the scale aspects.

The differences between the results of the upstream containment wall built with SCC and the downstream one built with shotcrete will be analysed and possible solutions to reach a better result will be suggested. For the filling of the bentonite core, the different difficulties appeared during the construction phase will be also analyzed and possible solutions to reach a better final dry density will be listed.



1. Introduction

The Full Scale Seal (FSS) experiment, which is part of the DOPAS project, is one of various experiments implemented by Andra, within the frame of the Cigéo Project (the French Deep Geological Repository) development, to demonstrate the technical construction feasibility and performance of the seals to be built at time of closure of the various repository components (shafts, access ramps, drifts, disposal vaults).

FSS was built inside a drift model constructed in a hangar, on surface, for the purpose. The dimensions are close to the actual dimensions of the deal structures to be built in Cigéo (approximatively with the same diameter, but with a shorter length). To build this seal prototype, Andra specified to the contractors different requirements to be fulfilled in the emplacement of the bentonite core or in the construction of its associated low pH concrete containment walls.

A French laboratory (CEA/LECBA), a member of the consortium of companies contracted, developed the various materials (low pH self-compacting concrete (SCC), low pH shotcrete and bentonite admixture) necessary to backfill the drift mock-up in accordance with predetermined specifications. All these materials were initially designed and tested at a small scale (laboratory test size) to validate the results at this scale. In parallel backfilling methods, and means, were designed jointly by the four members of the consortium (CEA/LECBA, LAVIOSA: a company specialized in bentonitic products, EIFFAGE TP in charge of the emplacement and SOLEXPERTS in charge of instrumentation), in accordance with their pre-existing knowhow and with the results obtained in preliminary laboratory studies. Afterwards, during the FSS mock-up backfilling with the different materials and following the different measurements carried out during advancement or post construction, it was shown that the real results were not in total accordance which those expected.

This presentation will show the influence of scale effects between the initial design and the final emplacement case for the bentonitic materials and cementitious materials used for the FSS experiment and how this situation has modified the design basis or the requirements of the Cigéo seal concept.

2. Scope and objectives of FSS

2.1 General objectives

The FSS experiment is one piece of a set of tests, designed to demonstrate the industrial feasibility of the drifts seals to be built for long term safety of Cigéo. The objectives specifically designated for this experiment, were:

- To show the industrial feasibility of emplacing large volumes of bentonite (core) and low pH concrete (containment walls) that correspond to a full scale seal of a drift in the Cigéo Project (order of magnitude: decametric diameter and multi-decametric length). The practical modalities to use these materials have to guarantee the achievement of specified requirements of the core and of the containment walls.
- To define the operational requirements useful to obtain the properties (especially mechanical and hydraulic ...) expected; for example, requirements for tolerances on the bentonitic material dry density distribution inside the core.
- The decametric size of the experiment does not permit to envisage a total and complete re-saturation of the core to check its swelling and permeability; this information has to be obtained from another test at a smaller scale (REM presentation – cf. Nathalie Conil et al.).
- To define and deploy the control means of monitoring during filling operations, to verify the compliance of the implementation of the materials in relation with defined requirements.

- To define and deploy the control means to verify "post-mortem" that the objectives are fulfilled; e.g. thorough filling (before swelling takes place) of the upper parts of the seal (which are also called recesses and are sections simulating the partial deposition of the drift concrete liner).

In parallel with the drift mock-up construction which was not a construction objective but just a tool useful to simulate a drift in which the full scale seal could be emplaced, the main challenges were to elaborate the 2 low pH concrete formulations and bentonite material mix to reach the expected requirements.

2.2 Low pH self-compacting concrete and shotcrete requirements

For these materials the most important requirements were:

- The low pH value to reach;
- The period of use of the material.

For the period of use, the need was to wait 2 hours before emplacement (SCC or shotcrete) to simulate the transport duration between fabrication at the surface and casting underground. The table below shows the main requirements concerning the low pH SCC and shotcrete to be emplaced in the 2 containment walls of FSS (SCC upstream and shotcrete downstream).

<table>
<tr><th colspan="2">Upstream containment wall</th><th colspan="2">Downstream containment wall</th></tr>
<tr><th>SCC
(Self Compacting Concrete)</th><th>Injection grout</th><th>Precast concrete blocks</th><th>Shotcrete</th></tr>
<tr><td colspan="4">pH of poral solution (28d) ≤ 11.0 (ideally between 10.5 and 11.0)</td></tr>
<tr><td>Slum flow ≥ 65 cm</td><td></td><td rowspan="6">The same SCC as for upstream containment wall was used, but without any constraint for the period of use.</td><td></td></tr>
<tr><td>Period of use ≥ 2 h</td><td></td><td>Period of use ≥ 2 h</td></tr>
<tr><td>Max. temperature ≤ 50 °C</td><td></td><td>Max. temperature ≤ 50 °C</td></tr>
<tr><td>$f_c(28d) \geq$ 30MPa
$f_c(90d) \geq$ 40MPa</td><td></td><td>$f_c(28d) \geq$ 25 MPa
$f_c(90d) \geq$ 35MPa</td></tr>
<tr><td>Shrinkage (90d) ≤ 350 µm/m</td><td></td><td>Shrinkage (90d) ≤ 350 µm/m</td></tr>
<tr><td>Pumpable</td><td>Pumpable</td><td>Sprayable</td></tr>
</table>

Table 1 Requirements for self-compacting concrete and shotcrete used to build the containment walls

2.3 Bentonite admixture requirements

The initial bentonite admixture requirements were:

- To use a pure Wyoming sodium bentonite (Montmorillonite) such as MX80 or WH2;
- To make a granular admixture constituted for example by pellets and bentonite powder to fill the voids between the pellets;
- To construct the core with an industrial method which could be used underground at a depth of 500 meters;
- To verify the results with measurement means compatible with the underground localization of Cigéo (those means had to be qualified).

The final requirements on the bentonite core, even if no full scale hydration[1] was realized, were:

- Hydration swelling pressure expected above 4[2] MPa;
- Permeability after saturation ≤ 10^{-11} m/s.

3. Methods used to develop the seal components

3.1 General methods

All the methods used to develop the various seal components were empirical methods based on a progressive approach to reach the expected results.

3.1 Low pH concrete and shotcrete formulations developments

Here is the list of the different main steps of the global method used to determine the best compositions of a low pH SCC:

- Bibliographical analysis to investigate the different solutions used over the world (Finland, Spain, Switzerland, Sweden …) to decrease the pH value of concrete.
- Test of different binders (binary and ternary bends) to find the most appropriate composition to decrease the pH: 4 binders were selected.
- Determine with the software "BétonLab Pro 3" the different possible compositions regarding the availability of local materials: cement, aggregates, sand.
- Test in laboratory to determine the most promising compositions in batches of 30 liters.
- Verify the rheology of theses compositions after 2 hours (visual examination, slump flow test, and sieve segregation test).
- Determination of the values of different parameters (hydration temperature, pH, porosity, compressive strength… after 28 and 90 days).
- Improvement, step by step, of the results (3 iterations and around 300 SCC mixes were virtually studied) to determine the 3 best compositions to be practically tested in industrial-like conditions.

[1] Test of hydration was made at very small scale (a few liters cell) during FSS experiment and later in the REM experiment with an approximate volume of one cubic meter.

[2] At the beginning the value used to design the admixture was 7MPa; but as the result was not obtained during the metric tests, Andra decided for the final emplacement to specify 4 MPa. However all the initial conception of the admixture was made with an objective of 7 MPa.

Compound (kg/m^3)	B50 CEM I 52,5 Le Teil (100% nano-silica)	B50 CEM III/A 42,5 Héming (100% silica fume)	B50 CEM III/A 52,5 Rombas (100% silica fume)
Gravel 5/12 (dry)	807,7	737,8	682,1
Sand 0/4 (dry)	531,2	457,7	487,0
Sable 0/2 (dry)	230,9	198,9	211,7
Cement	108,0	132,0	130,0
Silica fume	0,0	132,0	130,0
Nano-silica Slurry	216,0	0,0	0,0
Limestone filler	335,5	396,9	408,4
Glenium Sky 537	≈ 8,0%	≈ 2,0%	≈ 2,2%
Prelom 510	0%	≈ 0,3%	≈ 0,3%
Water	70,2	205,7	204,1

Table 2 Identification of compositions to test in industrial conditions

- Test of these compositions to determine the different values of the principal requirements.
- The composition with nano-silica was not successful because the concrete began to harden too early (less than 2 hours). Another formulation using the same components but with silica fume instead of nano-silica was finally tested.
- After a new analysis of the different results, the choice was made to use the "Rombas composition".
- This formulation was then tested in a larger quantity (12 m^3) to see the scale effects before final emplacement.

For the shotcrete the analysis was similar but we did not test a larger quantity as we did for SCC (this wall certainly a mistake).

3.2 Bentonite admixture development

For the development of the bentonite admixture, the problem was not the same as for SCC or shotcrete because the only problem was to reach a dry density around 1.62 g/cm^3 permitting to obtain a hydration pressure of 7 MPa. Two subjects were studied:

- How to have the best dry density for each of the components?
- How to emplace these components in the most homogeneous possible way and with the smallest possible voids between them?

For the first subject, as the swelling material was imposed (pure sodic bentonite) and the use of granulate components was also imposed, all the investigation was to find how to obtain the highest possible dry density of the admixture components.

First, the investigation was on the pellets production machine because the pellets which form around 70% of the total volume had to have the highest possible density. The machine developed permitted to have a pellet dry density around 2.04 g/cm^3.

With that result for the pellets we began different laboratory tests to see how to elaborate the final admixture (test with 2 or 3 different components). The best result was obtained by combining 32 mm pellets with a powder (made of crushed pellets) used to fill the voids between the pellets.

In the laboratory with this admixture we effectively reached the expected dry density of 1.62 g/cm^3 while pouring the 2 components separately (first the pellets and then the powder).

Testing this solution inside a mock-up of a few cubic meters (a metric size concrete pipe) we noticed that what was possible in a laboratory could not be fully transposed. After several tests we could not obtain more than 1.52 g/ cm^3. So the newly specified dry density was revised down to 1.5 g/cm^3 in accordance with the metric test results.

4. Results

4.1. Low pH self-compacting concrete and shotcrete results

For the low pH SCC, the result was at the level of the different preliminary tests and the emplacement of the upstream containment wall was quite successful.

For the low pH shotcrete, the result was not at the level expected: hydration temperature was too high (67°C instead of less than 50°C) and a lot of cracks in the downstream containment wall were noticed.

4.2. Bentonite core results

During the first part of the filling operations (2/3 of the total volume composed by all the lower part of the mock-up and first part of the top) the dry density measured was better than expected (1.58 g/cm^3), but in the second part (end of the top of the drift model) the result was lower than expected (1.28 g/cm^3) for a global result which didn't reach totally the expected requirements (1.48 g/cm^3 instead of 1.5 g/cm^3).

5. Discussion

It's always possible to be satisfied or not by the FSS experiment outcomes; it depends of what was your own objective; and this objective is not obligatory the same for all people working on the subject: it depends of their sensitivity… For example is the 1.48 g/cm^3 density value a bad result when at the beginning your requirement was 1.62 g/cm3 and finally you opted for a theoretical value of 1.5 g/cm^3? To answer this question it is necessary to take a little height and consider there is room for improvements!

In the case of FSS a few people were not satisfied of the results because all the requirements were not totally fulfilled… It's very often in the case of difficulties that you learn the most part and that you can also provide improvement solutions for your future tests.

6. Conclusions

Globally for Andra FSS was a technical success because this experiment showed the feasibility of emplacing great quantities of low pH self-compacting concrete, shotcrete ant bentonite admixture… which was its main objective; but different ameliorations could have been done, and will have to be taken into account in the future conception, to reach in totality the expected requirements in terms of shotcrete use (if it is used) and naturally bentonitic material which is the main component of the seal.

7. Acknowledgements

We should like to acknowledge the Consortium in charge of the construction of the construction of the test drift and its filling (EIFFAGE TP, CEA/LECBA, LAVIOSA and SOLEXPERTS) which did with their own subcontractors a positive work, as well as the different other contracted companies in charge of the safety, the quality and the technical assistance to Andra.

Andra also acknowledges the EC financial support of its FSS related activities within the DOPAS project (EC Contract Agreement 323273).

8. References

8.1. Concrete and shotcrete

- FSS-1 : Choix des liants pour les bétons bas pH « CG-TE-F-NTE-CFS1-GC0-4000-12-4001/A »
- FSS-1 : Bétons bas pH autoplaçants : bilan des études de laboratoire « CG-TE-F-NTE-CFS1-GC0-4000-13-4044/A »
- FSS-1 : Bétons bas pH autoplaçants : bilan des essais à l'échelle industrielle « CG-TE-F-NTE-CFS1-GC0-4000-13-4045/A »
- FSS-1 : Rapport final remplissage du massif amont en béton bas pH : « CG-TE-F-NTE-CFS1-GC0-4000-13-0039/A »
- FSS-1 : Bétons bas pH projetés : bilan des études de laboratoire « CG-TE-F-NTE-CFS1-GC0-4000-13-4046/A »
- FSS-1 : Bétons bas pH projetés: bilan des essais à l'échelle industrielle « CG-TE-F-NTE-CFS1-GC0-4000-13-4047/A »
- FSS-1 : Rapport final remplissage du massif aval en béton projeté bas pH : « CG-TE-F-NTE-CFS1-GC0-4000-14-0007/A »

8.2. Bentonite

- FSS-1 : Conception des matériaux à base d'argile gonflante « CG-TE-F-NTE-CFS1-GC0-4000-12-4000/B »
- FSS-1 : Rapport final réalisation du noyau de bentonite « CG-TE-F-NTE-CFS1-GC0-4000-14-0005/A »