Use and management of sulphated excavation material from the Montcenis Base Tunnel

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ABSTRACT: The 57.5 km long Montcenis Base Tunnel will link up Saint-Jean-de-Maurienne in France to Bussoleno in Italy, with some 45 km being excavated on the French side producing almost 27 million tons of material.The exploratory works already carried out have shown the presence of sulphates within the excavated material, which could not allow the production of concrete aggregates according to the dedicated standards. TELT has launched tests as part of a research and development programme focused on developing concretes produced with sulphated aggregates by using specific cements. The results are very encouraging. However, taking into account the boring progress and the small available space at the Villarodin-Bourget/Modane jobsite, the implementation of the chemical analysis of the excavated material is being critical, and especially for the SO_3 content, with the convenient accuracy and within a very short notice. The only reliable way to do this is to set up a chemical characterisation unit on site directly on the conveyor belt, for example a Prompt Gamma Neutron Activation Analysis (PGNAA)-type unit. Tests have been implemented on behalf of the French atomic energy commission (CEA) in order to certify the use of this kind of equipment. This paper is presenting all the information regarding the Villarodin-Bourget/Modane jobsite, the quality and the quantity of the dedicated excavated material, the need of aggregates and the details of all the tests carried out.

1 INTRODUCTION

The Montcenis Base Tunnel is the main part of the international section of the new Lyon-Turin rail link. This 57.5 km long twin-tube will link up Saint-Jean-de-Maurienne in France to Bussoleno in Italy, some 45 km being excavated on the French side from six main tunnelling faces. The French side will produce some 27 million tons of material, able to produce 7.7 million tons of aggregates for the concrete tunnel lining and ancillary works. Tunnelling from the Villarodin-Bourget/Modane adit will produce over 12.7 million tons of material.

The latest 2017 estimation is showing the aggregate needs for the whole cross-border section of about 11.4 million tons, including 8.6 million tons for the French side alone. It means that TELT would have to face a potential shortage on the French side as the production of aggregates is not enough to cover the needs. Explorations and other works already carried out have shown the presence of sulphates impacting 1.7 million tons of materials, with a knock-on effect equivalent to approximately 1 million tons of aggregates, i.e. almost 24 per cent of the material required to produce concrete for this sector. When boring the Villarodin-Bourget/Modane access tunnel, some of the excavated material could not be used as concrete aggregates, as planned, because their sulphate content was higher than the standard requirements. The NF EN12-620 and NF EN 206 standards limit sulphate content in aggregates to 0.2% in order to protect the concrete from deterioration caused by sulphated reactions.

In order to comply with the EU environmental rules by maximizing the use of excavated material, TELT undertook a research and development programme in 2009 to check the sulphate content of this material and to find out a way of use. The first laboratory results and on-site studies are presented here. Furthermore, taking into account the forecasted excavation progress and the small available space at the Villarodin-Bourget/Modane site, the implementation of the chemical composition analysis of the excavated material is being critical, and especially their SO_3 content, with the convenient accuracy and within a very short notice. One reliable on-site chemical characterisation process today identified is the one provided by the Prompt Gamma Neutron Activation Analyser (PGNAA). TELT therefore asked the

CEA to carry out an expert appraisal of the equipment used and of the material submitted to radiation, in order to demonstrate that no residual radioactivity is remaining within the tested material. The details and results of the protocol, and the tests performed are presented here.

2 CONTEXT

In the Villarodin-Bourget/Modane sector, the material to be extracted over a length of approximately 10 km could have a significant sulphate content, in the form of gypsum and/or anhydrite in blocks or inclusions in the rock mass. Regarding the standards requirements, this material cannot be used as aggregates for civil engineering concrete applications, as their SO_3 content is ≥ 0.2%.

A research and development programme was initiated in 2009 by LTF and was carried on by TELT with the partnership of IFSTTAR (leadership), VICAT, HOLCIM and LERM. An initial laboratory study was concluded by the Jeremy Colas' thesis in 2012. It delivered some very promising results for the use of this excavation material in the future Base Tunnel, providing the use of special cements (Monin et al., 2013).

The tests were performed with aggregates produced by the experimental processing plant that had been set up to make the concrete of the access gallery. The SO_3 content divided by grain-size band of this material is given on table 1.

Table 1. Sulphate content by grain-size band

Grain-size band (mm)	0/0.315	0.315/1	1/4	4/8	8/16
Sulphate content (as a SO_3%)	7.2%	2.8%	1.6%	1.4%	1.2%

The results showed that calcium sulphates are encountered in the form of gypsum (40%) and anhydrite (60%) and are most accessible in grains smaller than 1 mm. Indeed, they are mostly found in the form of independent grains. In the case of grains larger than 1 mm, they are located at the periphery, or in inclusions into the aggregates that limit accessibility. Given these findings, two solutions stand out and could be considered to use this excavation material:

1/Extended washing time. Washing the excavated sand with water at 20°C would enable sulphate content to be reduced from approximately 3.5% down to 2.5%.

2/ Fine particle fraction of the sand removing. Indeed, the 0/315 µm band has a sulphate content up to 6 times greater than other grain-size bands. By eliminating the grains smaller than 315 µm, sulphate content into the excavated sand can be lowered down to 1.9%.

In both cases, this content is still over the standard, which limits the sulphate content to 0.2% in concrete aggregates

The IFSTTAR studies also showed that the different cement types analysed did not have the same behaviour in terms of sulphate reaction with the formation of ettringite or thaumasite. This leads to another possible use for this excavation material, i.e. using a special cement settled for aggregates having a high sulphate content. The current findings are showing that two cements could be suitable: Super Sulphated Cement (SSC) and Portland Cement with a very low C3A content, referred as CEM I 52.5 N PM SR 0.

A more in-depth study on an industrial scale should help to clarify the following issues :

- identification of the mechanisms responsible of the good behaviour of the SSC and CEM-I 52.5 N PM SR0 cements and the effects of using a correcting sand;
- long-term behaviour of sulphate in excess into the concrete;
- feasibility of using such concretes on an industrial scale;
- durability of these concretes.

3 INDUSTRIAL TEST PROGRAMME

The research partnership between TELT, IFSTTAR, VICAT and LAFARGE/HOLCIM was going on with the development of concrete blocks for on-site tests. The goal of this in-depth study is to check the durability of concretes in existing tunnel curing conditions and especially how they react to the internal sulphate attack when using super sulphated cement (CSS) and Ultimat cement (CEM-I 52.5 N PM SR0), which showed very good behaviour in the previous phase of the study (Colas, 2012).

Industrial-scale testing was performed in order to confirm the initial very encouraging results. These tests consisted of producing 11 demonstrators using 11 different concrete mixes.

3.1 *Concrete mix design*

It is the same as the one used during the first test phase and it is close to the mix design made with aggregates processed from the excavation material from the Villarodin-Bourget/Modane access tunnel, which is for 1 m^3 of concrete:

- Cement: 400 kg (reference 300kg of CEM I + 100 kg of fly ash)
- Sand 0/4 mm: 770 kg
- Grit 4/8 mm: 280 kg
- Gravel 8/16 mm: 700 kg
- Crushed gypsum: depending on the SO_3 content of the aggregates

3.1.1 *TELT aggregates*

Aggregates produced with the material excavated from the Villarodin-Bourget/Modane access tunnel were used and are referred as "TELT aggregates" in the remainder of this article. Each grain-size band was first homogenised and sampled (NF EN 932-1 standard) for chemical analysis and to check its SO_3 content (table 2).

Table 2. SO_3 content of grain-size brackets

	sand 0/4	aggregate 4/8	aggregate 8/16
SO_3 by gravimetry	2.03	0.89	0.91
Uncertainties	0.43	0.20	10.20

3.1.2 External aggregates

Some mix designs were developed by replacing the finest grains of the TELT 0/4mm sand, with a silico-limestone sand from external origin that is referred in the remainder of this article as "Barraux sand".

3.1.3 *Gypsum*

The TELT aggregates have been stored outside since 2008 and have therefore been exposed to the effects of the environmental agents. Consequently, the leaching of the aggregates has modified their sulphate content. In order to make concrete mixes with aggregates having sulphate content of up to 4%, crushed gypsum was added to some mix designs. Mixes with 2% of SO_3 are only produced with TELT aggregates without gypsum addition.

3.2 *List of the 11 concrete compositions*

No. 1) Control concrete made from external aggregates and CEM I PM ES cement + 25% fly ash

No. 2) Concrete Mix with external aggregates + Ultimat cement

No. 3) Concrete Mix with TELT aggregates as they are (2% SO_3) + Ultimat cement

No. 4) Concrete Mix with TELT aggregates as they are + SO_3 (4%) + Ultimat cement

No. 5) Concrete Mix with TELT aggregates with the 0/4mm bracket being replaced by Barraux sand + Ultimat cement

No. 6) Concrete Mix with external aggregates + SSC cement

No. 7) Concrete Mix with TELT aggregates as they are (2% SO_3) + SSC cement

No. 8) Concrete Mix with TELT aggregates as they are + SO_3 (4%) + SSC cement

No. 9) Concrete Mix with TELT aggregates with the 0/4mm bracket being replaced by Barraux sand + SSC cement

No. 10) Concrete Mix with TELT aggregates as they are (2% SO_3) + 320 kg/m3 of Ultimat cement + 80 kg/m3 of fly ash

No. 11) Concrete Mix with TELT aggregates as they are + SO_3 (4%) + 320 kg/m3 of Ultimat cement + 80 kg/m3 of fly ash

The concrete slump consistence class is S5 (NF EN 206): virtually self-compacting concrete with good flow characteristics and requiring very little vibration when used. The concrete strength development class is C30/37.

An initial laboratory optimisation study and was carried out by VICAT and LAFARGE/HOLCIM especially to fix the quality and the quantity of admixtures.

The concretes were produced by the Saint-Michel-de-Maurienne "Bétons VICAT" unit and cast in the Villarodin-Bourget/Modane access tunnel. Test Concrete samples for durability trials were cast at the same time as the test blocks, then stored on site with the same curing conditions as the test blocks, with a watering system in place until completion of the test period (i.e., for 3 months). They were then transported to IFSTTAR Laboratory to run the tests (Fig. 1).

Figure 1. The samples in the access tunnel

3.3 *Reference grain size distribution curve for the concrete*

Figure 2 shows the reference grain size distribution curve of the concrete.

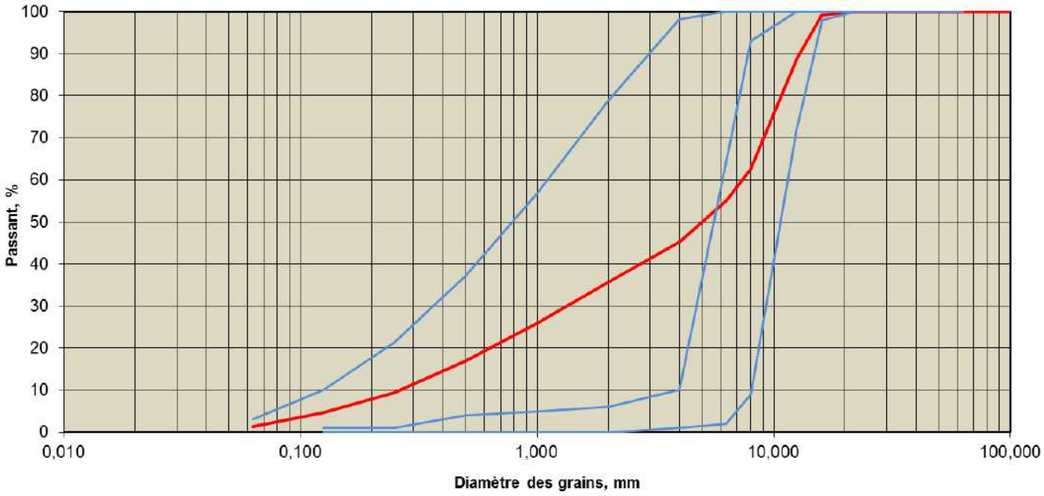


Figure 2. Reference grain size distribution curve for the TELT 0/16 mm concrete without binder and without gypsum addition

3.4 *The test blocks*

3.4.1 *Description*

Eleven L-shaped test blocks with the following dimensions were on-site cast :

- Slab: length = 3.3 m, width = 2.5 m, variable thickness; slab reinforced with a welded mesh 11 x 10 m^2, ø = 8 mm
- Sidewall: length = 3.3m, height = 2m, thickness = 0.40m; precast non-reinforced sidewall.

370 samples were produced under the guidance of a representative from the IFSTTAR research laboratory.

3.4.2 *Pouring and placing method*

The following tests to control the fresh concrete were carried out before leaving the production unit and again on the site: Flow-Test, air temperature, concrete temperature, air content. These data enabled to characterise the rheology of the concrete and to determine how it varies during transport.

The concrete was then cast. The slab was cast first and a welded mesh was put in place halfway through the casting process (Fig. 3).

Figure 3. End of casting of the slab after placing the welded mesh

Once the casting of the slab was completed, a formwork panel was placed over the slab to cast the sidewall. The sidewall was cast by discharging the concrete between the formwork panel and the wall of the tunnel. The strength developed during the casting of the sidewall led to the blocks being adapted. Only the control block (F1) was cast in place. The sidewall elements were finally cast on an horizontal formwork, then placed upright and sealed to the side wall of the access tunnel (Figs 4, 5).

Figure 4. Slabs in place after formwork removal and sidewall with rods used to seal the block in the siding of the access tunnel

Figure 5. Test blocks in place with the sealed tacheometric monitoring marks

4 LABORATORY TESTS

Laboratory tests enable to assess the risk of internal swelling reactions for the different concrete type vs reactions resulting in the formation of ettringite and thaumasite. The first results are given on figures 6 and 7 below.

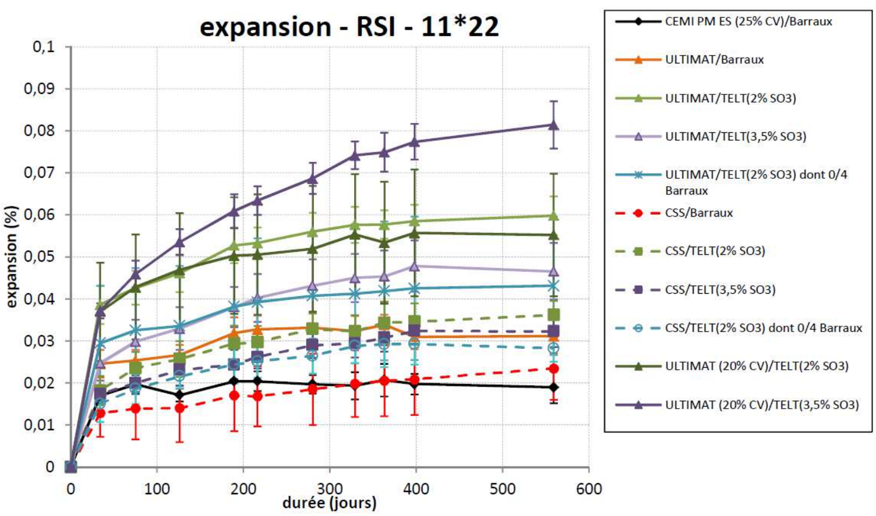


Figure 6. ISA (Internal Sulphate Attack) expansion test results

After monitoring during 550 days, 6 concretes (including the reference) presented swelling less than or equal to 0.04%. No damage was found, in light of the slow kinetics of the reactions and the small swelling value.

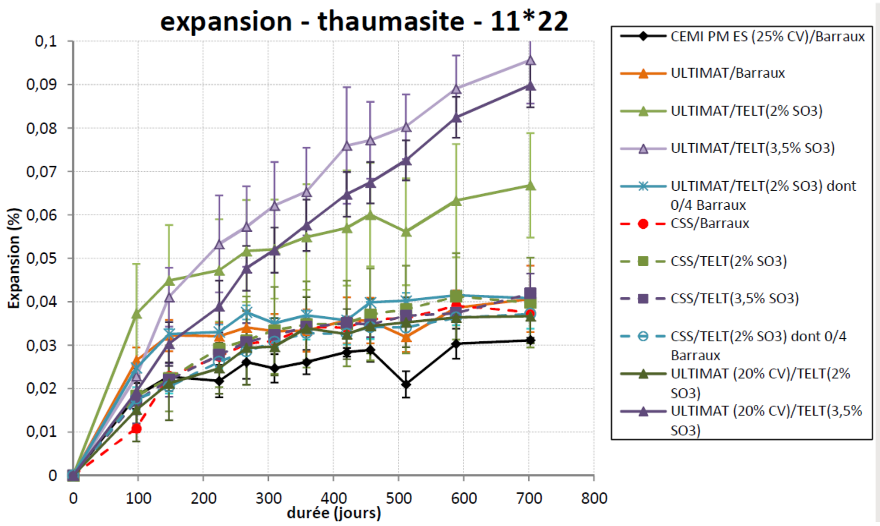


Figure 7. Thaumasite expansion test results

After 700 days monitoring, expansion measurements showed that 3 concretes were quite reactive (>0.05%). No damage was found, in light of the slow kinetics of the reactions and the small swelling value.

5 ON-SITE DEFORMATIONS MONITORING

5.1 *Equipment*

Each block was fitted out with 10 sealed bases, which will allow periodic monitoring readings to highlight and measure deformations and abnormal movements due to internal strains (Fig. 8).

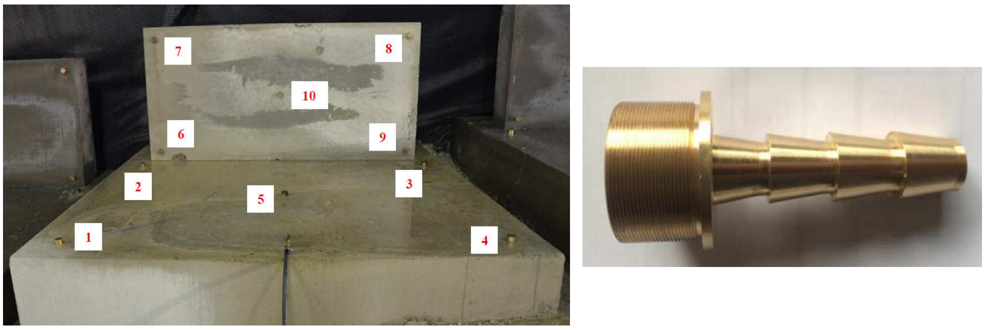


Figure 8. Names of the points by block and brass mark

The brass marks were sealed into the blocks one month after the blocks casting and the first measurement was made 15 days later. Taking into account the accuracy required (uncertainty less than 0.07mm), the measurements were carried out using a Laser Tracker of the Leica AT402 type.

5.2 *Operating mode*

Two sets of independent measurements were performed and combined in order to ensure consistency and thus determine the final coordinates of the points observed. The results are presented in a three-dimensional reference specific framework to each block, free of tunnel movements and by separating the sidewall block from the slab.

5.3 *Results*

The deformations observed are weak on most of the blocks (Fig. 9)

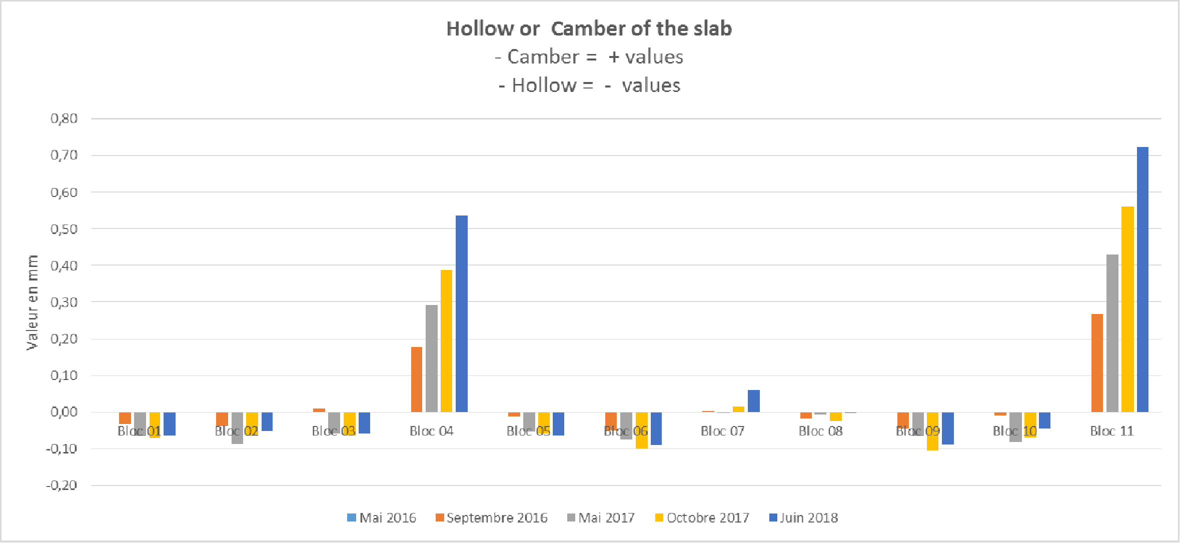


Figure 9. Monitoring of the deformations observed on the horizontal blocks

Only blocks 4 and 11 are presenting more deformations, showing a swelling phenomenon of the vertical and horizontal blocks.

6 RADIATION PROTECTION EXPERT APPRAISAL

The main problem will then come from the need to perform quickly chemical characterisation of the excavated material as it comes out of the tunnel. To do this, our research focused on continuous chemical analysis processes, used commonly and successfully by the time being in cement plants when preparing the raw mix, as well as in the mining industry.

6.1 *Description of the equipment*

The basic principle is to submit the material to neutron radiation and analyse the gamma radiation recovered above the bed of material to produce an elementary chemical analysis. This device is called a Prompt Gamma Neutron Activation Analyser (PGNAA) and is fixed on the conveyor belt.

It operates with a ^{252}Cf radioactive source that requires special authorisation from DGPR (French Risks Prevention General Directorate) and ASN (French Nuclear Safety Authority). In order to speed up the preparation of this authorisation, TELT asked the CEA in Paris-Saclay to perform a radiation protection expert appraisal, the goal was to prove that no residual radioactivity is remaining within the material analysed. It also aimed to demonstrate that this type of device fully meets TELT's needs in term of chemical characterisation and accuracy of the percentages measured.

6.2 *Test protocol according to the CEA's requirements*

In order to get the necessary administrative authorisations, the CEA was asked to check that the material did not have any residual radioactivity after going through the neutron analyser. TELT therefore got in touch with the CEA who accepted to provide TELT with this expert appraisal request. LAFARGE, who is already a partner in the research program on sulphated materials presented above, gave the chance to TELT to carry out this expert appraisal by using the operating equipment of their Saint-Pierre-La-Cour plant.

TELT brought 60t of material from SMP4 (silico-limestone 0/40mm SMP4) and 60t of material stored in Villarodin-Bourget/Modane (0/4mm VBM sand) from the tunnelling works at this same access tunnel. These two families of material had chemical characterisation performed in the laboratory on the main component elements before delivery to Saint-Pierre-La-Cour, the site on which the tests would be carried out. Sulphate contents measured were: 2% in the VBM sand and 2.30% in the 0/40 SMP4.

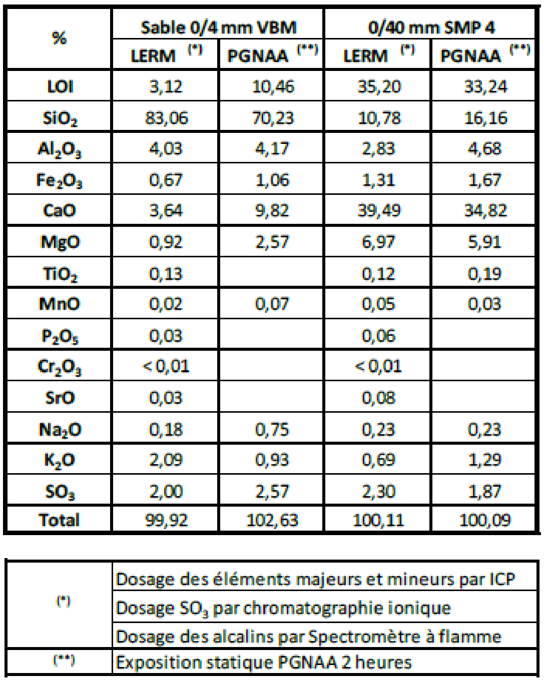
The radiation protection expert appraisal of the material passed through the neutron analyser was carried out in the normal way, with a belt speed of 2.3 m/s and a flow rate of approximately 1000 t/h, and with an accident simulation that shut down the conveyor belt and left the material exposed during 2h to radiation emitted by the neutron analyser. Each family of material was analysed individually.

The samples to determine the radioactivity level of the material before and after passing through the neutron analyser in these two exposure conditions were performed on-site and in the CEA's laboratory in Paris-Saclay (Fig.10).

Figure 10. Measuring equipment in the on-site laboratory measuring the radioactivity of the sample (0/40 SMP4)

6.3 *Results*

The results of the analyses carried out by the analyser and those carried out for comparison in the laboratory are shown on the following figure :



%	Sable 0/4 mm VBM		0/40 mm SMP 4	
	LERM (*)	PGNAA (**)	LERM (*)	PGNAA (**)
LOI	3,12	10,46	35,20	33,24
SiO_2	83,06	70,23	10,78	16,16
Al_2O_3	4,03	4,17	2,83	4,68
Fe_2O_3	0,67	1,06	1,31	1,67
CaO	3,64	9,82	39,49	34,82
MgO	0,92	2,57	6,97	5,91
TiO_2	0,13		0,12	0,19
MnO	0,02	0,07	0,05	0,03
P_2O_5	0,03		0,06	
Cr_2O_3	< 0,01		< 0,01	
SrO	0,03		0,08	
Na_2O	0,18	0,75	0,23	0,23
K_2O	2,09	0,93	0,69	1,29
SO_3	2,00	2,57	2,30	1,87
Total	99,92	102,63	100,11	100,09

(*)	Dosage des éléments majeurs et mineurs par ICP
	Dosage SO_3 par chromatographie ionique
	Dosage des alcalins par Spectromètre à flamme
(**)	Exposition statique PGNAA 2 heures

Figure 11. The results of the PGNAA chemical analysis vs laboratory results

The PGNAA SO_3 measurement results are showing a quite good accuracy. Some other elements show some discrepancy; this is probably due to the fact that the analyser used for these tests could not be calibrated before the test (too the short time available, there was no question to stop the cement production), TELT material is quite different from cement raw-mix (The analyser calibration must be achieved with the dedicated "reference" elements to get the convenient accuracy).

Furthermore, the readings also show that the neutron activation of the material required for chemical characterisation created almost zero residual radioactivity, in the form of radionuclides having a very short radioactive period of around a few hours. This radioactivity will therefore disappear by the time the material is used. The use of a neutron analyser does not therefore lead to the presence of residual radioactivity that can be differentiated from the natural radioactivity in the tunnel construction material.

6.4 *Perspectives in the framework of Future Operational Work Site CO 5a*

The contract N° CO 5a for Villarodin/-Bourget/Modane will be very shortly awarded by TELT. It will be dedicated to the preparatory works, to the construction of ventilation shafts and a range of different underground galleries, and the TBM assembly caverns. These works will be performed from the Villarodin-Bourget/Modane access tunnel and they will provide a possible testing site for managing, classifying, storing and processing the excavation material. On-site chemical analysis such above described will be used to check on site the reliability of the analysis method on an industrial scale and to develop the corresponding working procedures.

7 CONCLUSION

TELT, Alpetunnel and LTF, who were involved upstream in preparing the project, are committed and determined to apply a policy of using excavated materials for the construction of the Montcenis base tunnel. The above discribed work is giving a clear proof of its feasibility.

This policy has taken them on a path to innovation, innovation in a unique research programme conducted under the umbrella of qualified state agencies and innovation in using equipment never used before on such construction sites. The quality of the work carried out will hopefully become a reference in this field and will provide major results to prepare the improvement of the national standards. This step is on the way with the AFNOR Commission P 18 B in order to agree upon a Performance Test which will be able to check the durability of a concrete made with aggregates having SO_3 content over the requirements. If this NF standard improvement proceed correctly, the Villarodin-Bourget/Modane site would then be able to work in total self-efficiency to produce the concrete for the tunnel.

8 ACKNOWLEDGEMENTS

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