NR2C - New Road Construction Concepts

Work Package 2 – Interurban infrastructures

Deliverable 2.2

Concept and design of selected innovations for interurban infrastructure

Innovation 2.1B – Technical Report

Crack free semi rigid pavement incorporating two industrial by-products

Modifications follow-up

Ref draft	**date**	**date** of submitting to approval or date of approval	**Comments and/or brief description of the modifications** Ex : "*sending for approval to…","approved by …"* or "Comments from … dated …taken in account"
first			First draft
V2		1/05/07	Minor corrections
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A - Definition of the study

A.1 General scope of the innovation

In semi-rigid pavement structures, the well graded treated aggregate used as a base course always present transversal cracks because:

- it is submitted to different shrinkages: desiccation in the first months and thermal shrinkage during its all life;
- its shrinkage is restrained by the sub-base
- it's a rigid material, with an elastic modulus generally higher than 20 GPa.

Due to the traffic and the weathering, the longitudinal cracks inevitably reflect themselves in the wearing course. When the cracks are wide-opened, the interlocking of the pavement blocks on the both sides of the cracks is limited and then the structural efficiency of the pavement is lessened. Moreover, these cracks damage the aesthetic, the evenness and the comfort of the wearing course. They finally facilitate the penetration of water, which accelerates the ageing of the structure.

That is why regular maintenance (cracks silting up) is generally needed, approximately each 3 years. Yet, although it is efficient on the structural point of view, it does not solve the aesthetic and evenness matters. Moreover, maintenance works disturb the road users and represent an important cost.

So cracking appears less and less acceptable by the construction financing authorities and different strategies were developed to avoid its appearance:

- pre-cracking system in the construction phase. Thanks these techniques, it is possible to control the position of the cracks, then to limit the space between two cracks (around 2 meters) and consequently the thickness of the cracks;
- interface anti-cracking systems which try to block the cracks under the wearing course;

Unfortunately, the efficiency at long term of these techniques is not completely demonstrated and generate extra-cost at construction.

In conclusion, well graded aggregate is a durable material but its cracking tendency limits the life duration of semi-rigid pavement structure. So it would be interesting to develop crack free well-graded treated aggregate to obtain long life semi rigid pavement with low maintenance cost. The scope of this innovation is to evaluate the feasibility of such a material thanks the use of two by-products.

The idea is the following:

- some by-products (municipal solid waste incinerator (MSWI) bottom ash, steel slag…) display spontaneous swelling behaviour and release lime;
- pozzolans like fly ashes react with lime to give hydrates (CSH) and mechanical properties;
- optimized mixtures of such swelling by-products with inert materials and pozzolans could present structural properties in combination with a controlled swelling, which could overcome the thermal shrinkage.

If such mixtures could be realized, they would allow:

- construction cost savings (as a part of the components are by-products);
- maintenance cost savings (no cracks means thinner structure and no joint maintenance);
- high quality materials savings (by the use of by-products).

These goals are in perfect accordance with the main objectives of the Innovation task which are low cost pavement construction and maintenance techniques.

A.2 Bibliographical search

The use of expansive agents is today a confirmed practice in order to improve concrete performance and limit the cracking related to drying shrinkage. Expansive agents are special products increasing the volume of concrete due to specific chemical reactions. The most widely used are based on the formation of ettringite and calcium hydroxide. Besides, the combined use of CaO-based expansive agent and shrinkage reducing admixture (SRA- propyleneglycol ether base) seems to improve the dimensional stability of concrete (Collepardi and al., 2005; Maltese et al., 2005). These kind of products could be a first solution to avoid cracking in road pavement but more research is still needed.

Another solution is to use by-product with swelling behaviour such as steel slags.

In Europe and most other continents there is a great demand for aggregates mainly from civil engineering industry, especially in the field of road and concrete constructions as well as for hydraulic purposes. The use of iron and steelmaking slags represents a real opportunity to contribute to save natural resources.

During the production of iron and steel, the iron oxides and some of the metal oxides are reduced forming the metal melt. The remaining oxides will be bound into an oxide melt: the slag. The production of iron and steel is normally carried out as a series of discrete operations with essentially: the reduction in the blast furnace, the steel process using the Basic Oxygen Furnace (BOF) and Electric Arc Furnace (EAF) process following by the finishing of liquid steel in the secondary metallurgical treatment.

The pig iron production in the blast furnace leads to the blast furnace slag, which properties can be influenced by the cooling conditions: air cooling generates the crystalline air cooled blast furnace slag (ABFS) and rapid cooling with water or even with air generates the glassy granulated blast furnace slag (GBS). Both produce about 250-300 kg per ton of pig iron made (the European pig iron production are more than 60 million tons in 2005), they are fully used respectively as aggregate in road construction or concrete, and as cement compound or as addition to concrete.

Steel slag is produced from the further refining of iron in a Basic Oxygen Furnace (BOF Slag) or from melting recycled scrap in an Electric Arc Furnace (EAF slag). Both produce about 100 kg per ton of steel made and in Europe every year nearly 12 million tons of steel slags are produced. Owing to the intensive research work during the last 30 years, about 65% of the produced steel slags are used on qualified fields of application, today. But the remaining 35% of these slags are still dumped. In France, the dumping rate of steel slags is close to 25 %, for an annual production close to 1.7 million tons (in 2005).

Owing to their physical, chemical and mineralogical properties, the steelmaking slags are suitable for various kinds of applications in industrial areas. EAF slag is basically used in road construction (as layer with or without binder) and earthworks (road cover, road base, way's consolidation) and their high resistance to wear successfully promoted their use as mineral aggregates for wearing course in road surfaces. BOF slag has been previously used in the blast furnace to recover the iron in the slag and as lime carrier. Due to the extent requirements on the phosphorous content of steel, BOF slag recycling became more and more restricted and new applications had to be found. BOF slags are used in road construction, as aggregate for concrete or for hydraulic engineering, as fertilizer in agriculture, as pollutant removing filter or soil stabilization.

The BOF- and EAF-slags from different sources within Europe, are generally comparable and independent of their producers. Differences arise from the use of dolomite rather than lime as fluxes with the effect of a higher MgO-content in the slag. BOF- and EAF-slags are calciumsilicatic with a range of CaO between 42 and 55%, and a range of SiO2 between 12 and 18%. EAF-slags comprise CaO between 25 and 40% and 12 to 17% SiO2. Their MgO-content may be higher due to the reactions with the refractory lining. The main mineral phases of BOF- and EAF-slags are dicalciumsilicate, dicalciumferrite and wustite. The content of free lime and free MgO is the most important component for the utilisation of steel slags for civil engineering purposes, with regard to their volume stability. In contact with water, these mineral phases will react to hydroxides. Depending on the rate of free lime and/or free MgO hydration, it causes a volume increase of the slag mostly combined with a disintegration of the slag pieces and a loss of strength. So, the volume stability is a key criterion for using steel slags as a construction material.

Then, for many steelworks, a significant proportion of this slag will be landfilled, and of the materials dumped, it will often form the largest proportion. With increasing pressure in many countries for greater use of secondary aggregates to preserve the natural resources, steels slags offer a promising and relative abundant alternative. During the last twenty years, the problem of volume stability was the main objective of the research work on steel slag in Europe. Today, this problem can be avoided with a suitable weathering of the slag in order to favour the free lime hydration. Such slag can then be safely treated with bituminous binder for road wearing course notably. Moreover, steelmaking slags can be used at all levels (unbound in the lower layers, bituminous-bound in the upper courses, and as a surface dressing) (Piret et al., 1982). Yet the slag maturation still remains problematic because of the associated handling or the pressure imposed by the environmental policies. This is why, it is today necessary to promote a new approach for the valorisation of steel slag in civil engineering, considering slags of lower quality and trying to convert slag disadvantages into positive aspects.

The combination of BOF slag (with or without weathering) with other materials is another way to limit the volume instability. Numerous studies dealing with the composition of mixes of BOF slag aggregates with other materials, such as granulated blastfurnace slag, municipal solid waste incinerator bottom ash, fly ash, used for road construction can be found in the literature. For example, by mixing 70-85 % of weathered BOF slag with 15-30 % of granulated blastfurnace slag, a road base was produced without significant expansion damage. Moreover, a slowly setting composition is obtained which provides, at low cost, a quality road base which can be considered as semi-rigid in comparison with concrete bases (Piret et al., 1982). Best (1987) developed a well graded composite similar to the French 'graves-laitier', but containing both air-cooled blast furnace slag (5-20 mm, 57 vol.%), LD slag (0-5 mm, 28 vol.%) and quenched blast furnace slag (15 vol.%). The cementitious action of the quenched blast furnace slag, activated by the free lime embedded in the BOF slag binds the mix. Such a pozzolanic reaction consumes the free lime non-expansively, lowering the tendency of the aggregate for expansion. This new material referred to as "self-binding slag composites" presents the advantage to minimise the need of chemical activators owing to the free lime present in the slag. Juckes (1991) confirmed that the dilution of the BOF slag and the associated cementitious reaction lead to a limited expansion of such mixes, arguing in favour of an absorption of the expansion attributed to the BOF slag aggregate by the semi-rigid environment. This was recently shown again in a recent study made by Tikkakoski et al., (2005).

In these previous studies, the mix optimization was carried out in the laboratory by seeking the best geotechnical performances. It was assessed by classical techniques used in road engineering such as measurement of compressive strength, Proctor optimum, CBR, freeze-and-thaw and rutting resistance or volumetric stability. However, from a practical point of view, the use of BOF slag aggregates in road construction remains unusual because of the uncertainties about volume stability. In fact, this volume stability depends on numerous factors such as proportions of the different components, free lime content of BOF slag, residual potential volume increase after weathering. So, whereas such a technique of combination with other granular materials offers a promising way of valorisation for BOF slags in road, it requires more technical specifications and needs development of tools to be able to predict and ensure the volume stability of the obtained mixes.

In that context, Deneele et al. (2005) have proposed a new method to predict the swelling of any combination of swelling aggregate and inert aggregate fractions. This method is based upon the Compressible Packing Model developed at LCPC which was implemented in the software René-LCPC (Sedran and de Larrard 1995, Sedran and de Larrard 1996, Sedran 1999, de Larrard 1999). This software was first developed for the optimization of concrete, but the framework of the model is much more general and can be used for other types of granular packing or granular suspensions. The software needs three types of data for each granular component: the dimensions of the particles (as given by the grading curve), the specific gravity and the packing density. It then predicts, for any combination of the fractions, either the compaction index from the packing density, or the packing density from the compaction index. This latter parameter is a characteristic of the placing method tabulated thanks calibrations (for example, 9 for packing under vibration and 20 kPa pressure). The

software was widely validated in the field of the packing density of dry granular mixtures and gives an error lower than 1% in absolute value, in comparison with the experiments.
The authors have verified that the weathering of compacted BOF slag samples in an accelerated test with a steam apparatus (see below) induces swelling and grading changes of the material. The grading change can be directly evaluated by sieving, and swelling can be interpreted as a difference in packing density of the mix before and after weathering. In fact, swelling S% can be expressed as following:

$$S = 100\frac{V_f - V_i}{V_i} = 100\left(\frac{C_i \rho_i}{C_f \rho_f} - 1\right)$$

Where:
- V_i and V_f are respectively the volume of the sample before and after weathering
- C_i and C_f are respectively the packing density of the sample before and after weathering
- ρ_i and ρ_f are respectively the specific gravity of the BOF before and after weathering

Deneele et al. (2005) have then introduced the properties of the different classes of grains of BOF slag into Rene-LCPC for two cases: before and after weathering. From these data, they were able to calculate the packing density before and after weathering of several mixes made of BOF slag and Air-cooled Blastfurnace slag on one hand and BOF slag aggregates and limestone on the other hand. They were then able to calculate a theoretical swelling according to the previous equation. These results confirmed to be in good agreement with the experimental data for mixes containing less than 50% of BOF slag. For higher content of BOF slag, the theoretical swelling was overestimated. According to the authors, this is due to the fact that for high volume of BOF slag, the mixes were less porous so that, during the accelerated swelling test, the steam could not penetrate into the packing and then the experimental swelling was lower than could be expected.

Using the approach proposed in that study, it is then possible to optimize the mix composition of BOF slag with inert aggregate, in order to have an acceptable and limited swelling.

Finally, combining a BOF slag with a fly ash and an inert aggregate could be a good way to obtain a well-graded aggregate with noticeable mechanical properties and a controlled swelling. In fact the fly ash may react as a pozzolan with the lime released from the BOF-slag and the swelling could be controlled by the introduction of an inert aggregate thanks the use of Rene-LCPC.

A.3 Research plan

The research was divided in four tasks as explained below.

A.3.1 Task 1: Bibliographical search

The objective of this task was to identify a by-product (MSWI bottom ash, steel slag…) which displays spontaneous swelling behaviour and releases lime and a pozzolan to obtain a well graded treated aggregate with both good mechanical properties and a controlled swelling behaviour.
As explained in chapter A2, the bibliographical search lead us to select a BOF slag and fly-ash.

A.3.2 Task 2: Accelerated feasability tests

The objective of this task is to rapidly identify promising well graded aggregate mixtures producing at the same time some swelling to counteract the effect of the different shrinkages, and noticeable mechanical performances. Both are needed to produce a road layer with bearing capacity and no cracks. In a first approximation we will aim at a splitting tensile strength between 0,5 to 1 MPa which corresponds to GC1 or GC2 class of cement treated well graded aggregate in EN 14227. A rough calculation of swelling to be aimed at, can be made with the following assumptions:
- the well-graded aggregate have a long term splitting strength of 1 MPa and an elastic modulus of 20 000 MPa;

- the well-graded aggregate has a thermal expansion coefficient around 10^{-6}/°C, and the layer may be submitted to a maximum temperature variation in a range of 30°C (between night and day and summer and winter). This lead to a maximum 300 10^{-6} shrinkage between hot period and cold one;
- autogeneous shrinkage of the well graded aggregate is negligible and its drying shrinkage is around 300 10^{-6}.

The well graded aggregate is then submitted to a maximum 600 10^{-6} strain, yet the acceptable strain at long term before cracking is 1/20000=50 10^{-6}. So the swelling should be at least 250 10^{-6}. In fact this value is probably strongly underestimated because swelling may occur at young age while the well graded aggregate has a low value of elastic modulus. In that case strains generate few compressive strength to counteract the effect of thermal shrinkage which occurs during the all life of the road when the elastic modulus is higher. Moreover part of the benefit of the swelling may be lost with time due to relaxation in the material.

In that task, different mixtures of well graded aggregate will be designed with the by-product, the pozzolan and an inert aggregate. On that mixes the following test will be made:
- the determination of the water content and the density at the optimum proctor as classically done for such road material;
- samples will be produced and submitted to a 90°C curing for some days in order to accelerate the swelling reaction.
- free shrinkage/swelling as well as elastic modulus and splitting tensile strength will be measured at the end of the curing period;

At the end of this task, the mixtures with good swelling behaviour in unrestrained conditions and good mechanical properties will be selected for the further step.

A.3.3 Task 3: Validation of the concept at 20°C

In case of success in task 2, the selected mixtures will be tested in the same way but at 20°C and at longer term. In fact, 20°C is more representative of the temperature during the road life, moreover the temperature has a great influence on the chemical reactions involved: expansion of free lime, pozzolanic reaction between lime and fly ash. So the evolution of swelling compared to that of the elastic modulus and tensile strength may change in great proportions compared to tests at 90°C.

The knowledge of the elastic modulus and the shrinkage/swelling in unrestrained conditions is in fact not sufficient to evaluate the cracking risk in restrained conditions for different reasons: we have to account on the relaxation occurring in the mix, there may be interaction between swelling and compression… That is why a direct shrinkage test in restrained conditions should be realized with the best mixes.

Based on these results a preliminary pavement design could be realized.

A.3.4 Task 4: Material physico-chemical characterization

This task will be dedicated to the characterization of the different components and the analysis of the different mixes to describe the hydration reaction.

A.3.5 Expected results

At the end of the research the following products could be expected:
- validation of the feasibility of a well-graded aggregate made of steel slag and fly ash showing a swelling behaviour and mechanical properties of cement-treated well-grade aggregate;
- validation of the absence of cracking with such material;
- a typical mix-design;
- material data that can be used in a road structural calculation;
- preliminary pavement design using the innovative material

B - Results

B.1 Selection and characterization of the constituents

Materials selected for this study were:
- a 0-10 mm fresh Basic Oxygen Furnace slag (the same as presented in Deneele et al. (2005)) representative of French production
- a 0/6 mm and a 10/20mm "Le Boulonnais" limestone
- coal fly ashes from Surchiste company
- a quicklime (activator)

The technical sheets describing these components are given in Annex E1

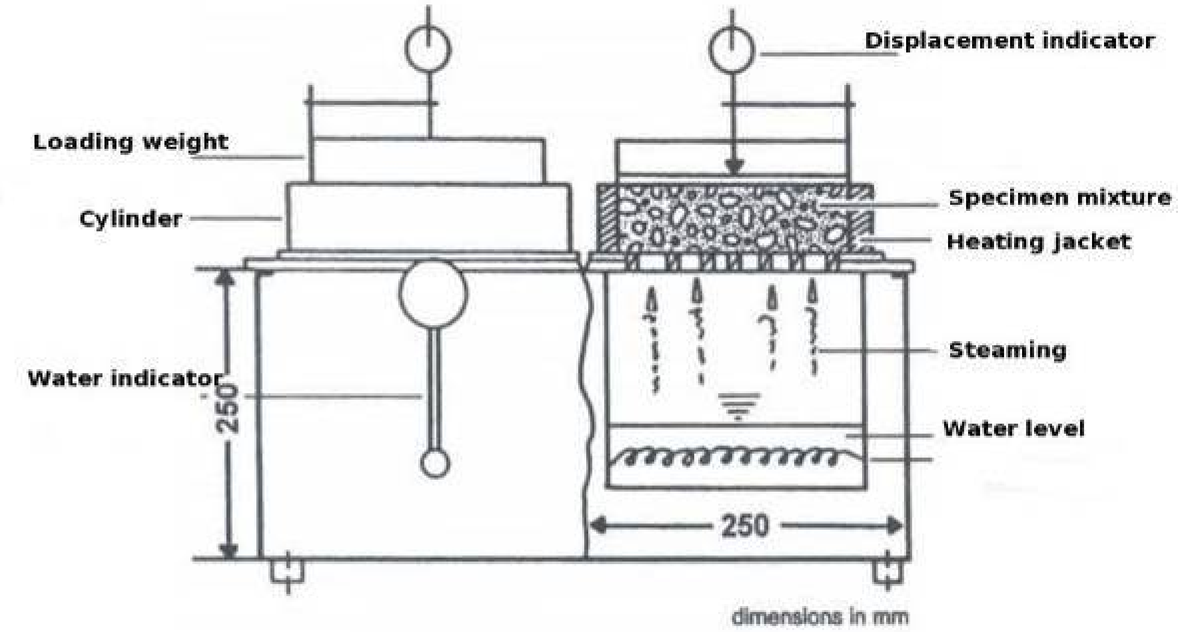
As explained in paragraph A-2, the theoretical estimation of the mixes swelling is based on the difference in packing density between a fresh mix and the same mix after weathering, calculated with René–LCPC software. The calculation of these packing densities requires the preliminary following data for the different components:
- the grading curve;
- the specific gravity;
- the packing density.

For the BOF slag, these properties were determined before and after weathering. As the other components were assumed to be inert, their characterization was made only without weathering. The effect of weathering on the slag particles is assumed to be dependant on their size. So, for a better characterization of the slag before and after weathering, its was first separated by sieving it in five fractions. Each fraction was then characterized individually. The respective percentage of each fraction is indicated in Table B.1.

Fraction	
0µ/80µ	13.90%
80µ/315µ	21.20%
315µ/2mm	17.10%
2mm/6.3mm	22.20%
6.3mm/10mm	25.60%

Table B.1: Percentage of each fraction in the fresh BOF-slag 0/10

For particles coarser than 80µm, the weathering procedure was carried out according to the procedure in EN 1744-1, paragraph 19.3, but a modification was brought to the classical procedure since samples were subjected to a very slight compaction with the vibrating table. The steam test equipment available at LCPC is described in the following graphics.
Another weathering procedure was applied to the finest aggregate class. In fact, when submitting the 0/0.08 mm fraction to the steam test, we observed a sudden raising of the slag sample and covering surcharge, which exceeded the height of the cylinder. Consequently, we have chosen to weather this finest fraction by immersion in water at 110°C (chamber temperature) during five days.

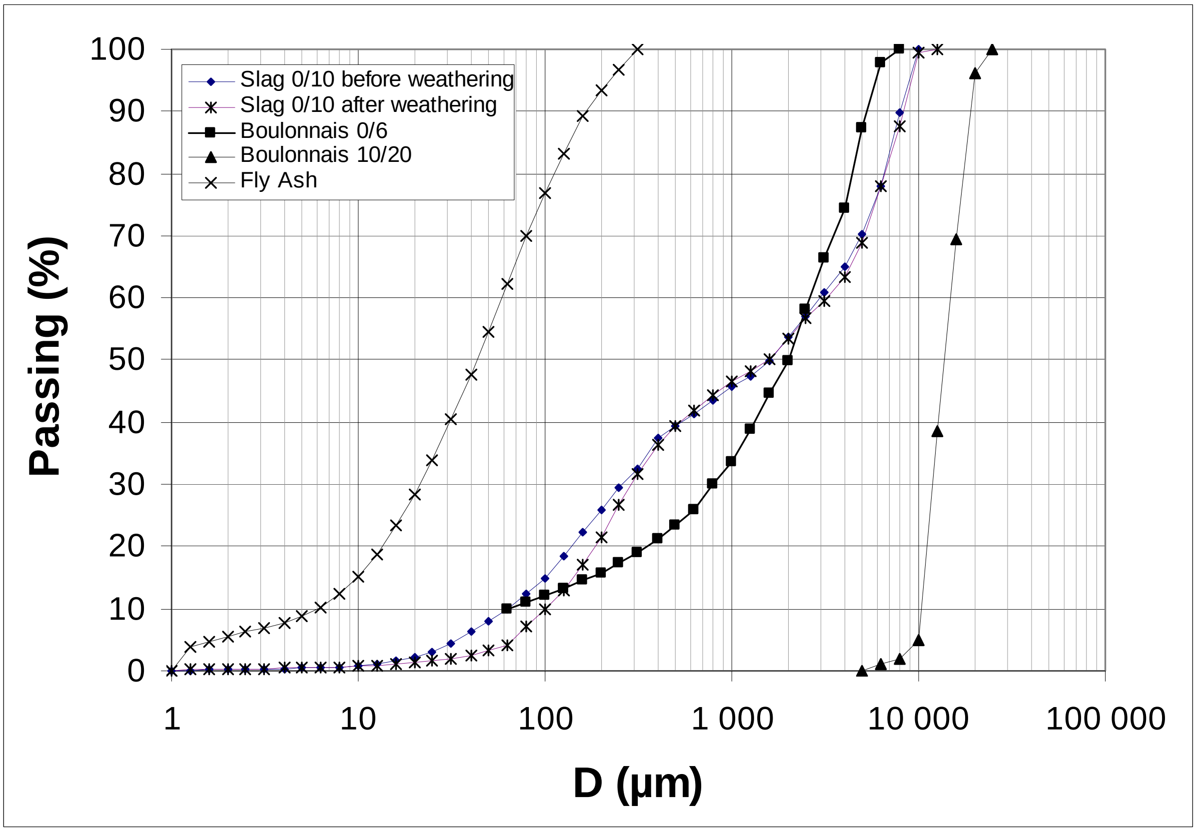


Graphic B.1: Principle of the steam apparatus: the sample is submitted to a steam flow while its height is monitored versus time

Graphic B.2: Vibration table and steel cylinder for the compaction of the granular sample

Graphic B.3: View of the apparatus with two samples

The grading curves of the different components were determined by sieving, according to NF EN 933.1 for particles with a diameter greater than 80 µm, and with a Malvern laser granulometer for finer particles (see Graphic B.4). For the slag before and after weathering, the grading curve was calculated from the grading curve of each fraction and the percentages presented in Table B.1.



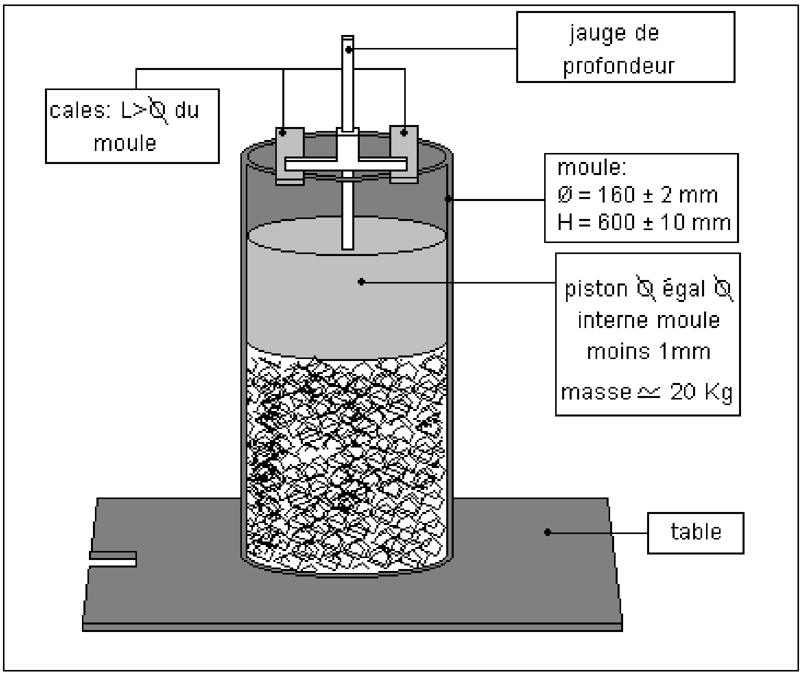
Graphic B.4: Grading curves of the components

The density measurements were made according NF EN 1097-6 for fraction upper than 0.080 mm and EN NF 1097-7 for fraction lower than 0.080 mm. Ethanol was used BOF slag aggregates in order to avoid any slag hydration during the test (see Table B.2); Ethanol was also used for fly ash.

Material	**Without weathering**	**After weathering**
Slag fraction 0/80µ	2.75	2.88
Slag fraction 80µ/315µ	2.76	2.88
Slag fraction 315µ/2mm	2.96	2.99
Slag fraction 2mm/6.3mm	3.06	3.11
Slag fraction 6.3mm/10mm	3.09	3.14
Limestone 0/6.3 mm	2.64	▨
Limestone 10/20	2.67	▨
Fly Ash	2.16	▨

<u>Table B.3</u>: Specific gravity of the components (in g/cm^3)

Packing density measurements were carried out on the aggregate size ranging between 0.08 and 20 mm following a method recently developed at LCPC (de Larrard et al. 2003, Lédée et al. 2004). This method consists in measuring the apparent volume of a 7 kg (+/-3g) sample of a granular fraction put in a cylinder and submitted to a compaction on a chock table under pressure of 10 kPa (see the following graphic). For the size fraction lower than 0.08 mm, the packing density was evaluated with the Rigden test (NF EN 1097-4). These two tests were assumed to correspond to a compaction index of 9.



<u>Graphic B.5</u>: Principle of packing density measurement in dry conditions. The apparent volume is deduced from the height of the sample after compaction.

The packing density of the fly ash was estimated from a water demand test (Sedran 1999, de Larrard 1999). This test consists in determining the water content necessary to transform a sample of powder from a wet soil state to an homogeneous paste state. This measurement corresponds to a compaction index of 6.7.

Material	Without weathering	After weathering
Slag fraction 0/80µ	0.46	0.43
Slag fraction 80µ/315µ	0.444	0.392
Slag fraction 315µ/2mm	0.482	0.446
Slag fraction 2mm/6.3mm	0.551	0.533
Slag fraction 6.3mm/10mm	0.568	0.548
Limestone 0/6.3 mm	0.628	▨
Limestone 10/20 mm	0.574	▨
Fly Ash	0.601	▨

Table B.3: Packing densities of the components

In conclusion, it can be observed that the weathering mainly leads to:
- a decrease of the packing density (mean value -7%);
- almost no change in the specific gravity (mean value +2,5%);
- aggregation of small particles and splitting of coarse particles.

All these data are summarized in Annex E2 and used to calibrate the components for a further use in René-LCPC: the packing densities of the individual granular classes (ie grains between two consecutive sieves) are supposed to be all the same for a given fraction. This value is calibrated to find back the experimental packing density of the fraction (which is considered as a mix of the individual classes according to its own grading curve).

The total composition of BOF slag and coal fly ashes was analysed with inductively coupled plasma emission spectroscopy, ICP and x-ray diffraction XRD. Microscopic examinations were performed on fresh BOF slag. Slag particles were set in resin, cut and polished with carbon. Polished sections were studied by reflected light optical microscopy and with an Environmental Scanning Electron Microscope (FEI Quanta 400) with an EDAX/EDS system operating at 20 kV. Free lime content of BOF slag was analysed by the Leduc method.

B.2 Accelerated feasibility tests at 80°C

B.2.1 Determination of the reactivity of the fly ash

In order to evaluate the reactivity of the fly ash activated by the quick lime, we have measured the compressive strength of 4x4x16 mm samples according to EN 196-1. The following table summarises the results obtained.

The measurements were made after a curing at 80°C (the sample were protected from desiccation).They confirm the reactivity of the selected fly ash with the lime. Moreover, one measurement was also done at 90 days after a 20°C curing. It shows that value at 7 days at 80°C underestimates the reactivity of the fly ash at long term at 20°C.

Water (in g)	Fly ash (in g)	CaO (in g)	CaO/Fa	Normalized sand (in g)	Compressive strength (in MPa)	Age (in days)	Curing temp (in °C)
220	314	31,4	0,10	1350	2,62	7	80
220	314	47,1	0,15	1350	2,75	7	80
220	314	62,8	0,20	1350	3,26	7	80
220	314	94,2	0,30	1350	4,07	7	80
220	314	94,2	0,30	1350	7,77	90	20
220	314	53,4	0,17	1350	4,74	15	80

Table B.4: Mortar composition and compressive strength

B.2.2 Determination of the first well-graded aggregate to be tested

The measurements made on the BOF-slag have shown that they contain approximately a total of 10% of free lime and that only 50% of this lime can be hydrated. Moreover the European norm EN 14227-3 and the French one NF 98118 suggest for classical fly ash/lime well graded aggregate the following mean dosages:

- 10% of fly ash (between 8 to 12%)
- 1,7% of CaO (1,4 to 2,1) or 2,5% of $Ca(OH)_2$ (2 to 3%)

These data lead to select a ratio of CaO/FA=0.17 in our mixes. When possible the CaO will be bring by the BO-slag. Which means a ratio BOF slag/ FA= 3.4. The previous results show that this ratio is not the best on the mechanical point of view but seems to be a good technical compromise between cost and mechanical properties.

René-LCPC software was used to generate different preliminary recipes (see Table B.5) with different theoretical swelling. Note that these swelling are probably overestimated here as the model was developed for packing without any hydraulic or pozzolanic reaction. In the present case, strength and so elastic modulus of the different mixes are expected to increase, thus restraining the swelling.

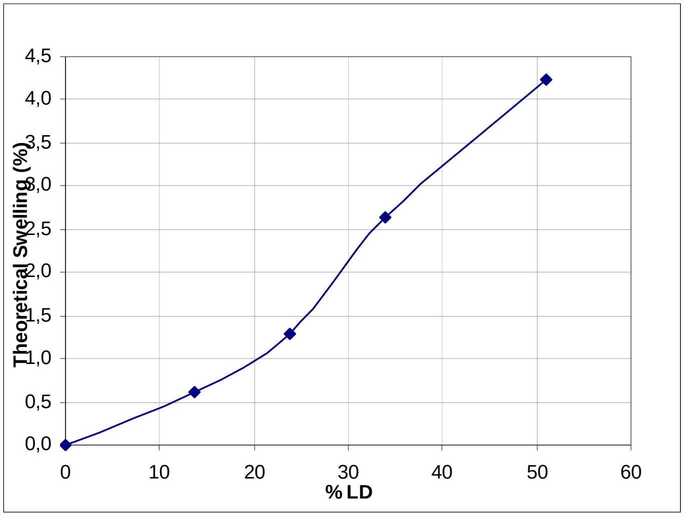
The assumptions of the calculations were the following:

- the packing index corresponding to the moulding of the sample is fixed 12. This value was fitted from the one obtained for packing at optimum proctor by Pouliot et al (2001). It is lower than the 14.44 value calibrated from the experiments made on the vibration table (see Graphic B.2) by Deneele et al. (2005) on dry mixes (this value is slightly different from the one obtained by these authors due to small correction in Rene-LCPC of the data concerning the fines particles of the BOF-slag). Yet the proctor value is supposed to be more representative of on site compaction;
- the calculations are made with no wall effect to be representative of free swelling of a huge sample of material.

In the first series (F1, F2, F3) we have:

- fixed the BOF-Slag/FA ratio to 3.4. By this way we have made the assumption that all the quick lime necessary for the fly ash was furnished by the slag;
- varied the BOF-Slag /limestone ratio to generate different swelling values. In a first time we have only selected the 10/20 limestone in order lessen the granular interaction with the slag particles. This theoretically allows moderate values of swelling even with high volume of slag ("the slag particles expand between the coarse inert particles with few effect on their packing arrangement).

The following graphic shows the simulations obtained with these assumptions.



Graphic B.5: **Theoretical swelling in% calculated with René-LCPC for the first series**

In the second series (F1, F4, F5) we have:

- the same BOF-Slag /limestone as in the first series to keep almost the same swelling level;
- imposed a content of 10% of fly ash to aim at higher theoretical mechanical properties (before swelling). In that case the quick lime furnished by the slag is not sufficient and we have to add directly a pat of it to maintain the CaO/FA ratio constant.

In the third series (F6, F7,F8) we have tried to cover almost the same range of theoretical swelling values but part of the limestone 10/20mm was replaced by limestone 0/6 to improve the grading of the well graded aggregate (see the granular specifications NF EN 14227-3) and increase the packing density (according to NF EN 14227-3 a value higher than 0.85 at the optimum proctor is required).

Mix	Fly Ash (%)	Lime stone 10/20 (%)	Lime stone 0/6 (%)	Steel slag 0-10 (%)	Cao (%)	Ca0/CV	LD 0-10 (% except CV and Cao)	Initial theoretical porosity	Initial dry apparent density (kg/m^3)	Theoretical swelling (%)
F1	10	56	0	34	0	0.17	37.8	0.1959	2162	2.63
F2	7	69.2	0	23.8	0	0.17	25.6	0.2455	2025	1.29
F3	4	82.4	0	13.6	0	0.17	14.2	0.3105	1846	0.60
F1	10	56	0	34	0	0.17	37.8	0.1959	2162	2.63
F4	10	66.4	0	23.1	0.5	0.17	25.8	0.2226	2070	1.30
F5	10	76.3	0	12.6	1.1	0.17	14.2	0.2634	1943	0.60
F6	10	41	15	34	0	0.17	37.8	0.191	2181.5	3.23
F7	10	48.8	17.6	23.1	0.5	0.17	25.8	0.1725	2210.1	2.02
F8	10	56.3	20	12.6	1.1	0.17	14.2	0.1635	2213.9	0.93

Table B.5: **Theoretical swelling of different well graded aggregate calculated with Rene-LCPC software**

B.2.3 Proctor measurements

In a first time the water content and the dry density were determined at the optimum proctor according to NF-EN 13286-2 for the two first series. All the data obtained are presented in annex E-3.The following table summarizes the results obtained at the optimum proctor.

Mix	W_{opm}(%)	ρd_{opm} (t/m3)	Packing density
F1	7.5	2.23	0.829
F2	5.5	2.13	0.792
F3	3.5	2.02	0.754
F4	6.8	2.20	0.824
F5	6.2	2.16	0.819

<u>Table B.6</u>: Water content and dry apparent density of the mixes at the optimum proctor

The properties at the optimum proctor were adopted to produce samples for mechanical characterisation and swelling measurements.

B.2.4 Mechanical results

For each mix, 3 Ø16x32 cm cylinders were moulded by vibro-compaction with the VCEC apparatus according to NF EN 13286-3. After casting the cylinders were slowly heated to 80°C during one day, then cured at 80°C for 5 days and finally slowly refresh to 20°C during one day. The cylinders were preserved from desiccation during curing. The following table summarises the results obtained.

Mix	Fly Ash (%)	Lime stone 10/20 (%)	Lime stone 0/6 (%)	Steel slag 0-10 (%)	CaO (%)	ρ_{dopm} (t/m3)	W_{opm} (%)	Spliting tensile strength (Mpa)
F1	10	56	0	34	0	2.23	7.5	0.16
F2	7	69.2	0	23.8	0	2.13	5.5	0.16
F3	4	82.4	0	13.6	0	2.02	3.5	0.19
F4	10	66.4	0	23.1	0.5	2.2	6.8	0.35
F5	10	76.3	0	12.6	1.1	2.16	6.2	0.49

<u>Table B.7</u>: Mechanical properties of the mixes at the optimum proctor

The results show that only limited performances in splitting tensile strength are reached with the mixes in the first series, where no quick lime is added. This can be explained in F1 by important swelling. The graphic B.6 shows that at the end of curing, cracks have appeared in the cylinders as well as brown zones which are typical of CaO hydration in the slag aggregates. In F3, the low performance is probably due to the low content of fly ash. Moreover, in that series, it is possible that even if pozzolanic reactivity is accelerated by the increase of curing temperature on one hand, the diffusion of the quick lime liberated from the slag aggregate is not accelerated on the other hand. The consequence may then be that the fly ash particles are not in contact with lime and that pozzolanic reaction does not occur much in the first week.

In the second series, F5 reach 0,5 MPa in tensile strength. This result is encouraging as theoretical swelling is around 6000 10^{-6}. As it can be seen in graphic 7, no cracks was visible on the sample after curing.

Graphic B.6: Pictures of the F1 mix after curing. Segregation is due to the gap graded skeleton. Cracks are visible as well as brown scaling due to quicklime hydration in slag particles

Graphic B.7: Pictures of the F5 mix after curing. Segregation is due to the gap graded skeleton. No cracks are visible.

B.2.5 Expansion measurement with the steam apparatus

In a first approach, we intended to use the steam machine presented in Graphic B.1 to make the swelling measurements in accelerated conditions. This apparatus allows a steam curing at 100°C and was already equipped with a displacement indicator.

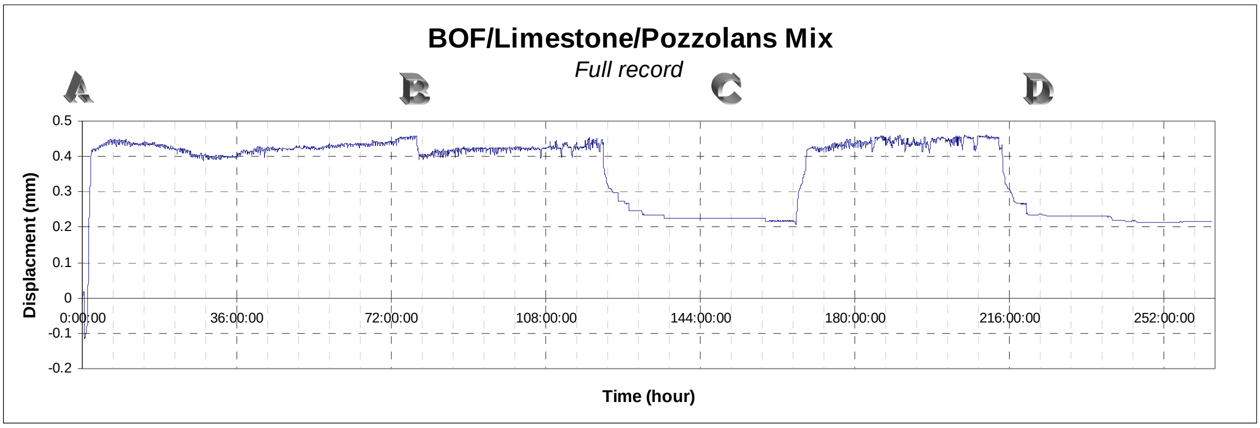
We expected to compact the well graded samples to be submitted to the steam flow with the vibrating table presented in Graphic B.2. The classical compaction protocol was 6 minutes at a frequency of (48+/- 3) Hz, with a hydraulic pressure (static load) of 35 kPa. This protocol was tested on the mix F1 but it failed to give a voids content around 17,1% as obtained in the proctor test. So, before measuring any expansion displacement, we had to test other compaction protocols to have a well graded sample representative of the in-site job. The following table summarizes the different tests done. We finally choose the last protocol which gives a voids content very near of the aim.

Compaction protocol	**Final void content (%)**
Vibration table+ sample with W=7,5%	**31,6 %**
	33,1 %
	33.8 %
Vibration table + sample dry	**19.1%**
Hand-held proctor hammer + Vibration table + sample with W=7,5%	**18.8 %**

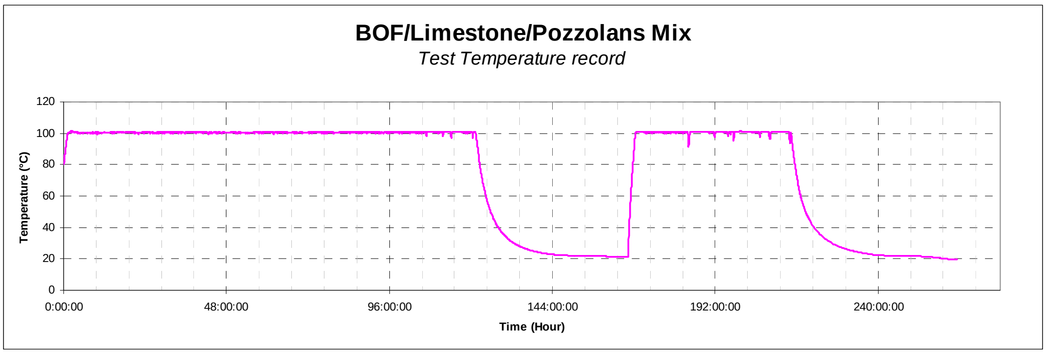
<u>Table B.8</u>: Mechanical properties of the mixes at the optimum proctor

Then two first expansion tests were realized on the F1 mix up to 168 hours under the steam flow at 100 °C. The following graphic describes a typical result obtained. It presents different areas:

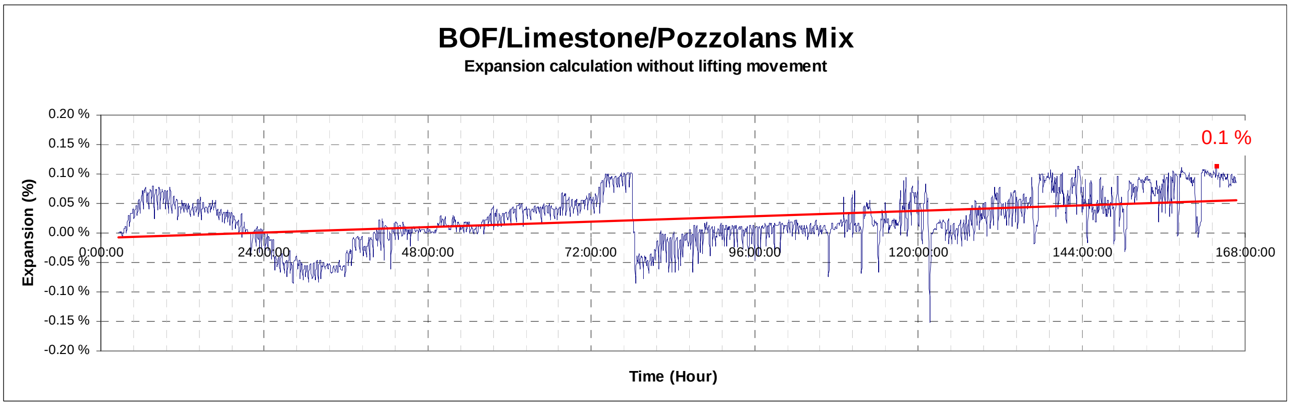
- Area A: in first 2-3 hours, the pressure increases in the chamber and push the sample with a displacement which reaches +0.4mm;
- Area B: the curve shows very small fluctuations (negative and positive) less than 0.01mm while water was regularly added in the steam unit;
- Area C: its corresponds to an accidental and brutal failure of steam flow during approximately 43 hours, due to a the temperature decrease in the chamber. Then displacement decreased from +0.4 to 0.2 and came back to +0.4 when steam flow restarted
- Area D: after cutting the steam flow, the sample comes back to a balance position around +0.2 mm.



<u>Graphic B.8</u>: Displacement record versus time (F1 mix)



Graphic B.9: Temperature record versus time (F1 mix)



Graphic B.10: resulting expansion (in %) calculated after correction of the lifting movements

These observations seem to show that in fact the steam is not able to go through the sample because of the low porosity of the sample. So we have a piston effect which is the main explanation of the displacement steps. Cutting off this piston effect we have calculated the residual expansion. It can be seen on the graphic 10 that the results are quite erratic and final value limited to less than 0,1% while a theoretical value up to 2% was expected, and several cracks were observed on Ø16x32 cylinder (see Graphic B.6). So it seems that it is not relevant to use the steam apparatus for the accelerated swelling measurements and that we have to develop another system.

B.2.6 Development of a new method for swelling measurements

Using the procedure classically used for concrete samples, the idea is to include two steel inserts on in the two faces of a Ø16x 32 cm. The distance between these two inserts will then be measured at different ages with the measurement device presented in the following graphic

<u>Graphic B.11</u>: Tool realized for length measurement of Ø16x 32 cm of well graded aggregate. The zero is made thanks an invar bar. The contact with the inserts of the sample or the bar are ensured by two steel balls.

Compared to concrete we have here two main difficulties:

- samples are compacted and not cast. A new device must be design to be included in the mould of the VCEC compacting machine, to be able to put the insert in the samples;
- measurements have to be started at a young age, when the well grade aggregate has almost no tensile strength. So the anchorage of the insert has to be well studied.

The graphic B.12 describes the system developed to include the inserts during compaction:

- a steel plate (9) is included in and empty millboard mould to which an insert (8) is screwed;
- the well-graded aggregate is included in the mould;
- another steel plate (7) with an insert is put on the material;
- the material is compacted with the piston (4).

Preliminary compacting tests were done and underlined some problems:

- the insert were fixed on the steel plate with a central screw. When removing the plate (see Graphic B.14), unscrewing lead to some rotation of the insert which disturbs its anchorage. Three screws were then placed at 120°C to avoid this problem;
- it is necessary to use a plastic sheet between steel plate and the material to facilitate their removing;
- the form of the insert first adopted and presented in Graphic B.13 was not adapted for mixes with coarse aggregates (filling around the insert was not satisfactory) leading to a bad anchorage.

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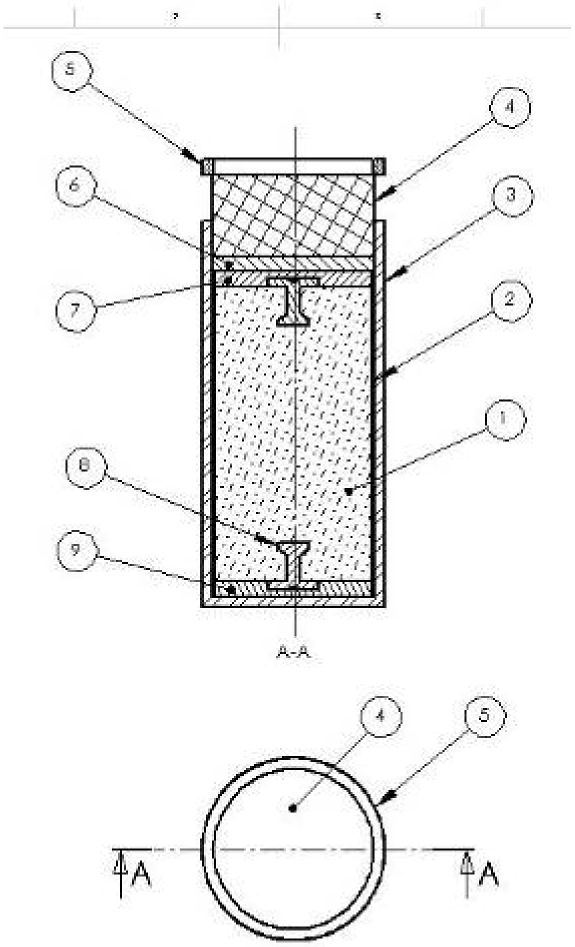

<u>Graphic B.12</u>: Principle adopted to include the insert while compacting

<u>Graphic B.13</u>: Detail of the steel plate (9) with the first version of insert (8)

Graphic B.14: The insert after removal of the steel plate

Graphic B.15: The second version of insert,with a conic form to facilitate the filling around the insert when coarse aggregates are used.

A new type of insert in stainless steel with a conic form was adopted (see Graphic B.15). A new series of tests were done consisting in compacting a Ø16x 32 cm with the inserts, removing the steel plates at the early age and measuring the stability of the length of the sample at early age (one day). These new trials have shown that the second generation inserts may rotate on their axis generating by the way a fluctuation of the length around 25µm (ie strain of 80 10^{-6}).

A third version of the inserts (see graphic 16) was then designed consisting in adding two flat parts in the conic part to avoid rotation. A first test has shown that this new version of inserts are well anchored (see graphic 17) and allow a stable evaluation of the sample length.

Graphic B.16: The third version of insert, with flat plates on the conic part

Graphic B.16: The third version of insert well anchored in the well graded aggregate

C - Conclusions

On the basis of the bibliographical analysis we have selected a set of constituants which could be adapted to produce well-graded aggregates with a swelling behaviour and mechanical performances similar to that of cement treated well-graded aggregates. We also have described a method potentially useful to make the design of such mixes.
Preliminary tests were done in hot conditions (higher than 80°C) in order to accelerate the mechanical performance increase as well as swelling in order to verify the feasibility of the innovation proposed. Unfortunately we met technical difficulties to develop a reliable free swelling test adapted to such well graded aggregate mixes. A promising prototype has been designed and tested but it still needs improvements.

The feasibility of the proposed concept could then not be verified during this project and need more research.

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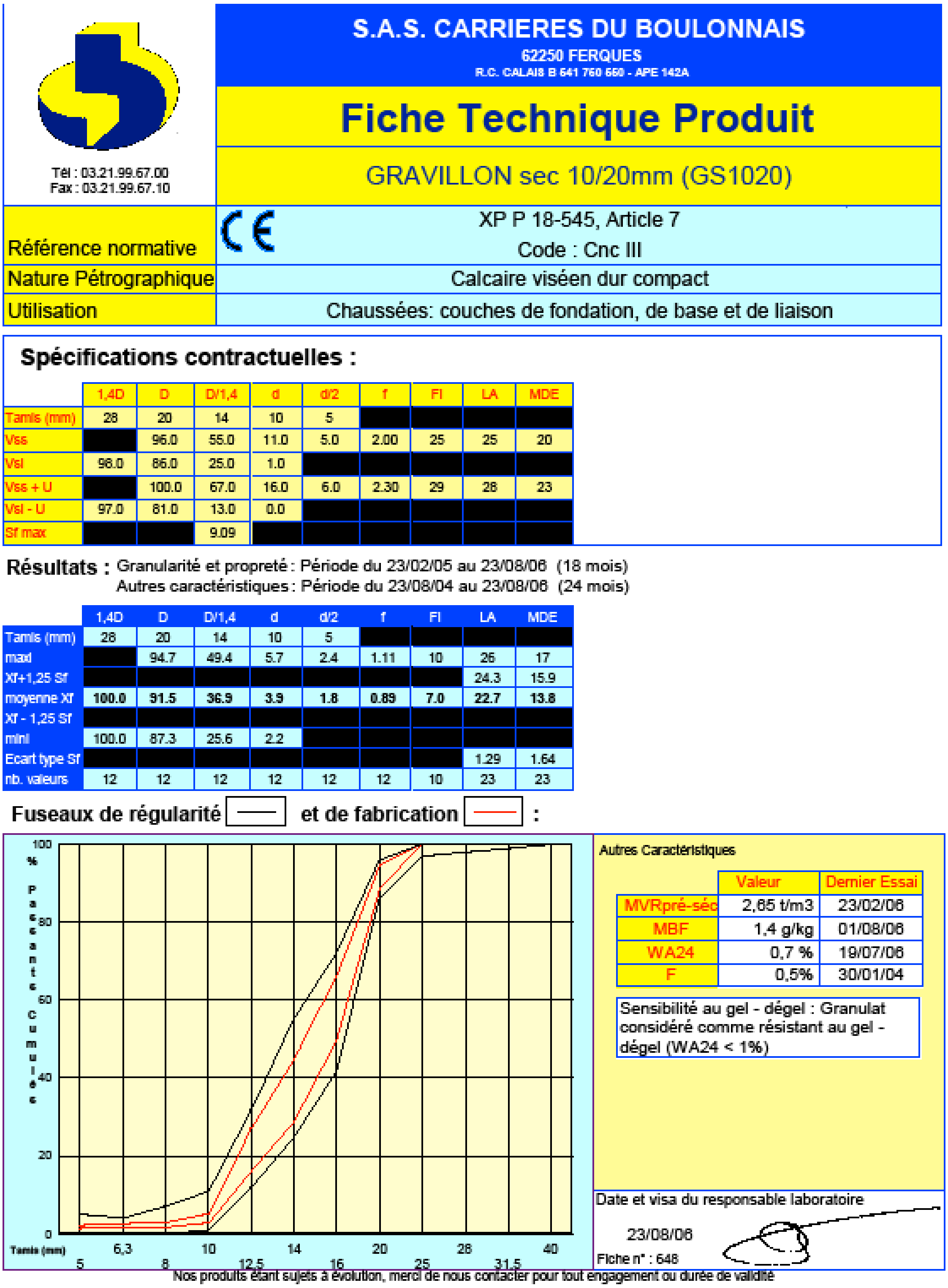
E - Annexes

Annex E1

Properties and data sheets of the components



S.A.S. CARRIERES DU BOULONNAIS
62250 FERQUES
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Tél : 03.21.99.67.00
Fax : 03.21.99.67.10

Fiche Technique Produit

GRAVILLON sec 10/20mm (GS1020)

Référence normative	CE XP P 18-545, Article 7 Code : Cnc III
Nature Pétrographique	Calcaire viséen dur compact
Utilisation	Chaussées: couches de fondation, de base et de liaison

Spécifications contractuelles :

	1,4D	D	D/1,4	d	d/2	f	FI	LA	MDE
Tamis (mm)	28	20	14	10	5				
Vss		96.0	55.0	11.0	5.0	2.00	25	25	20
Vsi	98.0	86.0	25.0	1.0					
Vss + U		100.0	67.0	16.0	6.0	2.30	29	28	23
Vsi - U	97.0	81.0	13.0	0.0					
Sf max			9.09						

Résultats : Granularité et propreté : Période du 23/02/05 au 23/08/06 (18 mois)
Autres caractéristiques : Période du 23/08/04 au 23/08/06 (24 mois)

	1,4D	D	D/1,4	d	d/2	f	FI	LA	MDE
Tamis (mm)	28	20	14	10	5				
maxi		94.7	49.4	5.7	2.4	1.11	10	26	17
Xf+1,25 Sf								24.3	15.9
moyenne Xf	**100.0**	**91.5**	**36.9**	**3.9**	**1.8**	**0.89**	**7.0**	**22.7**	**13.8**
Xf - 1,25 Sf									
mini	100.0	87.3	25.6	2.2					
Ecart type Sf								1.29	1.64
nb. valeurs	12	12	12	12	12	12	10	23	23

Fuseaux de régularité —— **et de fabrication** —— **:**

Autres Caractéristiques

	Valeur	Dernier Essai
MVRpré-séc	2,65 t/m3	23/02/06
MBF	1,4 g/kg	01/08/06
WA24	0,7 %	19/07/06
F	0,5%	30/01/04

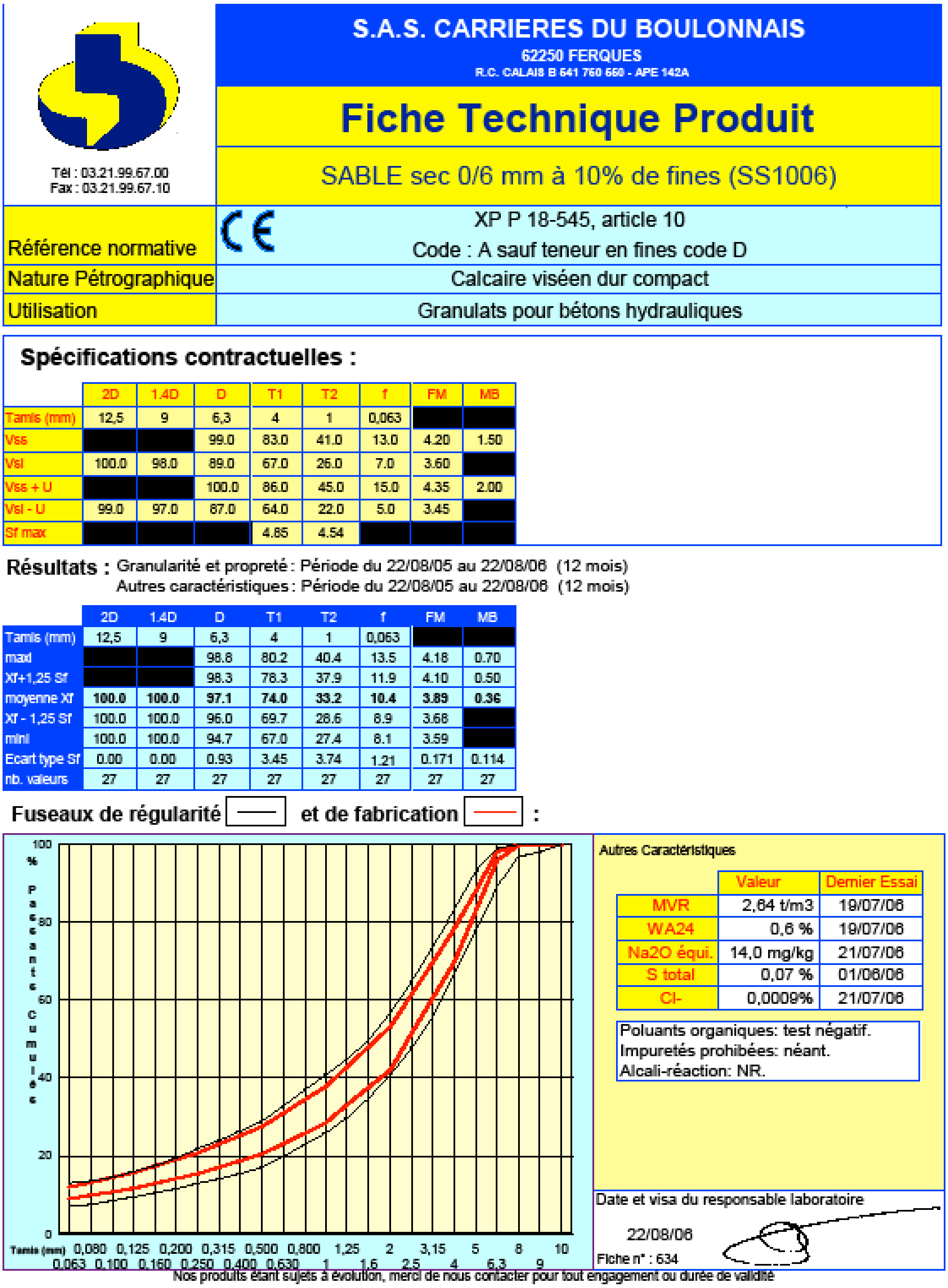
Sensibilité au gel - dégel : Granulat considéré comme résistant au gel - dégel (WA24 < 1%)

Date et visa du responsable laboratoire

23/08/06

Fiche n° : 648

Nos produits étant sujets à évolution, merci de nous contacter pour tout engagement ou durée de validité



S.A.S. CARRIERES DU BOULONNAIS
62250 FERQUES
R.C. CALAIS B 641 760 650 - APE 142A

Tél : 03.21.99.67.00
Fax : 03.21.99.67.10

Fiche Technique Produit

SABLE sec 0/6 mm à 10% de fines (SS1006)

Référence normative	CE XP P 18-545, article 10 Code : A sauf teneur en fines code D
Nature Pétrographique	Calcaire viséen dur compact
Utilisation	Granulats pour bétons hydrauliques

Spécifications contractuelles :

	2D	1.4D	D	T1	T2	f	FM	MB
Tamis (mm)	12,5	9	6,3	4	1	0,063		
Vss			99.0	83.0	41.0	13.0	4.20	1.50
Vsi	100.0	98.0	89.0	67.0	26.0	7.0	3.60	
Vss + U			100.0	86.0	45.0	15.0	4.35	2.00
Vsi - U	99.0	97.0	87.0	64.0	22.0	5.0	3.45	
Sf max				4.85	4.54			

Résultats : Granularité et propreté : Période du 22/08/05 au 22/08/06 (12 mois)
Autres caractéristiques : Période du 22/08/05 au 22/08/06 (12 mois)

	2D	1.4D	D	T1	T2	f	FM	MB
Tamis (mm)	12,5	9	6,3	4	1	0,063		
maxi			98.8	80.2	40.4	13.5	4.18	0.70
Xf+1,25 Sf			98.3	78.3	37.9	11.9	4.10	0.50
moyenne Xf	**100.0**	**100.0**	**97.1**	**74.0**	**33.2**	**10.4**	**3.89**	**0.36**
Xf - 1,25 Sf	100.0	100.0	96.0	69.7	28.6	8.9	3.68	
mini	100.0	100.0	94.7	67.0	27.4	8.1	3.59	
Ecart type Sf	0.00	0.00	0.93	3.45	3.74	1.21	0.171	0.114
nb. valeurs	27	27	27	27	27	27	27	27

Fuseaux de régularité — **et de fabrication** — **:**

Autres Caractéristiques

	Valeur	Dernier Essai
MVR	2,64 t/m3	19/07/06
WA24	0,6 %	19/07/06
Na2O équi.	14,0 mg/kg	21/07/06
S total	0,07 %	01/06/06
Cl-	0,0009%	21/07/06

Poluants organiques: test négatif.
Impuretés prohibées: néant.
Alcali-réaction: NR.

Date et visa du responsable laboratoire

22/08/06

Fiche n° : 634

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SILICOLINE®

Cendre volante silico-alumineuse issue de la combustion de houille pulvérisée en centrale à flamme à la température d'environ 1400 ° C.

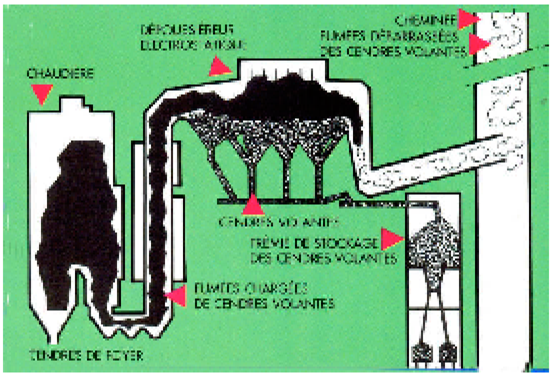


Schéma centrale à flamme

La Silicoline® se présente sous la forme de poudre grise, douce au toucher, ensemble de sphères pleines ou creuses, de nature vitreuse.

La Silicoline® est disponible sèche ou humide, en vrac ou conditionnée en big bag, et se transporte par camion, par bateau ou par fer.

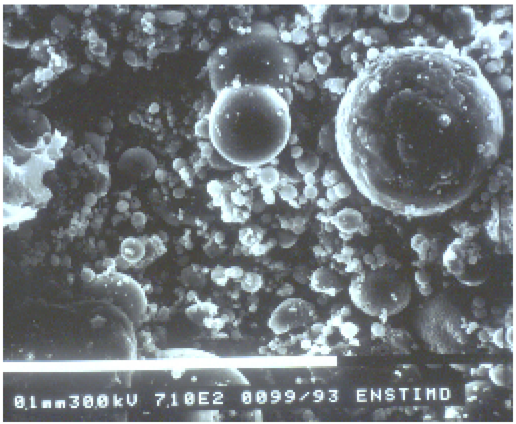


Photo microscopique de SILICOLINE®

ANALYSES		Moyenne
PHYSIQUES		
Perte au feu # Carbone résiduel	%	2 à 5
Masse volumique	t/m3	2.1 à 2.3
Granulométrie		
passants à 45 µ	%	65 à 75
passants à 80 µ	%	75 à 90
passants à 200 µ	%	96 à 99
passants à 315 µ	%	100
CHIMIQUES		
SiO2	%	50
Fe2O3	%	8,5
Al2O3	%	29
MgO	%	3
MnO2	%	0,5
CaO total	%	3
CaO libre	%	0,15
Na2O	%	0,7
K2O	%	4,5
SO3	%	0,6
TiO2	%	1,0
Chlore	%	0,04
P2O5	%	0,25
Total Alcalins disponibles	%	0,05 à 0,15

Siège Social : Rue Aimé DUBOST BP 21 – 62670 MAZINGARBE- Tél. 03 21 45 73 73
Fax 03 21 45 73 70
E-mail : siege@surschiste.com

Annex E2

Properties of the components for René-LCPC calculations

Fly Ash

Nom du matériau: calcaire.mat:\cendre volante

Masse vol.: 2160 kg/m3

Compacité expérimentale de l'échantillon inconnue
Compacité calculée de l'échantillon= 0,6012
Avec pour indice de compaction 6,7

Compacités propres de la forme: 0,0*d+0,43

Diamètre (µm)	Passant cumulé (%)	Diamètre moyen (µm)	Compacité
1	0	1,118	0,4255
1,25	3,8	1,414	0,4255
1,6	4,8	1,789	0,4255
2	5,6	2,236	0,4255
2,5	6,2	2,806	0,4255
3,15	6,9	3,55	0,4255
4	7,7	4,472	0,4255
5	8,7	5,612	0,4255
6,3	10,2	7,099	0,4255
8	12,4	8,944	0,4255
10	15,1	11,18	0,4255
12,5	18,6	14,142	0,4255
16	23,3	17,889	0,4255
20	28,3	22,361	0,4255
25	33,9	28,062	0,4255
31,5	40,4	35,496	0,4255
40	47,6	44,721	0,4255
50	54,6	56,125	0,4255
63	62,2	70,993	0,4255
80	70	89,443	0,4255
100	76,9	111,803	0,4255
125	83,3	141,421	0,4255
160	89,2	178,885	0,4255
200	93,5	223,607	0,4255
250	96,6	280,624	0,4255
315	100		

BOF-Slag 0/80 µm before weathering

Nom du matériau: laitld.mat:\0.0/0.08b

Masse vol.: 2750 kg/m3

Compacité expérimentale de l'échantillon= 0,46
Cette mesure a été effectuée en milieu infini
Compacité calculée de l'échantillon= 0,46
Avec pour indice de compaction 9

Compacités propres de la forme: 0,0*d+0,3682

Diameter (µm)	Passing (%)	Mean diameter (µm)	Packing density
1	0	1,118	0,3682
1,25	0,5	1,414	0,3682
1,6	1	1,789	0,3682
2	1,5	2,236	0,3682
2,5	1,8	2,806	0,3682
3,15	2	3,55	0,3682
4	2,2	4,472	0,3682
5	3	5,612	0,3682
6,3	4	7,099	0,3682
8	4	8,944	0,3682
10	5	11,18	0,3682
12,5	7	14,142	0,3682
16	11	17,889	0,3682
20	15	22,361	0,3682
25	22	28,062	0,3682
31,5	31	35,496	0,3682
40	45	44,721	0,3682
50	58	56,125	0,3682
63	71,62	70,993	0,3682
80	83,41	89,443	0,3682
100	91,41	111,803	0,3682
125	100		0,3682

BOF-Slag 80/315 µm before weathering

Nom du matériau: laitld.mat:\0.080/0.315

Masse vol.: 2760 kg/m3

Compacité expérimentale de l'échantillon= 0,444
Cette mesure a été effectuée en milieu confiné
Les paramètres du polynome P(x)=Ax^3+Bx^2+Cx+D
exprimant le rapport du volume
non perturbé sur le volume total en fonction du diamètre
du grain (en mm) sont:

A=	-1,38E-07
B=	8,31E-05
C=	-1,60E-02
D=	1

Compacité calculée de l'échantillon= 0,444
Avec pour indice de compaction 9

Compacités propres de la forme: 0,0*d+0,3808

Diameter (µm)	Passing (%)	Mean diameter (µm)	Packing density
63	0	70,993	0,3808
80	3,6	89,443	0,3808
100	10,49	111,803	0,3808
125	21,92	141,421	0,3808
160	39,06	178,885	0,3808
200	56,46	223,607	0,3808
250	72,96	280,624	0,3808
315	86,58	354,965	0,3808
400	100		0,3808

BOF-Slag 315 µm/2mm before weathering

Nom du matériau: laitld.mat:\0.315/2

Masse vol.: 2960 kg/m3

Compacité expérimentale de l'échantillon= 0,482
Cette mesure a été effectuée en milieu confiné
Les paramètres du polynome P(x)=Ax^3+Bx^2+Cx+D
exprimant le rapport du volume
non perturbé sur le volume total en fonction du
diamètre du grain (en mm) sont:
A= -1,60E-07
B= 9,03E-05
C= -1,66E-02
D= 1
Compacité calculée de l'échantillon= 0,482
Avec pour indice de compaction 9

Compacités propres de la forme: 0,0*d+0,3987

Diameter (µm)	Passing (%)	Mean diameter (µm)	Packing density
200	0	223,607	0,3987
250	0,8	280,624	0,3987
315	1,41	354,965	0,3987
400	13,84	447,214	0,3987
500	25,7	561,249	0,3987
630	37,19	709,93	0,3987
800	49,45	894,427	0,3987
1 000	62,12	1118,034	0,3987
1 250	72,03	1414,214	0,3987
1 600	86,33	1788,854	0,3987
2 000	100		0,3987

BOF-Slag 2mm/6.3mm before weathering

Nom du matériau: laitld.mat:\2/6.3

Masse vol.: 3060 kg/m3

Compacité expérimentale de l'échantillon= 0,551
Cette mesure a été effectuée en milieu confiné
Les paramètres du polynome P(x)=Ax^3+Bx^2+Cx+D
exprimant le rapport du volume
non perturbé sur le volume total en fonction du
diamètre du grain (en mm) sont:

A=	-1,89E-07
B=	9,97E-05
C=	-1,73E-02
D=	1

Compacité calculée de l'échantillon= 0,551
Avec pour indice de compaction 9

Compacités propres de la forme: 0,0*d+0,4978

Diameter (µm)	Passing (%)	Mean diameter (µm)	Packing density
1 600	0	1788,854	0,4978
2 000	7,4	2236,068	0,4978
2 500	22	2806,243	0,4978
3 150	38,93	3549,648	0,4978
4 000	57,77	4472,136	0,4978
5 000	81,77	5612,486	0,4978
6 300	99,27	7099,296	0,4978
8 000	100		0,4978

BOF-Slag 6.3mm/10mm before weathering

Nom du matériau: laitld.mat:\6.3/10

Masse vol.: 3090 kg/m3

Compacité expérimentale de l'échantillon= 0,568
Cette mesure a été effectuée en milieu confiné
Les paramètres du polynome P(x)=Ax^3+Bx^2+Cx+D
exprimant le rapport du volume
non perturbé sur le volume total en fonction du
diamètre du grain (en mm) sont:

A=	-1,97E-07
B=	1,02E-04
C=	-1,75E-02
D=	1

Compacité calculée de l'échantillon= 0,568
Avec pour indice de compaction 9

Compacités propres de la forme: 0,0*d+0,5574

Diameter (µm)	Passing (%)	Mean diameter (µm)	Packing density
5 000	0	5612,486	0,5574
6 300	14,54	7099,296	0,5574
8 000	60,1	8944,271	0,5574
10 000	100		

BOF-Slag 0/80 µm after weathering

Nom du matériau: laitmat.mat:\0/0.08M(mod)b

Masse vol.: 2880
kg/m3

Compacité expérimentale de l'échantillon= 0,43
Cette mesure a été effectuée en milieu infini
Compacité calculée de l'échantillon= 0,43
Avec pour indice de compaction 9

Compacités propres de la forme: 0,0*d+0,284

Diameter (µm)	Passing (%)	Mean diameter (µm)	Packing density
1	0	1,118	0,284
1,25	1,18	1,414	0,284
1,6	1,5	1,789	0,284
2	1,9	2,236	0,284
2,5	2,32	2,806	0,284
3,15	2,79	3,55	0,284
4	3,28	4,472	0,284
5	3,74	5,612	0,284
6,3	4,23	7,099	0,284
8	4,81	8,944	0,284
10	5,48	11,18	0,284
12,5	6,35	14,142	0,284
16	7,65	17,889	0,284
20	9,27	22,361	0,284
25	11,46	28,062	0,284
31,5	14,52	35,496	0,284
40	18,68	44,721	0,284
50	23,51	56,125	0,284
63	29,3	70,993	0,284
80	35,79	89,443	0,284
100	41,98	111,803	0,284
125	48,09	141,421	0,284
160	54,86	178,885	0,284
200	61,29	223,607	0,284
250	68,3	280,624	0,284
315	76	354,965	0,284
400	83,58	447,214	0,284
500	89,34	561,249	0,284
630	93,43	709,93	0,284
800	95,99	894,427	0,284
1 000	97,47	1118,034	0,284
1 250	100		0,284

BOF-Slag 80/315 µm after weathering

Nom du matériau: laitmat.mat:\0.080/0.315M

Masse vol.: 2880 kg/m3

Compacité expérimentale de l'échantillon= 0,392
Cette mesure a été effectuée en milieu confiné
Les paramètres du polynome P(x)=Ax^3+Bx^2+Cx+D exprimant le rapport du volume non perturbé sur le volume total en fonction du diamètre du grain (en mm) sont:

A=	-1,27E-07
B=	7,97E-05
C=	-1,57E-02
D=	1

Compacité calculée de l'échantillon= 0,392
Avec pour indice de compaction 9

Compacités propres de la forme: 0,0*d+0,3279

Diameter (µm)	Passing (%)	Mean diameter (µm)	Packing density
63	0	70,993	0,3279
80	10,71	89,443	0,3279
100	19,64	111,803	0,3279
125	29,81	141,421	0,3279
160	44,69	178,885	0,3279
200	61,26	223,607	0,3279
250	76	280,624	0,3279
315	92,71	354,965	0,3279
400	98,7	447,214	0,3279
500	100		0,3279

BOF-Slag 315 µm/2mm before weathering

Nom du matériau: laitmat.mat:\0.315/2M

Masse vol.: 2990 kg/m3

Compacité expérimentale de l'échantillon= 0,446
Cette mesure a été effectuée en milieu confiné
Les paramètres du polynome P(x)=Ax^3+Bx^2+Cx+D
exprimant le rapport du volume
non perturbé sur le volume total en fonction du
diamètre du grain (en mm) sont:

A=	-1,50E-07
B=	8,70E-05
C=	-1,63E-02
D=	1

Compacité calculée de l'échantillon= 0,446
Avec pour indice de compaction 9

Compacités propres de la forme: 0,0*d+0,359

Diameter (µm)	Passing (%)	Mean diameter (µm)	Packing density
200	0	223,607	0,359
250	6,27	280,624	0,359
315	9,25	354,965	0,359
400	22,39	447,214	0,359
500	33,63	561,249	0,359
630	45,08	709,93	0,359
800	57,37	894,427	0,359
1 000	68,78	1118,034	0,359
1 250	77	1414,214	0,359
1 600	87,96	1788,854	0,359
2 000	98,5	2236,068	0,359
2 500	100		0,359

BOF-Slag 2mm/6.3mm before weathering

Nom du matériau: laitmat.mat:\2/6.3M

Masse vol.: 3110 kg/m3

Compacité expérimentale de l'échantillon= 0,533
Cette mesure a été effectuée en milieu confiné
Les paramètres du polynome P(x)=Ax^3+Bx^2+Cx+D
exprimant le rapport du volume
non perturbé sur le volume total en fonction du
diamètre du grain (en mm) sont:
A= -1,86E-07
B= 9,86E-05
C= -1,73E-02
D= 1
Compacité calculée de l'échantillon= 0,533
Avec pour indice de compaction 9

Compacités propres de la forme: 0,0*d+0,4792

Diameter (µm)	Passing (%)	Mean diameter (µm)	Packing density
1 600	0	1788,854	0,4792
2 000	7,12	2236,068	0,4792
2 500	20	2806,243	0,4792
3 150	32,48	3549,648	0,4792
4 000	49,78	4472,136	0,4792
5 000	75,31	5612,486	0,4792
6 300	99,05	7099,296	0,4792
8 000	100		0,4792

BOF-Slag 6.3mm/10mm before weathering

Nom du matériau: laitmat.mat:\6.3/10M

Masse vol.: 3130 kg/m3

Compacité expérimentale de l'échantillon= 0,548
Cette mesure a été effectuée en milieu confiné
Les paramètres du polynome P(x)=Ax^3+Bx^2+Cx+D
exprimant le rapport du volume
non perturbé sur le volume total en fonction du diamètre
du grain (en mm) sont:
A= -1,93E-07
B= 1,01E-04
C= -1,74E-02
D= 1
Compacité calculée de l'échantillon= 0,548
Avec pour indice de compaction 9

Compacités propres de la forme: 0,0*d+0,5349

Diameter (µm)	Passing (%)	Mean diameter (µm)	Packing density
5 000	0	5612,486	0,5349
6 300	14,41	7099,296	0,5349
8 000	51,2	8944,271	0,5349
10 000	97,45		0,5349
12 500	100		

Limestone "Le Boulonnais" 0/6mm

Nom du matériau: calcaire.mat:\boulonnais 0/6

Masse vol.: 2640 kg/m3

Compacité expérimentale de l'échantillon= 0,628
Cette mesure a été effectuée en milieu confiné
Les paramètres du polynome P(x)=Ax^3+Bx^2+Cx+D
exprimant le rapport du volume
non perturbé sur le volume total en fonction du diamètre
du grain (en mm) sont:
A= -1,86E-07
B= 9,86E-05
C= -1,73E-02
D= 1
Compacité calculée de l'échantillon= 0,6283
Avec pour indice de compaction 9

Compacités propres de la forme: 0,0*d+0,43

Diameter (µm)	Passing (%)	Mean diameter (µm)	Packing density
50	0	56,125	0,43
63	9,8	70,993	0,43
80	10,9	89,443	0,43
100	12	111,803	0,43
125	13,2	141,421	0,43
160	14,5	178,885	0,43
200	15,7	223,607	0,43
250	17,3	280,624	0,43
315	18,9	354,965	0,43
400	21,2	447,214	0,43
500	23,3	561,249	0,43
630	26	709,93	0,43
800	29,9	894,427	0,43
1 000	33,5	1118,034	0,43
1 250	38,8	1414,214	0,43
1 600	44,7	1788,854	0,43
2 000	50	2236,068	0,43
2 500	58,1	2806,243	0,43
3 150	66,5	3549,648	0,43
4 000	74,5	4472,136	0,43
5 000	87,2	5612,486	0,43
6 300	97,8	7099,296	0,43
8 000	100		

Limestone "Le Boulonnais" 10mm/20mm

Nom du matériau: calcaire.mat:\10/20

Masse vol.: 2670 kg/m3

Compacité expérimentale de l'échantillon= 0,574
Cette mesure a été effectuée en milieu confiné
Les paramètres du polynome P(x)=Ax^3+Bx^2+Cx+D
exprimant le rapport du volume
non perturbé sur le volume total en fonction du diamètre
du grain (en mm) sont:

A=	-1,72E-07
B=	9,41E-05
C=	-1,69E-02
D=	1

Compacité calculée de l'échantillon= 0,574
Avec pour indice de compaction 9

Compacités propres de la forme: 0,0*d+0,5612

Diameter (µm)	Passing (%)	Mean diameter (µm)	Packing density
5 000	0	5612,486	0,5612
6 300	1	7099,296	0,5612
8 000	1,87	8944,271	0,5612
10 000	5	11180,34	0,5612
12 500	38,52	14142,14	0,5612
16 000	69,44	17888,54	0,5612
20 000	96,01	22360,68	0,5612
25 000	100		

Fly ash

Nom du matériau: calcaire.mat:\cendre volante

Masse vol.: 2160 kg/m3

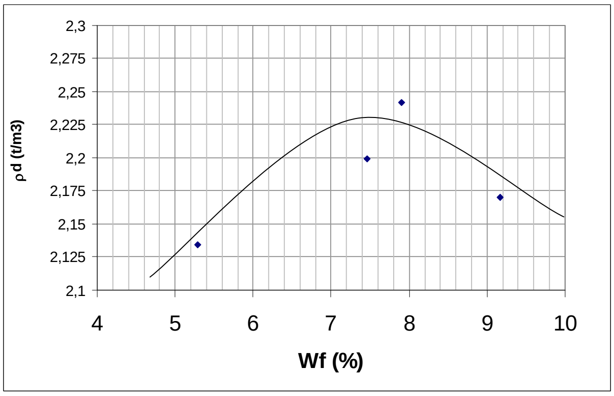
Compacité expérimentale de l'échantillon inconnue
Compacité calculée de l'échantillon= 0,6065
Avec pour indice de compaction 6,7

Compacités propres de la forme: 0,0*d+0,43

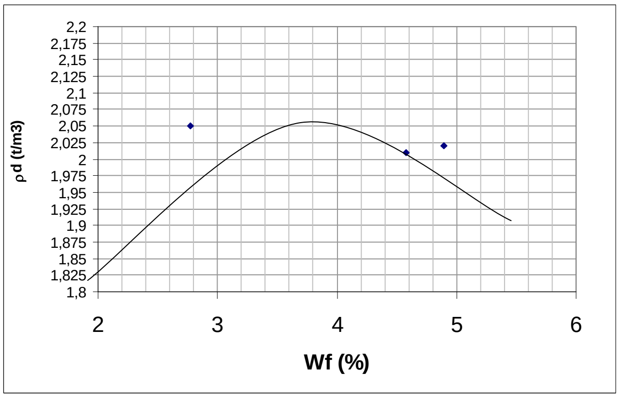
Diameter (µm)	Passing (%)	Mean diameter (µm)	Packing density
1	0	1,118	0,43
1,25	3,8	1,414	0,43
1,6	4,8	1,789	0,43
2	5,6	2,236	0,43
2,5	6,2	2,806	0,43
3,15	6,9	3,55	0,43
4	7,7	4,472	0,43
5	8,7	5,612	0,43
6,3	10,2	7,099	0,43
8	12,4	8,944	0,43
10	15,1	11,18	0,43
12,5	18,6	14,142	0,43
16	23,3	17,889	0,43
20	28,3	22,361	0,43
25	33,9	28,062	0,43
31,5	40,4	35,496	0,43
40	47,6	44,721	0,43
50	54,6	56,125	0,43
63	62,2	70,993	0,43
80	70	89,443	0,43
100	76,9	111,803	0,43
125	83,3	141,421	0,43
160	89,2	178,885	0,43
200	93,5	223,607	0,43
250	96,6	280,624	0,43
315	100		

Annex E3

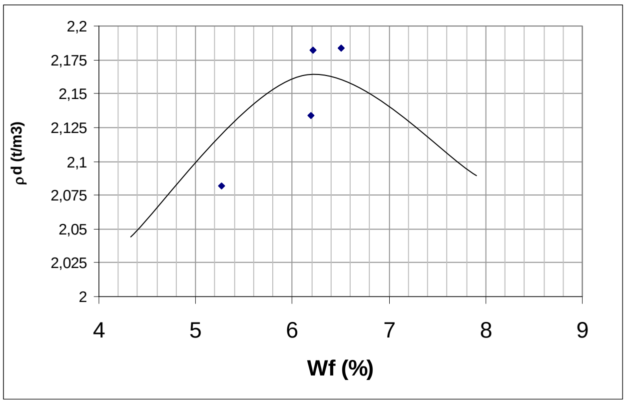
Proctor curves



F1



F3



F5