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Waste paper ash as an alternative binder to improve the bearing capacity of road subgrades

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ABSTRACT: The interest on alternative hydraulic road binders to replace cement is increasing these days aiming at reducing the carbon footprint of road projects. The PaperChain project, an EU funded project under the H2020 programme, tackles the use of one of these binders, Waste Paper Fly Ash (WPFA), a waste stream coming from the energy recovery of paper rejects and sludge, as alternative binder for subgrade stabilisation and cement-modified subbase layers. WPFA has been extensively tested at laboratory scale and demonstrated at real scale in three field tests covering the three types of stabilised soils recognised in the Spanish Road Regulations, complying with all technical requirements. Nonetheless, the complete replacement of cement by WPFA is a challenge from the design point of view. This paper focuses on the construction and monitoring of one of those cases, specifically the one allocated for the pavement subgrade with the highest bearing capacity. Pairs of cement and WPFA-stabilised laboratory specimens have been tested showing a different hardening pattern and different reaction modulus evolution. Field-testing (load plate tests) and compressive resistance results confirmed this trend. These differences can result in positive effects on cracking development thanks to the slower hardening speed during the first days but the current design values should be reviewed when applied to WPFA, given the notable differences expected over the long term.

Keywords: Waste paper ash, alternative binder, stabilized soil, road subgrade, monitoring

1 INTRODUCTION

The subgrade is a stable and uniform platform for the overlying pavement structure of a road. To meet these properties of stability and uniformity, the subgrade depends on the bearing capacity and the resistance to volumetric changes of the soil used. Subgrades are built, in principle, with the native soils of the road area, but when they do not meet adequate minimums, they must be avoided or improved to ensure good performance of the pavement. Among the most common solutions is the replacement and stabilization of poor quality soils.

The Guide prepared by Jones et al (2010) for the State of California, recognizes 4 types of stabilization: mechanical, cementitious, asphalt and non-traditional with additives. Mechanical stabilization consists of improving the resistance of the structure by compaction, although it can also be done by mixing with other better quality soil. Cementitious stabilization consists of adding cement or lime to increase the bearing capacity of the poor soil (using cement) or to reduce the high plasticity of a clay (using lime). Other alternative cementitious stabilizers are

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fly ash, cement kiln dust, lime kiln dust, and ground-granulated blast furnace slag. Stabilization with asphalt binders (emulsions, foamed asphalt and cutbacks) is not so common because it is more often used with well graded soils with a low percentage of fines, with the purpose of building flexible and water resistant platforms. And there are also the non-traditional additives, such as chlorides, polymers, resins, synthetic emulsions and sulfonated oils. Some of them act as dust palliatives and do not provide enough strength to be considered as a soil stabilizer.

In the specific case of fly ash, the object of study in this paper, the pozzolanic reaction when mixed with the soil increases the strength although this increase cannot be generalized since the composition of fly ash is variable depending on its source. There are previous studies on the use of fly ash for road stabilization, thanks to the high content of calcium oxides and silicates that provide pozzolanic properties and increased compressive strength to the soil, such as those conducted by Mulder (1996), Lahtinen (2005), Tuncan (2000), Zhou (2000), Zuber (2013), Ohenoja (2020). It has also been confirmed that thaw resistance and bearing capacity are improved when fly ash is used, Vestin (2012), Zhang (2019), Wang (2016), Arm (2014).

When talking about fly ash stabilization, some researchers like Lahtinen, (2001) classify fly ash (FA) with different abbreviations according to the fuel used. It is usually called CFA for coal fly ash, PFA for peat fly ash, WFA for wood fly ash, and MFA for miscellaneous fly ash (e.g., fly ash from the combustion of mixed fuel like fibre sludge and wood).

One of the sources of fly ash is the paper industry, which currently produces a significant amount of municipal solid waste. While the demand for printed books and newspapers has recently decreased due to digital media substitution, (Hänninen, 2014), the consumption of other types of products, such as tissues or packaging, have greatly increased (Cherian, 2019).

Much of the ash from this industry (WPFA) goes to landfill, causing a significant economic impact for producers. For this reason, the pulp and paper manufacturing sector in Europe has been developing many alternative products in order to achieve a circular economy. Among the most outstanding studies, it is worth mentioning the research program called Environmentally friendly use of non-coal ashes, also known as "the ash programme" developed by the Swedish Thermal Engineering Research Institute (Ribbing, C., 2007), in order to increase knowledge on the by-products of energy producers and their application. The results obtained allowed the elaboration of a handbook for using these ashes in unpaved roads.

The PaperChain project, an EU funded project under the H2020 programme, tackles the use of Waste Paper Fly Ash, a residue coming from the energy recovery of paper rejects and sludge, as alternative binder for subgrade stabilisation and cement-treated pavement layers.

This paper focuses on the construction and monitoring of one of the three Spanish field trials executed in Spain under the Paperchain framework (The paperChain Project, 2017), which consists of a stabilised soil for a subgrade of a paved periurban road.

2 OBJECTIVE

The study aims at describing and construction and monitoring of one of the pilots constructed to demonstrate the technical, environmental and economic feasibility of using WPFA as an alternative hydraulic road binder instead of cement commonly used in the different stabilized soil layers foreseen in the Spanish Road Pavement Catalogue (Ministerio de Fomento, 2003).

This pilot was built in Villamayor de Gállego (Zaragoza, Spain), in a section of a periurban road of 1,000 m long and 5.7 m width with no records of heavy traffic intensity but busy with heavy agricultural vehicles and trucks trafficking to avoid the centre of the village to access the local service area. The solution consisted of a layer stabilized with ash as a substitution of a conventional stabilized soil with cement type 3 (S-EST3, according to the Spanish Road Regulations, Ministerio de Fomento, 2015). In order to provide a more comfortable and at the same time, economical surface, a double bituminous treatment was performed over the improved subgrade, Figure 1.

Figure 1. Schematic solution for the pilot built in Villamayor de Gállego.

3 MATERIALS AND JOB MIX FORMULA

The soil was characterised prior to its treatment and then, mixed with different rates of WPFA in order to define the job mix formula. This soil met the specifications to be stabilized according to the Spanish requirements. Maximum dry density from Modified Proctor test (EN 103501) was 2.047 g/cm3 t/m^3 and optimum moisture content was 10%. The WPFA composition is described in section 5.1. The Spanish requirements for the stabilization with cement and the results obtained with the WPFA are collected in Table 1.

At laboratory scale, compressive strength tests allowed to obtain this formula with 5% of WPFA and 8.2% of water, taking into account a different compaction procedure with respect to that used in the cement stabilization. In this case, a 30-minute delay time is necessary to be applied before compaction and the compaction degree must reach the maximum Modified Proctor density, instead of the 98% required for the conventional solution. (Baloochi et al., 2020). Complementary leaching and durability tests (wetting/dry cycles) were also carried out with the objective of ensuring the adequate long-term behaviour of the layer.

A mixture of soil and cement was also designed for the reference section, with 3% of cement type CEM IV/B (Q) 32.5N and 7% of water. These specimens were compacted up to 98% of the corresponding maximum Modified Proctor density and no delay time was applied.

Table 1. Spanish requirements for S-EST3 stabilised soil with cement and results with WPFA.

Characterization	Unit	Standard	S-EST3 (with cement)	Stabilized with WPFA
Unconfined compressive strength at 7 days	MPa	UNE-EN 13286-41	≥ 1.5	≥ 1.5
Density (Modified Proctor)	% of max density	UNE 103501	≥ 98	98
Organic matter	% of mass	UNE 103204	< 1	0.08
Soluble sulphate	% of mass	UNE 103201	< 0.7	0.04
Atterberg limits	-	UNE 103103 + UNE 103104	Liquid Limit ≤ 40 Plasticity Index ≤ 15	Non plastic
Particle size	% pass through #sieve	UNE-EN 933-1	#80mm = 100% #2mm > 20% #0.063mm <35%	#80mm = 100% #2mm = 32% #0.063mm = 9%

4 CONSTRUCTION

Due to the heterogeneity of the materials in the road section, it was necessary to remove 10 cm of the original surface layer and replace it with the borrowed pit soil, which was levelled and compacted simulating an *in situ* soil for S-EST3 stabilisation with cement (Figure 2).

Figure 2. Milling procedure of the original surface and levelling process of the borrow soil.

Then, the experimental field trial was executed following the job mix formula determined in the laboratory. The WPFA was spread out with a dosing machine and mixed with the underlying soil (in a depth of 25 cm) by the stabilizer (Figure 3), after which the compaction and levelling tasks went on. Four passes of a standard vibratory roller compactor were applied and a grader passed to level the surface. Then, a final pass with the roller compactor on static mode was applied to get smoothness. Immediately after the final compaction, a double bituminous treatment was laid out generating a protective surface layer.

Figure 3. Stabilizer and dosing machinery.

In order to evaluate the quality achieved in the section, samples were taken from the mix spread and compacted. Table 2 collects the results of the Unconfined Compressive Strength (UCS) after 7 days of specimens moulded with these samples at 98 % of the maximum dry density (modified proctor test) and the modulus calculated after performing the load plate test on the field trial.

Table 2. Quality control results of the experimental section.

Test	Requirement	Stabilized soil with WPFA
Unconfined compressive strength after 7 curing days (MPa).	≥ 1.5	1.8 (average)
Load plate test at 14 days (diameter 300 mm) as a function of the subgrade type (MPa)	Ev2 > 60 for subgrade E1 Ev2 > 120 for subgrade E2 Ev3 > 300 for subgrade E3	Ev2 > 334 (average) ⇒ subgrade E3

5 MONITORING

5.1 *Environmental monitoring*

The Environmental Monitoring Plan (EMP) was stated according to the results of a preliminary environmental risk analysis based on the following findings:

a) Determination of the environmental base line, taking samples from vegetation, soils and surficial waters from the road surroundings (Figure 4). Gathering of relevant information about the groundwater and irrigation water quality.
b) Chemical composition of WPFA, paying attention to the resulting concentrations of elements of concern at the defined WPFA dose rates (5 %) in the stabilised soil. The results were compared against the Generic Levels of Reference (GLR) for the soils of Aragon (Departamento de Medioambiente Aragón 2008), in order to assure that the threshold limits for the "urban uses" category were not surpassed.
c) Pathways of WPFA distribution. Air dispersion during WPFA spreading works and at a lesser extent, water transport through runoff along the roadsides during the service life.
d) Potential receivers of the WPFA along the road life cycle, mainly workers during building.

According to these premises, the EMP included sampling and analysis of construction materials (borrowed soil and WPFA), surrounding natural soils, vegetation (dust on leaves) and finally, ground and surficial waters before and after the pilot construction. Samples from the stabilised layer were also taken one month later to determine their leaching properties and the trace elements content. A piezometric network was also built in order to control the leaching properties evolution beneath the stabilised layer (3 piezometers, 2m deep) and three more boreholes were drilled up to 10 m deep aiming at controlling potential impacts in groundwater levels originated by irrigating waters (Ebro River Quaternary alluvial is too distant, 60-70 m below the road surface). Table 3 compiles the material tested, the purpose of the testing and the type of sampling conducted.

Table 3. Summary of the EMP. Sampling and testing strategy.

Material	Purpose	Sampling & testing strategy
WPFA	Comparison of the used WPFA against the historic chemical variation identified.	Total content of elements of concern Daphnia toxicity test and leaching tests
Borrowed soil	Soil baseline. Chemical characteristics of the untreated soil.	Total element content (elements of concern) and leaching tests according to (EN-12457-4. 2 samples taken before building works.
Stabilised soil	Chemical characterisation of the stabilised layer and its variability.	Concentration of elements of concern Leaching test according EN-12457-4. 1 sample from the stabilised layer
	Forecast over the long term of the stabilised soil layer, risk assessment.	3 boreholes drilled along the road. 1 sample from each one.
Soil (roadsides and surrounding crop areas)	Wind dispersion of WPFA particles to the nearby soils. Before building (baseline) and after	Total element content. Soil quality control along roadsides (<2 m). 10 samples in total.
Vegetation	Impact control by WPFA dust on the vegetation.2 sampling campaigns before and after the stabilisation works	Total element content. Sampling of most interesting vegetation for humans (food). 2 points per roadside.
Underground waters	Control of the potential affection to the underground waters.	Total elements of concern content in waters. Three control wells up to 10m depth.
Surficial waters (canals)	Impact control of WPFA dust on surficial waters in irrigation canals near the pilot, sampling before (baseline) and after construction.	Total element content Two sampling points (upstream and downstream) in waters from two canals crossing the pilot road.

The analysis of the trace elements concentration in soils and in dust collected from the vegetation were similar before and after construction works, showing no conclusive differences. Antimony and Vanadium increased around 15 %, Aluminium, Cobalt, Copper in 10 % and Manganese, Barium and Zinc raised a 5 %. The rest of elements remained constant in concentration or diminished. Some of the increments (Antimony, Aluminium, Copper, Barium and Zinc) could be consistent with the relative abundance in WPFA compared with natural soils, although in general, they are below the standard deviation, not being conclusive to prove WPFA dispersion occurred during the construction stage by means of the identified pathways.

Figure 4. Sampling soils after works (baseline definition) and sampling of vegetation before.

The total concentrations of these elements were below the threshold limits set for "urban uses" according to the GLR (Department of Environment of Aragon, 2008).

Leaching of the original components of the stabilised layer and the resulting blend were assessed according to EN-12457-4. The results have been compared with the threshold limits for landfilling laid down in the Royal Decree 646/2020. Finally, a representative leachate could be sampled from two piezometers on January 2020 after a heavy rainfall event (60 mm), being possible to classify the material as inert according to the aforementioned Decree (Table 4).

The WPFA-stabilised material complies with the inert waste criteria except for Antimony, however, the leachate collected in the piezometers showed very low metal mobility. All metals remained below the threshold limits for inert waste when compared with the percolation test.

Table 4. Leaching behaviour of borrowed soil, WPFA and stabilised layer compared against the reference values for inert waste according to Royal Decree 646/2020.

Anions/cations (Mg/kg dry mass)	Borrowed Soil (mean)	WPFA	Stabilised Layer (SL)	Cores from SL (mean)[1]	Leachate piezometer (mean)[2]	Reference for inert waste Agitation L/S=10 l/Kg (mg/l)	Percolation[3]
Chlorides	<50	12000	761	911±117	272	800	450
Fluorides	<5	6.2	<5	<5	0.17	10	2.5
Sulphates	<50	62.2	<50	78.5±3.1	629	1000	1500
Antimony	<0.01	0,041	0.19	0.23±0.02	0.009	0.06	0.01
Arsenic	<0.01	<0,05	<0.01	<0.01	0.009	0.5	0.06
Barium	0.335	98	1.4	3.2±2.3	0.05	20	4
Cadmium	<0.01	<0.004	<0.01	<0.01	< 0.001	0.04	0.02
Cobalt	-	-	-	-	< 0.02	-	-
Copper	<0.2	0.26	0.37	0.23±0.04	0.16	2	0.6
Chromium	<0.2	0.13	0.31	0.30±0.02	<0.005	0,5	0.1
Mercury	<0.01	<0.0005	<0.01	<0.01	< 0.0005	0.01	0.02
Molybdenum	<0,2	0,18	<0,2	<0,2	< 0.02	0,5	0.2
Nickel	<0,2	<0,1	<0,2	<0,2	<0.005	0.4	0.12
Lead	<0,2	0,40	<0,2	1.13±0.67	0.018	0.5	0.15
Selenium	<0,05	<0,039	<0,05	0.07±0.01	-	0.1	0.04
Zinc	<0,2	0,21	<0,2	<0,2	0.10	4	1.2

1) Mean of 3 core samples from the stabilised layer. 2) Mean of 2 samples from piezometers. 3) EN 14405.

5.2 *Technical monitoring*

5.2.1 *On-site inspection*

Two inspections were performed from October 2018 to February 2020. The first one (6 months after completion) showed no damages related to a WPFA malfunction. Some defects were occasionally observed associated with joints. The pavement was observed in good condition 15 months after completion during the second inspection, although some minute defects like potholes and loose aggregates not related with the stabilization itself were seen (Figure 5). Some transverse cracks were observed every 4 m in the reference section of stabilized soil with cement. In the section with WPFA no cracking and swelling were seen

Figure 5. Cement stabilized stretch (1) and WPFA stretch (2) showing a joint. Bituminous treatment integrity (3) and potholes in the joint (4).

Two years after the road construction, new plate load tests were carried out in the same points showing an average raise of 17 % of the static modulus in the WPFA stretch, up to of 336 Mpa on average. The static modulus of the cement-treated stretch was 711 Mpa, half of the modulus obtained two years before (1500 Mpa), most probably, an anomalous value.

5.2.2 *Laboratory testing*

The laboratory technical monitoring comprised three types of testing with specimens manufactured with the materials taken from the construction site and under the placement conditions. These specimens were preserved in a climatic chamber for curing and then tested at different ages in order to evaluate: a) the strength evolution of the stabilized soil; b) durability analysis: swelling/shrinkage and c) X-Ray diffraction analysis.

5.2.3 *Strength evolution of the stabilised soil*

To study the strength evolution of the mixtures of soils and WPFA or cement, specimens were prepared and tested at different ages, according to standards EN 13285-41, after curing them in a moist room with 95% humidity at 20°C.

Considering the mechanical property required by the Spanish Specification, the results show that both stabilized soils, with WPFA and cement, were able to achieve a compressive strength higher than 1.5 MPa after 7 days. In the case of the stabilization with WPFA, the effect of curing time on the compressive resistance was not significant. The soils used for this study had no plasticity but it is important to highlight that the organic matter content of the stabilized soil was considerable high, what could be a potential obstacle for the strength increase.

5.2.4 *Durability of the stabilized soil*

Durability can be affected when the stabilized soil is exposed to a sulfate source. This source may come from runoff through the pavement surface or from the groundwater if the underlying soil is rich in sulfate. Calcium and aluminum oxides present in the binder (cement or ash) react with water containing sulfate leading to expansion. To carry out the durability analysis of the soil using WPFA, a new experiment was carried out.

The Spanish Specifications for Roads and Bridges (PG3) indicate an analysis of the free swelling of soil prior to the stabilization, according to UNE 103601 standard; however, this type of test is specific for plastic soils with fine particles and so, not appropriate for the soil used in this pilot, which did not show any plastic behavior. Therefore, a novel test was developed for measuring the vertical swelling or shrinkage under horizontally confined conditions when subjected to dryness/humidity cycles as well.

This experiment is carried out to measure the displacement in vertical axis in a confined system using PVC molds. The job mix formula is reproduced with a representative soil sample, 5% WPFA, 8.2% water and the application of a delay time of 30 minutes. After the delay time passes, the material is poured into a cylindrical PVC mold and compacted in 3 layers with a vibrocompactor until reaching the reference density. Then, a metal lid and small balls are placed inside it to have a uniform surface. Then the samples are cured at 20°C and 95% RH for 7 days and after that, put in a bath with water at 20ºC to allow water absorption, as shown in Figure 6.

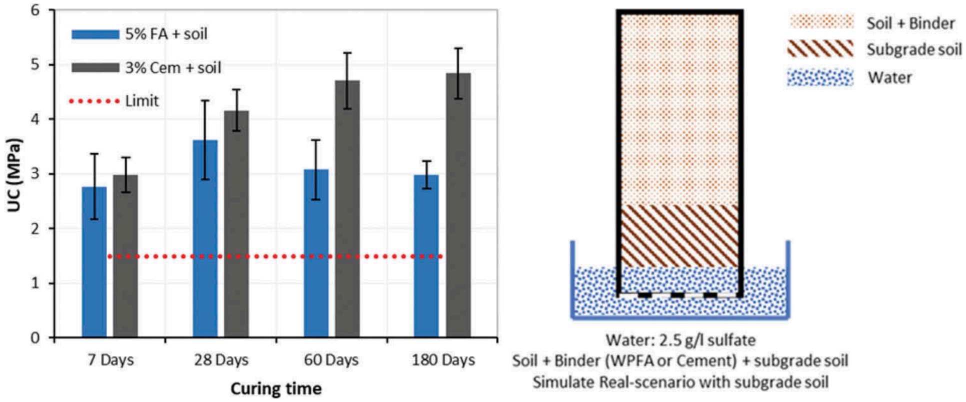

Figure 6. UCS evolution (left). Test scheme for evaluation of swelling or shrinkage (right).

The water in the bath contained a sulfate concentration of 2.5 g/l, simulating on site conditions. The height and weight increases were measured up to 200 days. Figure 7 shows the results obtained for the samples with WPFA and cement, subjected to the aforementioned sulfate concentration solution, placed over a subgrade layer. Despite the weight increase due to water absorption, no swelling was detected and a small shrinkage was measured instead.

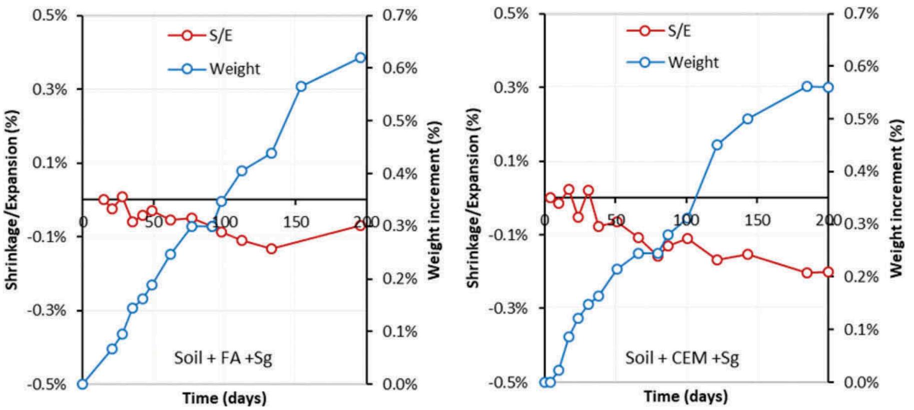

Figure 7. Weight and displacement evolution for samples with FA (left) and cement (right).

5.2.5 *X-ray diffraction analysis of stabilized soil in presence of sulfates*

This study puts in contact the components of the stabilised soil with a sulfate source and analyze by XRD at 14, 30, 90 and 180 days at 20ºC the minerals resulting from this interaction which may be damaging for the overall structure of the road pavement. For this purpose, the mixtures of soil, cement and WPFA are ground to a particle size smaller than 63 µm with the aim of accelerating the chemical reactions when they are subjected to the sulfate attack. The sample conditioning uses the same amount of sulfate and same temperature of the previous test.

The slow formation of ettringite (common cause of swell), is observed in WPFA and cement samples. As can be seen in Figure 8, the XRD spectrum intensity in the ettringite angle are similar in both samples. However, perhaps samples with WPFA have higher available Ca and Al, which could foster the reaction. Another reason for the slower ettringite formation rate in the cement specimens could be due to the cement type IV used, which is high in pozzolans, preventing from sulfate attack.

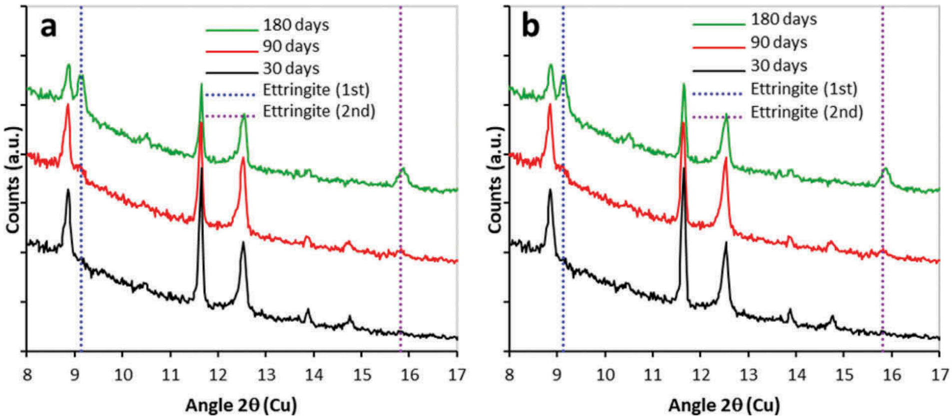

Figure 8. XRD difractograms for samples with FA (a) and cement (b).

6 CONCLUSIONS

After confirming the cementitious properties of WPFA, it was used as a substitute of cement in a stabilized soil aiming at improving the subgrade bearing capacity of a road. An experimental section was built and monitored from a technical and environmental point of view.

The results achieved in laboratory and onsite monitoring showed higher strength and modulus than those specified in the Spanish regulations, which allows to state that WPFA is an alternative hydraulic binder. However, it is important to avoid mixing with soils with a high sulphate content, since the formation of ettringite is highly favourable.

Regarding the environmental monitoring, the mixture with WPFA meets the criteria to be considered inert except for Antimony; although the leachate collected onsite indicated that all metals remained below the threshold limit for inert classification.

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