Implementation of Circular Case 2

D5.3 - February (M33)

Authors: *Roberto Orejana, Juan José Cepriá, Asier Oleaga, Hani Baloochi, Diego Aponte, Adriana Martínez, Marilda Barra*

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0. Executive summary

The three pilots that cover Circular Case 2, corresponding with the three types of stabilised soil layers included in the Spanish road regulation; S-EST2, S-EST3 and Soil-cement are described in this deliverable. Geographycal location, pilot design, the execution of the works and the monitoring planned and performed are described along the document.

S-EST2 has been demonstrated in a 1 km long pilot in Ejea (Zaragoza). The pilot was built with a 3 % of WPA blended with the natural soil with the objective of improving the bearing capacity. 0.1 km were performed with the conventional solution (3 % of hydrated lime) for benchmarking purposes. The quality control plan carried out has demonstrated a proper technical performance, even slightly better than with the standard solution. The environmental monitoring did not find any affection after comparing the initial status (baseline) and the condition after the works.

S-EST3 was executed in a 1.0 km long field trial in Villamayor (Zaragoza) where 0.1 km were carried out with the conventional solution (3 % cement) and the rest with a 5 % of Waste Paper Ash (WPA). The trial has demonstrated a proper technical performance, fullfiling all technical requirements compiled in the Spanish Road Regulation (PG3). Monitoring showed a proper technical performance with no damages after one year and a half after construction. Durability seems to be good, as no effects appeared at field and lab scale related to swelling and shrinkage, although certain susceptibility to ettringite formation was measured. From an environmental point of view, no changes in chemical composition was clearly observed comparing soils, waters, vegetation of the pilot surroundings.

Soil-cement pilot was recently finished in La Font de la Figuera (Valencia), although the covering asphalt layers are pending of completion. During construction stage, no relevant differences were observed with respect to the standard solution (3 % of cement addition). In this case, 0.560 m long field trial has been executed with a 5.2 % of WPA addition. Quality control points out that all technical requirements has been fulfilled. From an environmental point of view this pilot was identified as little sensitive, as the layer is completely isolated from the atmospheric conditions between asphalt pavement and the bitumen emulsion curing coat placed on top of the subgrade.

Keywords

Soil Stabilisation	Soil cement	S-EST2	S-EST3	Durability
Environmental Risk Analysis	Swelling	Shrinkage	Bearing capacity	Leaching
Inert	Compressive Strength	Stiffness	Load test	

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Abbreviations and acronyms:

WPBA: Waste Paper Bottom Ash

WPFA: Waste Paper Fly Ash

PPI: Pulp and Paper Industry

QA: Quality Assurance

S-EST2: Estabilised soil type 2

S-EST3: Estabilised soil type 3

CBR: Californian Bearing Ratio

MDD: Maximum Dry Density

OMC: Optimum Moisture Content

PRA: Preliminary Risk Assessment

LCSA : Life Cicle Sustainability Assessment

UCS: Uniaxial Compressive Strength

GLR: Generic Levels of Reference

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1. Introduction

ACCIONA and SAICA, pulp & paper company that generates the WPA, have been cooperating for the last five years to find an alternative and sustainable solution for the fly and bottom ash they produce at their waste to energy plant located in El Burgo de Ebro (Zaragoza, Spain). From the very beginning, it was intended to use this ash as to replace cement and lime in soil stabilised road layers due to its chemical properties.

After having enough data at laboratory scale and small field trials, there were certain confidence of its technical feasibility, but the legal situation seemed to block the valorisation.

This Circular Case aimed at unblocking the past situation by completing the research and demonstrating in real operation environments large-scale demonstrators that help all the actors to understand the material, adjust the use and convince potential technology adopters.

Three pilots were planned corresponding with the main three cement/lime stabilised road layers foreseen in the Spanish Road Regulation (PG3), i.e. S.EST2, S-EST3 and Soil Cement layer.

The pilots have been conducted in long stretches of real operating roads from the less complex (an unpaved road) to the most exigent (a highway) in order to cover the three named layers and the potential applications in different type of roads and traffic conditions.

1.1. Objectives

The project aims at demonstrating the technical, environmental and economic feasibility of using WPFA as an alternative hydraulic road binder instead of cement and lime commonly used in the different stabilized soil layers foreseen in the Spanish Road Regulation (PG3).

This project is definitively market-oriented and the final target is to reach the market, for this purpose, most of the activities have been designed to show that this material can be used effectively in real operating environments in order to overcome the reluctance towards secondary raw material of many of the actors involved in the value chain.

This reluctance comprises most of the actors of the value chain, including;

- The main users (builders), who are used to manage the same binders (cement) and do not feel comfortable with changes, as changes of normal procedure usually implies lower productivity because of the need of expend some time in getting expertise (learning curve).
- Final users, normally the public administrations that receive the final infrastructure. They are usually concerned about quality and durability of the structure, as responsible organism in charge of getting the best value for the taxpayers.
- Environmental authorities, which normally associate waste to pollution and apply the precautionary principle extensively.

The demonstration activities try to involve all the actors of the value chain, in an open innovation process where all the aspects can be shared to reduce reluctance and cooperate to improve the solution from all the perspectives.

For this reason, the pilots have been built in real conditions and use, following standard construction practices and using the same equipment and machinery as for regular soil stabilization works. By this strategy, the impact of the new product in the productivity can be measured and improved and the builders can evaluate in a better way the advantages and disadvantages of the proposed application. Productivity can be measured and compared and the impact in terms of potential economic savings can be calculated more precisely thanks to the scale of the pilots.

The pilots are submitted to the traffic and everyone can observe the technical performance of the new solution. Durability is a key issue in this sector so that, both onsite monitoring and laboratory specimens must be kept to demonstrate the proper durability aspects of using WPA.

Finally, assessing WPA environmental performance is necessary in order to demonstrate to the general audience and to the environmental authorities the feasibility of its use and its harmless nature.

In detail, these general objectives comprise:

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- To adjust the present testing procedures to the nature of these ashes, creating new protocols adapted to their behavior and proposed use.
- To understand their chemical composition and variation along time, stablishing potential treatments for their valorization and quality assurance protocols.
- To identify the differences between this material and the standard ones (cement, lime) and the effect in the construction stage, stablishing modifications and adaptations in the execution procedures in order to optimize the ashes 'properties.
- To calculate the impact of the new materiales on the productivity and efficiency during the construction stage.
- To determine the final cost of the whole operation for all scenarios.
- To identify the leaching quality of the stabilized soil along time, seeing the aging effect on the metals fixation. Furthermore, the leaching properties is measured on site to identify the potential environmental impact in different environments.
- To assess the environmental benefits of replacing cement and lime by WPA through an LCSA using the data gathered in the pilots.
- To check the technical performance and durability of the new solutions by monitoring the pilots along time, both on site and in samples and specimens obtained during the trials execution.
- To engage all the relevant players and stakeholders during the pilot´s execution.

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1.2. Pilot´s location

Three pilots have been built in Eastern Spain; Ejea de los Caballeros (Zaragoza), Villamayor de Gállego (Zaragoza), and La Font de la Figuera (Valencia).

The first two pilots were a renovation of a previous road and the third one was executed in a construction project of the ACCIONA´s portfolio.

TABLE 1. SUMMARY OF THE PILOTS´ CHARACTERISTICS.

Stabilized road layer	*Location*	*Type of road*
S-EST2	Ejea de los Caballeros (Zaragoza)	Unpaved rural road
S-EST3	Villamayor de Gállego (Zaragoza)	Paved periurban road
SOIL-CEMENT	La Font de la Figuera (Valencia)	A31 Highway

The three pilots correspond with the three main type of stabilized soil road layers differentiated in the Spanish regulation.

FIGURE 1: GENERAL LOCATION OF THE PILOTS.

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1.3. Regulatory framework of Spanish stabilised road layers

The Spanish Ministry of Public Works and Transport is responsible for preparation and implementation of government policy on land transport infrastructure. Thus, they published the **"*General Technical Specifications for Roadworks and Bridges (PG-3)*"** (PG-3, 2014), the reference law for the road construction sector, and particularly these two articles of its content:

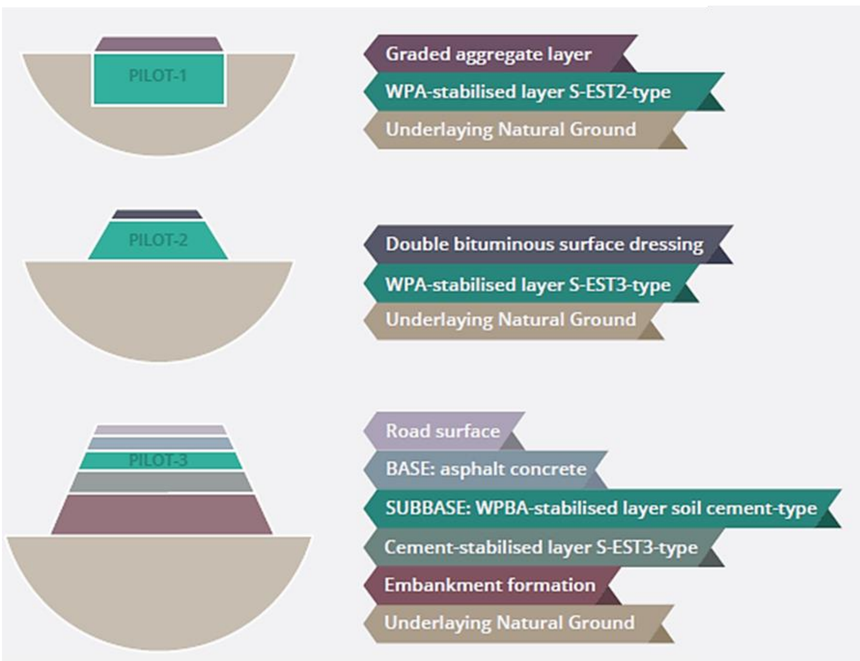
- Article 512: "*In situ stabilised soils*"
- Article 513: "*Cement-treated materials (cement-stabilised soil and cement-bound graded aggregate)*"

The cited articles described four potential stabilised soil layers depending on the technical requirements, position within the road section and type of starting soil to be stabilised. Table 2 reflects these relationships:

TABLE 2. SCHEMATIC RELATIONSHIP BETWEEN THE DIFFERENT STABILISED LAYERS, LOCATION AND REQUIREMENTS

S-EST1	In situ stabilised soil type 1	Stabilised soil for subgrade formation	↓ greater mechanical requirement
S-EST2	In situ stabilised soil type 2		
S-EST3	In situ stabilised soil type 3		
SC	Soil-cement	Road subbase material	

FIGURE 2: LOCATION OF THE DIFFERENT STABILISED LAYERS WITHIN THE ROAD SECTION (IN GREEN).



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Stabilised layers S-EST1 and S-EST2 correspond with the subgrade formation. Normally it corresponds with natural soils which are stabilized to improve their bearing capacity and/or to reduce swelling or collapse potential. These soils are normally clays or clayey silts and can be treated with hydrated lime or cement depending on their plasticity. High plasticity soils are treated with lime and low plasticity soils must be treated with cement.

Normally, this layer can form the embankment foundation and sometimes the core too, if there are no better material available. The main requirement is CBR (must be higher than 6 for S-EST1 and 12 for S-EST2 type). Swell or collapse must be eliminated.

High heavy traffic roads normally contain other additional stabilized layer on the embankment crown, like a capping layer. This is the S-EST3 stabilised layer. Sometimes, the overlying layer (the subbase) can be stabilised too, this would be the Soil-cement layer. The main differences with stabilised layers S-EST1 and S-EST2 are:

- The main technical requirement is Uniaxial Compressive Strength (UCS) of cylindrical specimens of stabilised soil after 7 curing days, instead of CBR.
- The stabilised soil is borrowed, must be granular and comply with certain grading.
- The binder has to be cement
- Soil cement requirements are higher than S-EST3 in both, UCS and grading.
- All layers are executed on site with a soil stabilizer machine except for the soil cement that has to be manufactured in a soil cement plant (similar to an already-mix concrete plant) and spread on the alignment with a paver.

Table 3 contains all the technical requirements of the different stabilised layers and the related standards.

TABLE 3. STABILIZED SOILS AND SOIL-CEMENT TECHNICAL REQUIREMENTS ACCORDING TO PG-3

CHARACTERISTIC	UNIT	STANDARD	MATERIAL TYPE			
			S-EST1	S-EST2	S-EST3	SC
Binder content	% by mass of dry soil	-	≥ 2	≥ 3		
CBR at 7 days (1)	CBR	UNE 103502	≥ 6	≥ 12	n/a	
Compressive strength at 7 days (1)(2)	MPa	UNE-EN 13286-41	n/a		≥ 1.5(3)	≥ 2.5 ≤ 4.5
Density (Modified Proctor test)	% of maximum density	UNE 103501	≥ 95(4)	≥ 97	≥ 98	

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Particle size distribution (of the original soil/aggregate)	-	UNE-EN 933-1	(Other prescriptions for original soil blended with cement or lime referred to Standard UNE 103101)			Grading envelope SC40 or SC20 depending on the traffic
Soluble sulphate content (of the original soil)	% by mass of dry soil	UNE 103201	$SO_3 < 0.7$[5] if not, volumetric expansion of stabilized soil after 7 days of immersion in water (UNE-EN 13286-49) < 5% and indirect tensile strength (UNE-EN 13286-42) ≥ 0.2 MPa			[5] (only PG-3 prescription)
Organic matter content (of the original soil)	% by mass of dry soil	UNE 103204	< 2	< 1		≤ 1
Plasticity index of treated material	-	UNE 103103 + UNE 103104	(Other prescriptions for original soil if blended with cement or lime)			Liquid limit < 30 Plasticity Index < 12
Free swelling test	%	UNE 103601	Formation level stabilised soil: 0 at 24 hours if not, 0 at 7 days			n/a
Collapse test at 0.2 MPa of pressure	%	UNE 103406	Formation level stabilised soil: $I_{pc} = 0$ at 24 hours if not, $I_{pc} = 0$ at 7 days			n/a
Layer thickness	cm	-	≥ 25 ≤ 30			≥ 20 ≤ 30
Workability period	hours	UNE-EN 13286-45	Full width procedure: $W_{pc} \geq 2$ Lane by lane procedure: $W_{pc} \geq 3$			$W_{pc} \geq 3$ $W_{pc} \geq 4$
Stabilised-soil moisture at compaction	% by mass of dry components	UNE 103300	± 2% of Modified Proctor test optimum moisture result			-1% / +0.5%
Transverse pre-cracking distance	m	-	n/a			≥ 3m ≤ 4m
Load test of plate soils	MPa (between 14	UNE 103808	$E_{v2} \geq$ 60	$E_{v2} \geq$ 120	$E_{v2} \geq$ 300	n/a

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	and 28 days of age)		E_{V2}/E_{V1} < 2.2	E_{V2}/E_{V1} < 2.2	E_{V2}/E_{V1} < 2.2	
Curing and surface protection of the stabilised layer	-	PG-3, art.:532	Formation level stabilised soil: bitumen emulsion curing coat within the same working day			Within 3 hours of finalisation
Traffic ban after execution	-	-	To light traffic: 3 days To heavy traffic: 7 days			

(1) In order to carry out these tests, the test specimens shall be compacted and stored (Standard UNE-EN 13286-51) at the density specified in the working formula.
(2) Average of the results obtained at least on three test pieces of the same mixture.
(3) For the upper layer of E1 ($E_{V2} \geq 60$MPa) subgrade category defined in Standard "*6.1 IC Pavement Sections*", this value shall be 97%.
(4) In cases where the frost effect could appear, this value may be increased to 2 MPa.
(5) According to PG-3: if SO_3 content by mass soil > 0.5%: employ sulphate-resistant cement. According to TRPDA recommendations: if SO_3 > 0.5%: do not stabilise the soil, if SO_3 > 0.1%: employ sulphate-resistant cement.

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2. Stabilised road layer type S-EST2

This pilot is representative of stabilised road layers type 1 and 2.

2.1. Location

The pilot was built on October 2018. It was built in Ejea de los Caballeros (Figure 3) and consisted in 1 km long field trial of an unpaved road. This road goes from the outskirts of Ejea through a periurban park, mainly used for recreational purposes. The daily average traffic is very low with a minimum contribution of heavy traffic, except for some temporary works on January 2020 when heavy traffic was diverted along this path.

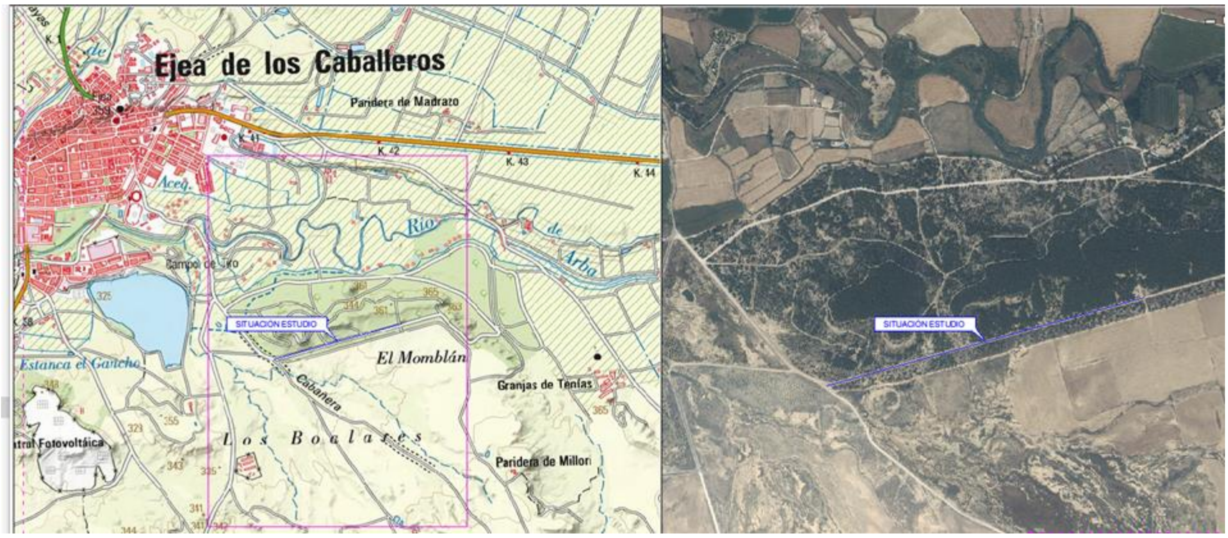

FIGURE 3: Field trial location.

The original unpaved road consisted in roughly 10 cm of graded gravel directly placed on top the clayey surface, locally known as "buro". This clay is well-known in the area for not being arable land due to the poor drainage and especially due to its naturally high salts content.

The municipality of Ejea is one of the largest in the Aragon territory and it has high expenditures in maintenance costs for its extensive network of rural roads, which holds an intense traffic of heavy agricultural vehicles. During rainy periods, animal feeding forces heavy trucks to move along this unpaved roads leading to damages in the clayey areas where water susceptibility is much greater to other areas. This field trial aims at demonstrating the economic feasibility in maintenance costs for this situation.

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2.2. Pilot design

The target stabilised-soil type for this purpose was an S-EST2 type according to Spanish standards. The selected path where the demonstration was conducted had been previously repaired by addition of a thin layer of gravel, so that layer was removed to treat just the clayey soil.

Along 1 km of the path, 7 trial pits were digged to characterise the underlying natural ground and test the working formula with WPFA. The Soil of trial pit 4 resulted with the poorer mechanical properties so, It was used as the base for the working formula (worst possible scenario), shown in Figure 5.

TABLE 4. Laboratory test results on soil samples

LABORATORY TEST	UNIT	STANDARD	STABILISED-SOIL REQUIREMENTS		TEST RESULTS OF SOIL SAMPLES		
			S-EST1	S-EST2	Trial pit 2	Trial pit 4	Trial pit 6
Soaked CBR at 7 days	CBR	UNE 103502	≥ 6	≥ 12		n/a	
Soaked CBR until saturation			n/a		5.4	2.3	10.3
Soluble sulphate content (of the original soil)	% by mass of dry soil	UNE 103201	$SO_3 < 0.7$		0.21	0.10	0.08
Organic matter content (of the original soil)	% by mass of dry soil	UNE 103204	< 2	< 1	0.07	0.13	0.11
Free swelling test	%	UNE 103601	Formation level stabilised soil: 0 at 24 hours if not, 0 at 7 days		0.21	2.94	0.40
Collapse test at 0.2 MPa of pressure	%	UNE 103406	Formation level stabilised soil: $I_{pc} = 0$ at 24 hours if not, $I_{pc} = 0$ at 7 days		0.13	0.48	0.04

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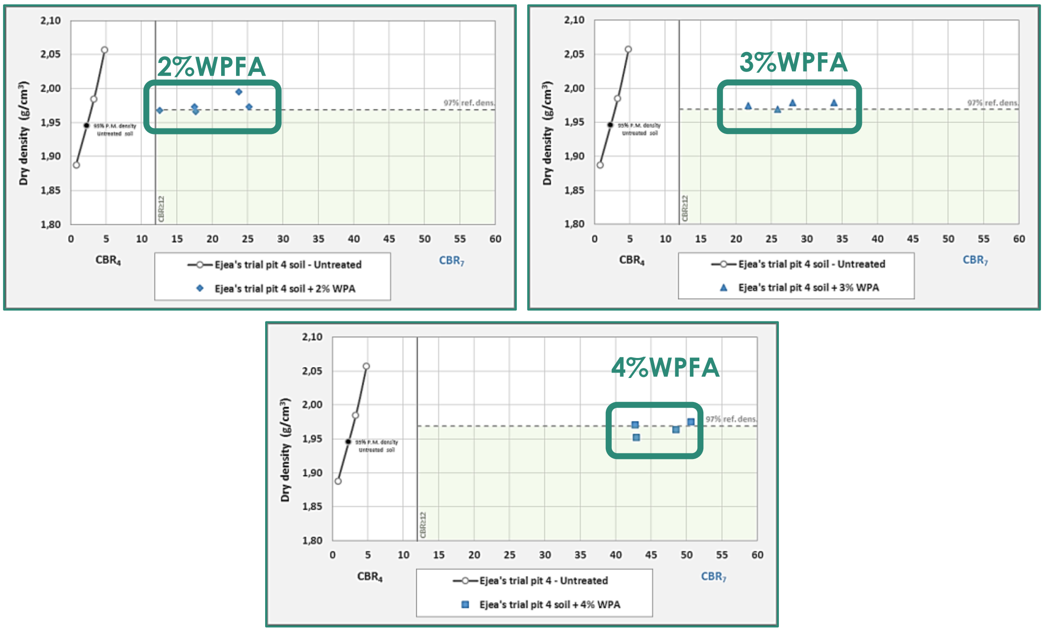

FIGURE 4. CBR soak test at 7 days on Boalares soil samples

All dosages reached the necessary CBR value for considering the soil as S-EST2 type (CBR>12) but 2% WPFA content was discarded in order to adopt a more reliable working formula (3%) for the first trial with this kind of stabiliser.

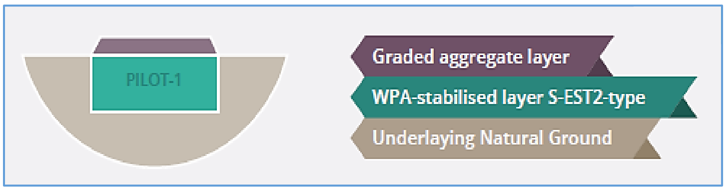

FIGURE 5. Outline of pilot 1 section

The final design was outlined with 25cm-thick of WPFA soil-stabilised layer and the replacement of the 10cm-thick graded aggregate on the surface.

2.3. Pilot execution

As mentioned, the first step of the execution was to remove the layer of gravel ripping and digging 10 cm of the thickness of the path. The ripper device of a bulldozer and a light digger was used for this task.

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FIGURE 6. Original surface (left) and surface after gravel removing

A dosing machine for powdery materials was employed to spread out the accurate amount of WPFA needed to fit the working formula. Then, the stabiliser machine mixed the WPFA with 25 cm of underlying soil meanwhile the optimum water content was being injected. Behind the mixer, a vibratory roller pre-compacted the soil, a grader levelled the layer til the correct thickness and, the roller again, finished the compaction procedure.

FIGURE 7. Soil stabilisation process: 3% WPFA dosing and mixing, levelling and compacting

During the execution, samples of blended material were taken to carry out the laboratory quality control test. The resulting layer was checked with plate load test to measure its bearing capacity. All tests fulfilled the requirement for this type of stabilised soil as shown in the following table.

TABLE 5. QUALITY CONTROL TESTS OF WPFA-STABILISED SOIL S-EST2 TYPE EXECUTION

TEST	ORIGINAL SOIL	REQUIREMENT	WPFA-STABILISED SOIL
Soaked CBR at 7 days	at 95% MDD: **4.2** at 98% MDD: **5.6** at 100% MDD: **6.7**	at 97% MDD ≥ **12**	at 95% MDD: **30** ✓ at 98% MDD: **47** ✓ at 100% MDD: **70** ✓
Load test of plate soils at 14 days (diam=30 cm)	N/A	E_{V2} >60 MPa for subgrade E1 E_{V2} >120 MPa for subgrade E2 E_{V2} >300 MPa for subgrade E3	**E_{V2} >224 MPa** (average) **Improved subgrade E2**

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As a curiosity, a rainfall event occurred a week after stabilisation and previous to the execution of the protection of graded aggregate layer. The performance of the pilot was excellent as shown in the following pics.

FIGURE 8. NATURAL AGED SOIL (1ST), WELL COMPACTED NATURAL SOIL AFTER RAINFALL (2ND) AND WPFA-SOIL STABILISED LAYER AFTER THE SAME RAINFALL (3RD)

The final process consisted of cover the pilot with 10cm of graded aggregate.

2.4. Monitoring

Monitoring covers both environmental and technical parameters, described along the following paragraphs.

2.4.1. Environmental monitoring.

Prior to the commencement of the works, a preliminary environmental risk analysis was conducted by TECNALIA in order to assess any potential harm for the Environment due to the foresee actions to be taken. The report was presented to the regional Environmental authorities and included the preliminary risk assessment (PRA) and the Monitoring Plan (MP).

The PRA was based on a deep analysis of the chemical composition of the ashes, paying an especial focus on the metal content, and the main pathways of ash distribution. The main conclusions were:

- A first list of Pollutant of interest was selected by bibliographical study, as part of the initial WPFA and soil baseline analytical characterization.
- The WPA pollutants content of the ash were below the threshold limits for the Generic Levels of Reference (GLR) for industrial soils. Considering the dose rate of 3 % of WPA in the soil, the GLR remained under the threshold limits for "other uses", category which includes agricultural purposes.
- The main potential pathways for WPFA distribution, and therefore, potential risks, were determined to be associated with air dispersion during the WPFA spreading,

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just before the on-site soil mixing stage. That implies a few minutes to seconds when the WPFA is exposed to the air action, avoiding very windy (>20m/s) or rainy scenarios.

- At a lower extent, the water transport through water runoff in the road margins could also be a transportation pathway, although it appears to be much less sensitive.
- The potential receivers identified were the workers during construction stage and at a lesser stage during maintenance works, workers equipped with appropriate protection cloths. People practicing leisure activities were other group of potential receivers, but no direct contact of the layer with these last ones was expected, and then the risk factor minimum or inexistent.
- Working conditions had to be suitable: absence of important wind (<20m/s) in order to avoid wind spreading, and no rain, to avoid leachates and runoff water.

In general, the conclusion is that the potential risk associated to this demonstration activity was very low, even for very conservative scenarios and for a safety side, and that the PRA granted the absence of potential risks through the working method and conditions, which were optimal, and was confirmed throught the monitoring campaigns associated to the works . The document included an Environmental Plan considering the initial status of the road and its sides and the status after the soil stabilisation works with WPA and monitoring strategy and methodologies. The following samples were analysed:

- 10 soil samples prior the commencement of the works and 10 more after the soil stabilization works in the same sampling points. The maximum distance from the roadside were 2 m.
- 6 soil samples at same points within the road sides before the stabilization works, pre and post works.
- 3 natural soil samples before works, from the natural soil below the stabilized layer, along the road as a reference soil.
- 3 samples of the stabilized soil mix, representative of the spread material volume. Leaching tests with these samples showed values far away from potential impacts for groundwater quality standards.
- 4 samples of the vegetation before and 4 additional vegetation samples after the works to see the accumulation of WPA on the leafs.
- 3 boreholes were also drilled and piezometers were installed to store infiltration water and sample if accumulated after relevant rainfalls. The bores were intended to be used for water tank leachate analysis but the samples were not monolithic enough to be tested by this technique.

The general conclusion is that the potential risk associated to the demonstration activity was very low and there were no need of conducting an Environmental Risk Assessment. The document included an environmental plan considering the initial status of the road and its sides and the status after the soil stabilisation works with WPFA. The following samples were analysed:

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- 10 soil samples prior the commencement of the works and 10 more before the soil stabilization in the same locations. The maximum distance from the roadside was 2 m.
- 6 soil samples within the road sides before the stabilization works.
- 3 natural soil samples from the natural soil below the stabilized layer, along the road.
- 3 samples of the stabilized soil.
- 4 samples of the vegetation before and 4 additional vegetation samples after the works to see the accumulation of WPFA on the leafs.
- 3 boreholes were also drilled and piezometers were installed to store infiltration water and sample if accumulated after relevant rainfalls. The bores were intended to be used for water tank leachate analysis but the samples were not monolithic enough to be tested.

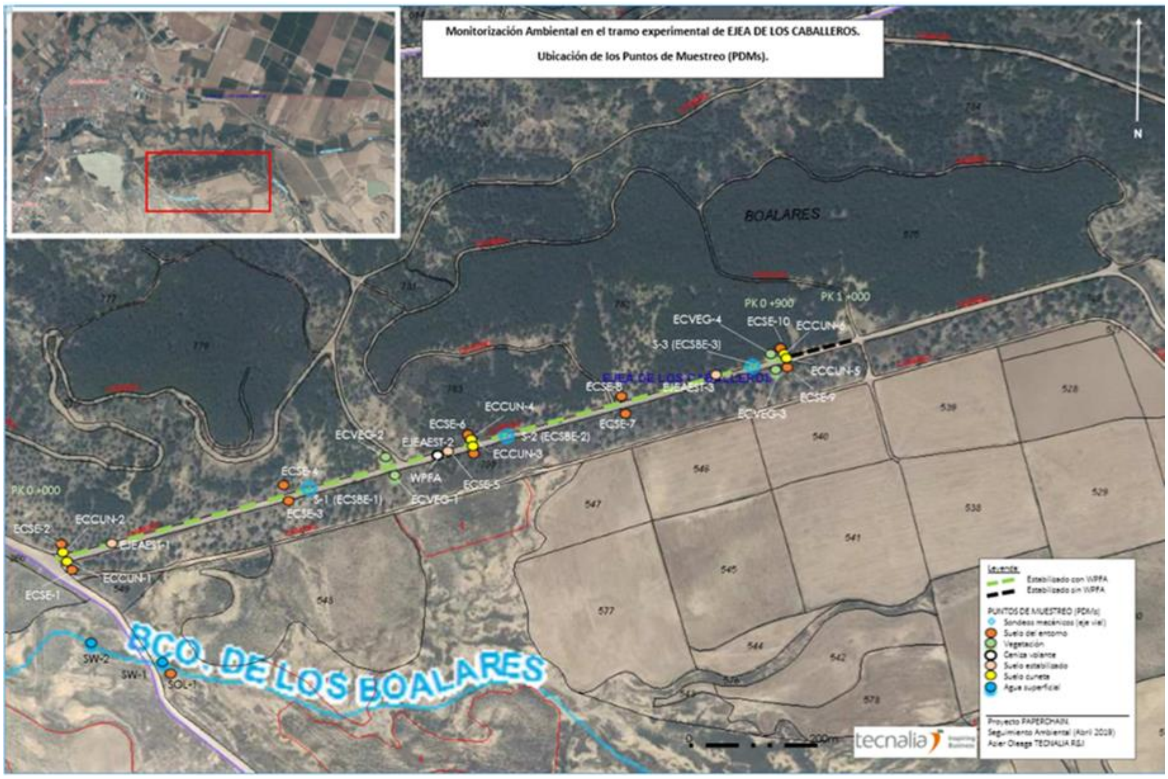

FIGURE 9: LOCATION AND TYPE OF SAMPLING POINTS

The detailed results of this monitoring programme can be found in the document "Monitorización Ambiental Demo Case 2. Ejea de los Caballeros" by TECNALIA, May 2019. In this report, the following conclusions were stated:

- The leaching toxicity of the WPFA was assessed through the "Daphnia Magna test", resulting as "non-toxic".

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- Apart of being rich in chlorides and sulphates, the natural soils used for the stabilization were high in total Aluminum and Beryllium, being higher than the GLR for Aragon. These values are compatible with their clayey nature.
- Stabilised soil: it shows the same trend as for the natural soils, with no values above the GLR except for Aluminum and Beryllium, which is logical according to the aforementioned base mineralogical soil nature.
- Soil from the surroundings: No impact identified
- Soil from the roadsides: No impact identified
- Surficial and underground waters: It was not possible to be sampled. The area is semi-arid and the clayey soil has a very low hydraulic conductivity. Waters, both surficial and underground) were not considered as relevant or impactable for this matter. No water has been detected within the piezometers or runoff, since the trial completion in 4 inspection campaings.
- Vegetation. Only one single sample (ECVEG-3), a pine tree leaf near the roadside, showed an increase in elements of concern due to dust accumulation during construction works. No crops were very close (>30m) to the path.

FIGURE 10: SAMPLING SOILS NEAR THE ROADSIDE WITH A HAND AUGER.

No water has been detected within the piezometers since the trial completion.

2.4.2. Technical monitoring.

The simplicity of this road section (25 cm of stabilised soil and 10 cm of graded aggregates) and the type of technical requirements for this application (the lowest grade for a stabilised soil) suggested a basic monitoring. Monitoring has been based on visual inspections of the pilot road and a subjective comparison between the alternative stabilisation, the traditional stabilisation and the non-stabilised unpaved road.

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Observations from the last inspection resulted in the following conclusions:

- The surface was perfectly preserved, being smooth due to certain fines pumping after compaction of the graded aggregates.
- No deformation of the subgrade was detected or transferred to the graded aggregates surface.
- Some specific points were affected by water runoff due to the loose of drainage in the roadside, which has no connection with the stabilization works. This rework is going to be carried out by the municipality conservation team.

FIGURE 11: GENERAL VIEW OF THE ROAD ON JANUARY 2020 (R) AND CHECKING PIEZOMETERS (L)

FIGURE 12: WATER RUNOFF AFFECTIONS DUE TO BAD DRAINAGE IN CERTAIN POINTS OF THE PILOT

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FIGURE 13: DETAIL OF THE SMOOTH SURFACE (R) AND CONNECTION WITH THE MAIN UNPAVED ROAD, BAD PRESERVED (L)

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3. Stabilised road layer type S-EST3

3.1. Location

Pilot 2 was located in Villamayor de Gállego, a small village near Zaragoza (NE Spain). The stretch comprises 300 m long of a local paved road and 700 m of a rural unpaved road. Unexpectedly, these roads had a relevant heavy traffic due to the presence of an agricultural cooperative and because the dwellers use this way as a by-pass to avoid the village centre. The Annual Average Daily Traffic remains unknown.

In detail, the experimental trial corresponds with Balsa Street (41°41'29.0"N 0°46'42.8"W) (Figure 9 and Figure 10).

FIGURE 14: LOCATION - VILLAMAYOR (ZARAGOZA), BALSA STREET (41°41'29.0"N 0°46'42.8"W).

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FIGURE 15: AREA SELECTED FOR THE FIELD TRIAL CLOSE TO ZARAGOZA.

3.2. Pilot design

The soil of the borrow pit was characterised prior to its treatment and then, treated with different doses of WPFA. Table 6 shows the requirement S-EST3 layer, according to PG-3. The objective is to fulfil these requirements substituting cement with fly ash.

TABLE 6: PG-3 REQUIREMENT FOR STABILIZED SOIL IN-SITU AND RESULTS FOR VILLAMAYOR SOIL.

Characterization	*Unit*	*Soil type S-EST3*	*Villamayor soil*
Compressive strength at 7 days	MPa	≥ 1.5	≥ 1.5 adding 4% of WPFA
Density (Modified Proctor)	% of maximum density	≥ 98	98
Organic matter	% of mass	< 1	0.08
Soluble sulphate	% of mass	< 0.7	0.04
Atterberd limits	-	Liquid Limit ≤ 40 Plasticity Index ≤ 15	Non plastic ✓
Particle size	% pass through #sieve	#80mm = 100% #2mm > 20% #0.063mm <35%	#80mm = 100% #2mm = 32% #0.063mm = 9%

TABLE 7: WPFA DOSE TESTS BLENDED WITH VILLAMAYOR SOIL

Dosage	*Compressive strength at 7 days on 98% of the reference density*
Soil + 3% cement (reference)	5.2 MPa
Soil + 3% WPFA	1.6 MPa

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Soil + 5% WPFA	2.9 MPa
Soil + 7% WPFA	3.3 MPa
Soil + 9% WPFA	4.7 MPa

At the laboratory scale, the working formula with 3% of WPFA fulfilled the strength requirement but, due to not accurate dosing at the employment of heavy machinery, the selected dose rate was 5% of WPFA. With that amount of fly ash, the optimum moisture content of the soil is 8.2 according to compaction tests.

Currently, the stabilized soil is sampled for further studies, which are: evolution of compressive strength over time, leaching tests and durability tests (wetting/dry cycles).

During the design works it was taken into account the agricultural machinery traffic, so it included and additional covering treatment. The standard solution for that is a double bituminous surface dressing, that consists of a layer of bituminous emulsion compacted with 4-8mm gravel and another layer above of the same emulsion and 2-6 mm gravel.

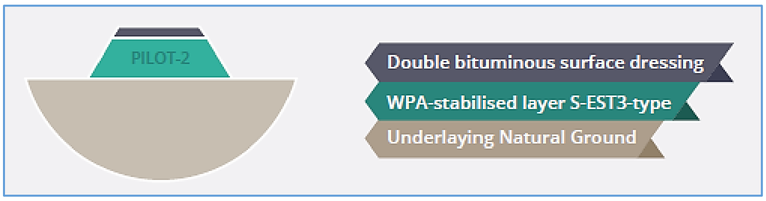

FIGURE 16. Outline of pilot 2 section

3.3. Pilot execution

Due to the heterogeneity of the materials in the path, it was necessary to remove 10 cm of the original surface layer. After that disposal process, several trucks hauled the borrowed pit soil, which was levelled and compacted simulating an *in situ* suitable soil for S-EST3 stabilisation purposes.

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FIGURE 17. Milling procedure of the original surface. Levelling process of the borrow soil

After the series of laboratory studies with the objective of determining the fly ash amount as well as defining the use of this material in order to achieve similar properties to those of stabilized soil with cement type S-EST3, the experimental field trial was carried out with the following dosage and conditions:

- Fly Ash content 5%.
- Water content 8.2%.
- Delay time of half hour after mixing the soil, fly ash with water.
- Compaction until obtaining the maximum dry density of the Modified Proctor test with lower moisture content than the optimum

As the pilot 1 (S-EST2), the WPFA was spread out by dry process and the machinery employed and the procedure was exactly the same. The only aspect that changed was the dose of WPFA and the amount of water.

FIGURE 18. STABILISER AND DOSING MACHINERY (PROFILE AND BACK). DOSING 5% WPFA (DRY PROCESS). MIXING AND WATER INJECTION

Immediately after the final compaction of the WPFA-soil, the emulsion-gravel treatment was laid out generating a protective surface layer.

FIGURE 19. DOUBLE BITUMINOUS SURFACE DRESSING AND DETAIL VIEW

The final material was evaluated at the laboratory level by compressive strength of remoulded specimens and at field level testing its bearing capacity with direct load tests.

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TABLE 8: QUALITY CONTROL DURING PILOT 2 EXECUTION

TEST	ORIGINAL SOIL	REQUIREMENT	WPFA-STABILISED SOIL
Unconfined Compressive Strength at 7 days	N/A	at 98% MDD≥ **1,5 MPa**	at 98% MDD: **1,8 Mpa** ✓ (average)
Load test of plate soils at 14 days (diam=30 cm)	N/A	E_{V2} >60 MPa for subgrade E1 E_{V2} >120 MPa for subgrade E2 E_{V2} >300 MPa for subgrade E3	**E_{V2} >334 MPa** (average) **Improved subgrade E3**

FIGURE 20. LOAD TEST (AFTER 14 DAYS)

3.4. Monitoring

This type of roads usually goes through sensitive areas including crops and farms, because of that, this pilot will include an intensive environmental monitoring to demonstrate the proper environmental performance, in addition to the economic and technical feasibility.

3.4.1. Environmental monitoring.

An intensive control has been deployed in the area to detect any potential affection of the trial. The methodology was the same as in Pilot 1 (Ejea). Firstly, a preliminary environmental risk analysis (PRA) was conducted following the same methodology: comparison of the concentration of metals of concern in the WPFA and consequently, the expected amount when diluted at a 5 % in the soil. Once it has been checked that the total concentration does not exceed the GLR for the area or the values for an industrial site, it is analysed the potential transmission pathways taking into account the construction characteristics, including:

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- A first list of Pollutant of interest was selected by bibliographical study, as part of the initial WPFA and soil baseline analytical characterization.
- WPFA is spread on top of the borrowed soil along the trial and it is immediately blended, hydrated and compacted.
- After compaction, the stabilised layer is covered with a double bituminous surface dressing, which protects the layer against water leaching or runoff, and direct contact with end-users.
- Spreading by wind in the form of dust and runoff were considered as the main concerns. Optimal working conditions were stablished: absence of strong wind (<20Km/h), and rainfall during the works.

After the preliminary analysis, the main conclusions are the same as in the case of Ejea, except for the fact that a bituminous dressing, a factor reducing the potential risk of leaching and impede the direct contact with humans, covers the layer. It means a protective layer for the hydrogeological context; as Villamayor is located in the alluvial system of the Ebro River, with a relevant associated deep aquifer (>60m groundwater level depth). It must be remarked that due to the underneath aquifer depth, already base pollution (nitrates, chlorides, etc.) no probable risks were contemplated for the quality of its water. After site specific preliminary Risks scenario, an evaluation was done, and an environmental monitoring plan was proposed (see table below) according to the construction process and the surroundings nature, including many crops and potentially, dispersed groundwater levels, focusing in the most sensible areas and receptors.

The original status of the area was analysed in order to compare the before and after status thorugh a pre and a post- works monitoring / sampling campaings.

TABLE 9. MONITORING PLAN FOR VILLAMAYOR DE GÁLLEGO. STRATEGY.

Media	Justification	Sampling strategy
WPFA	Characterisation and control of the ashes chemical variety before being used.	Chemical analysis of total content of elements of concern (major, minor and trace elements). Daphnia toxicity tests. Characterisation: Sampling and testing of the area before the trial construction.
BORROWED SOIL	Chemical composition and leaching tests	Total element content (elements of concern) and leaching tests according to (EN-12457-4) Sampling prior to the Works, at least two samples.
STABILISED SOIL	Chemical characterisation of the stabilised layer and its variability.	Total element content (elements of concern). Leaching test of the sample taking from the pilot before compaction and leaching test according EN-12457-4.

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	Forecast over the long term of the stabilised soil layer and assessment of the potential risk.	Sampling through 3 boreholes along the road. One representative sample to be taken in each one. Tank leaching test (NEN 7345:1995 nl) if possible.
SOILS (SURROUNDINGS AND CROP AREAS)	Wind dispersion of WPA particles to the nearby soils.	Total element content (elements of concern) Soil quality control near the roadside (<2 m distance) before (baseline) and after the works (potential impacts verification. -5 check points at both roadsides, 10 points per sampling campaign, 20 samples in total.
VEGETATION	Impact control by WPA dust on the vegetation. 2 sampling campaigns prior and after the stabilisation works.	Total element content (elements of concern) Sampling of most interesting vegetation from a human point of view (food). 2 points per roadside. Total = 4 samples per campaign, 8 in total.
UNDERGROUND WATERS	Control of the potential affection to the underground waters.	Total element content (elements of concern) in waters. Installation of three control wells up to 10 m depth or until reaching a sub-surficial water table. Installed with plastic pipes of 101 to 86mm Ø, with 2 m of grooved tube at the bottom.
SURFICIAL WATERS AND RUNOFF (CANALS)	Impact control by WPA dust on surficial waters. Status control of surficial waters of the irrigation canal near the pilot, sampling before and after the construction works.	Total element content (elements of concern) Two sampling points in waters from two canals, which are crossed by the pilot road. Two samples upstream and downstream (4 in total).

The samples obtained were finally as follows;

- WPFA. One representative sample made by 3 subsamples taken from the construction site.
- 2 borrowed soil samples used to form the stabilised layer.
- 4 stabilised soil samples taken along the pilot. Leaching tests with these samples showed values far away from potential impacts for groundwater quality standards.
- 10 soil samples prior the commencement of the works and 10 more before the soil stabilization in the same locations. At maximum of 2 m distance from the roadside.
- 4 samples of the vegetation before and 4 additional vegetation samples after the works to see the accumulation of WPFA dust on the leafs. Focusing on crops harvested for human and anmal consume.
- 4 samples of surficial waters from the canal. 2 before and 2 more after the construction works.

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- 2 samples of leaching waters accumulated in the piezometers installed in the three boreholes.

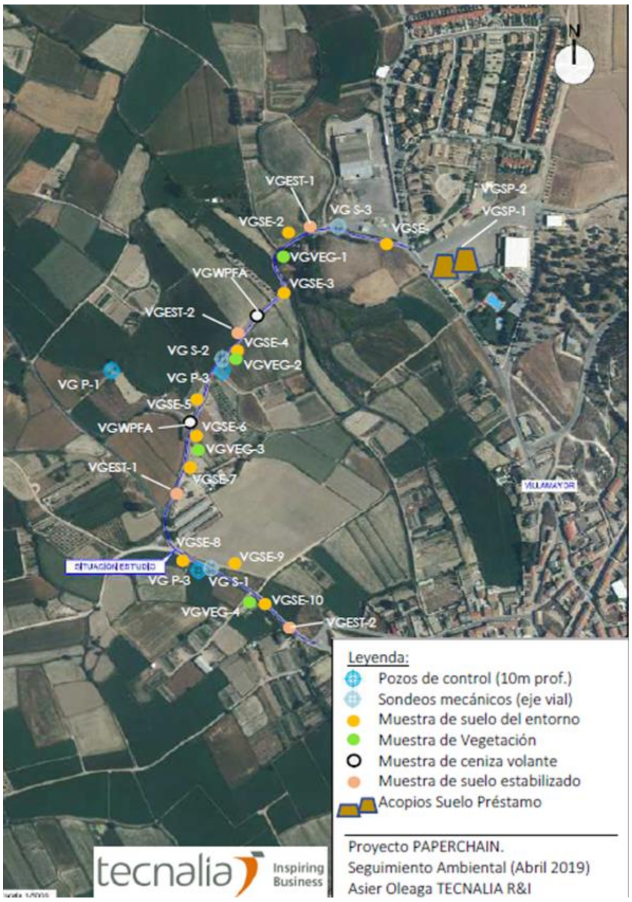

FIGURE 21: LOCATION AND TYPE OF SAMPLING POINTS

FIGURE 22. SOIL SAMPLING FOR THE BASE LINE (BEFORE WORKS)

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FIGURE 23. WPA SAMPLING (LEFT) AND VEGETATION SAMPLE (CROPS). BEFORE WORKS.

FIGURE 24. DRILLING FOR STABILISED SAMPLES AND INSTALLING PIEZOMETERS ALONG THE PILOT

The detailed results of this monitoring programme can be found in the document "Monitorización Ambiental Demo Case 2. Villamayor de Gállego" by TECNALIA, April 2019. In this report, the following conclusions were stated:

- The stabilised soil contains similar amounts of elements of concern to the original soils. Certain metals (Sb, Cu, Mo, and Zn) and chlorides are slightly increased but below the threshold limits for industrial/urban uses according to regulation.
- The leaching properties in mixed soils are similar after the stabilization except for certain increase in Sb, Cr, Ba, Cu and chlorides. All the values remained in the inert category according to the European Waste Directive except for some slightly higher values of Sb and chlorides.
- Not toxic for Daphnia Magna.
- Evolution of the nearby soils. No significant differences were detected pre and post execution. Differences were both, positive and negative and in general below 20%, compatible values with the expected lab error/dispersion. Certain anomalies (Cu) are associated with the baseline (fertilizers, pesticides).
- Vegetation. No clear trend has been identified showing an increase in any pollutant. Only phosphorous seems to be slightly increased in the post-stage.

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- Collected leaching and surficial waters on January 2020: Results indicates that the material leaching during a rainfall -considering that all the sampled water was representative of the leaching of the mix of both EST and covering layer, in absence of a real groundwater level-, can be comparable to values for leaching of a Inert type material according to the Royal Decree 1481/2001.
  Considering the previous statement and that raining episodes are rare and very scarce, it can be concluded that the potential leaching does not seem to represent a thread for the media, nor the underneath big and deep aquifer water quality.

Parameter	Piezometer 2	Piezometer 3	Surficial water (irrigation canal)	Inert waste (percolation test)
Chlorides	425	118	15.6	450
Fluorides	0.29	0.34	0.7	2.5
Nitrates	366	142	8.28	-
Sulfates	1080	178	32.4	1500
Sb	0.016	0.0016	< 0.001	0.01
As	0.0021	0.016	< 0.001	0.06
Ba	0.060	0.046	< 0.02	4
Cd	< 0.001	< 0.001	< 0.001	0.02
Co	< 0.02	< 0.02	< 0.02	-
Cu	0.060	0.26	< 0.005	0.6
Cr	<0.005	<0.005	<0.005	0.1
Hg	< 0.0005	< 0.0005	< 0.0005	0.02
Mo	0.021	< 0.02	< 0.02	0.2
Ni	<0.005	<0.005	<0.005	0.12
Pb	0.0061	0.029	<0.005	0.15
Zn	0.18	0.025	< 0.02	1.2

TABLE 10. SAMPLED GROUNDLEACHING WATERS AND SURFICIAL WATER QUALITY (IN MG/L)

Values from percolation test according to EN 14405 (more restrictive) has been selected. Collected leachates would be concentrated when sampled due to evaporation.

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3.4.2. Technical monitoring.

Technical monitoring comprises two different types of testing:

On site monitoring, including visual inspections and load plate tests:

Two visual inspections were performed along this period of time, from October 2018 to February 2020. The results of the inspections can be summarised as follows:

1st inspection 29 March 2019 (6 months after completion). Main findings: The road integrity was good. No damages related to a WPFA misfunction where identified. Some fails (potholes) were found associated with joints, although very punctually. An excess of aggregates from the surface bituminous dressing provoked an accumulation of loose aggregates in the junction between the local road and the originally unpaved road.

FIGURE 25. CEMENT STRETCH (L) AND WPFA STRETCH (R) SHOWING A JOINT

FIGURE 26. POTHOLE IN THE ROAD JUNCTION (L) AND POTHOLE IN A JOINT (R)

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FIGURE 27. END OF ROAD (L) AND DETAIL OF LOOSE AGGREGATES ACCUMULATION (R)

2nd inspection 29 Enero 2020 (15 months after completion). Main findings: The road integrity was similar to the status found in March 2019 except for some details:

- The loose aggregates were not found. Maintenance works by the The municipality conducted some maintenance works to remove them. Regular traffic also eliminated most of them.
- Some potholes were enlarged due to traffic activity.
- A trench was excavated through the road creating a lack of integrity at PK 0+250.
- Some incipient regular cracks (each 4 m) were observed in the cement stretch as a consequence of the high and quick rigidity developed by cement.

Other appreciations:

- No cracking was observed in the WPFA stretch due to the lower rigidity deployed by WPFA and the slower strength development.
- No swelling effects observed.

FIGURE 28. DRESSING INTEGRITY (L) AND POTHOLES IN THE JOINT (R)

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FIGURE 29. EXCELLENT ROAD INTEGRITY IN THE WPA STRETCH (L). POTHOLES IN THE JUNCTION (R)

All the potholes were repaired with cold pavement in order to preserve the road integrity to be able to observe any misfunction due to the WPFA.

FIGURE 30. EXAMPLE OF POT REPARATION

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Laboratory monitoring, conducted at the Polytechnical University of Catalonia

The laboratory technical monitoring comprised three types of testing with specimens manufactured with the materials direclty taken from the construction site and under the placement conditions. Cement stabilised speciments were also manufactured for benchmarking purposes. These specimens have been preserved in a climatic chamber for curing after being tested at diferent ages. The following tests have been performed:

- Strength evolution of the stabilised soil.
- Durability characteristics: Swelling/shrinkage under different testing conditions and experimental methods specifically designed for this purpose.
- Ethringite formation analysis.

The following paragraphs summarises the obtained results. Further information will be compiled in deliverable 5.7 and in peer-review publications.

<u>Strength evolution of the stabilised soil</u>.

Strength in cementitious materials increases over time, but it also depends on cement type and curing time. The usual curing times are 1 day (for high early strength cement), 3 days, 7 days, 28 days and 90 days (for low heat hydration cement).

Since WPFA has cementitious properties, the study of its strength over time becomes necessary.

To study the strength evolution of WPFA, samples are made to be tested at different ages (7, 30, 60, 180, and 360 days). Four samples are made for each time. In order to compare the results and have a reference value, compressive strength tests are also performed on samples made with cement (four for each time).

The soil-WPFA and soil-cement samples are made using standard EN 13285-41 for compressive strength for S-EST3 soil type in situ. However, instead of carrying out the experiment at 7 days, the samples are cured in a moist room with 95% humidity at 20°C at the aforementioned ages.

The job mix formula for preparing the samples of stabilized soil with WPFA (previously defined), indicated the use of 5% WPFA, the application of a delay time of 30 minutes (to slake the WPFA), and an optimum water content of 8.2%, with the aim of reaching a density around 2000 kg/m^3 (as obtained in the field trial).

For the samples of stabilized soil with cement, a cement type CEM IV/B (Q) 32.5N was used in a 3% (the minimum value for a S-EST3 according to PG-3), no delay time was applied and the optimum water content was 7% (due to not being as porous as WPFA, the water amount decreases). Regarding the density target, it was 2050 kg/m^3.

After 2 months, the samples kept in a dark and humid environment promoted the growth of mildew and mold as shown in figure below. Hence, to avoid further spreading, it was

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decided to move them to a less humid environment (around 50~40 % RH) and spray water on the samples twice a week to simulate the necessary humidity for WPFA or cement to gain strength. Furthermore, 7 days before each experiment time, the specimens were placed inside the moist room and then on the 7th day, the usual compressive strength test is carried out.

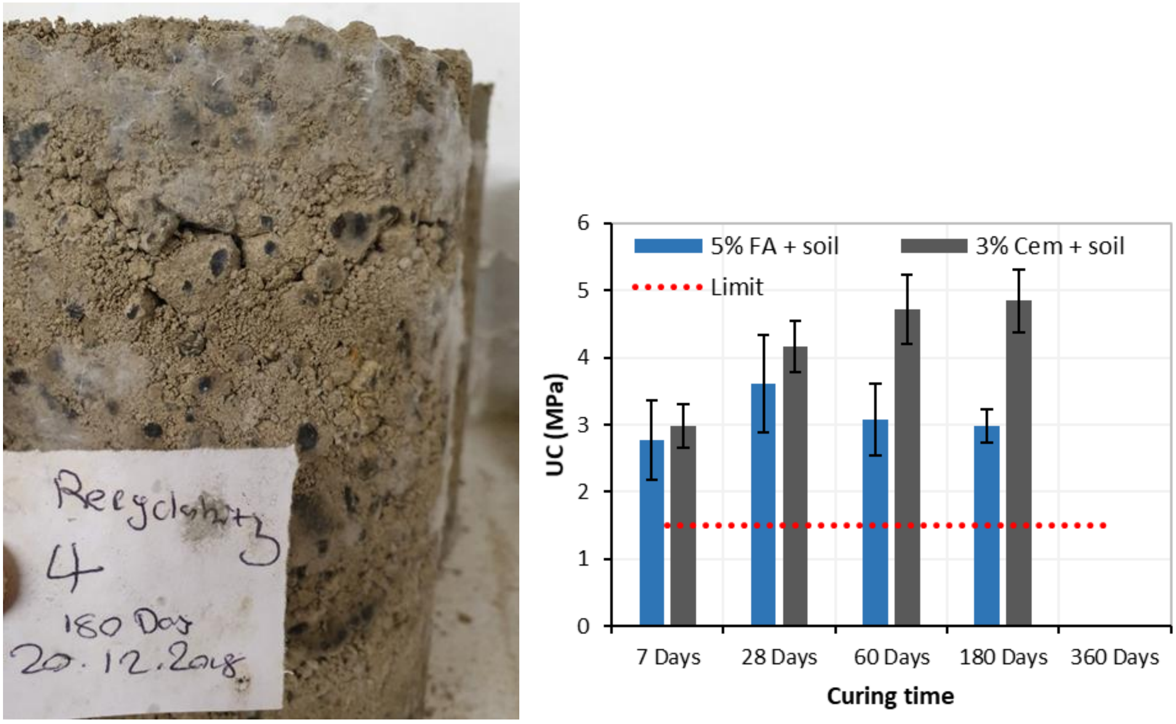

FIGURE 31. MOLD IN THE COMPRESSIVE STRENGTH SPECIMENS (L) AND UCS EVOLUTION

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, a delay time before compaction is necessary to allow the reactions take place. Moreover, the effect of curing time on the compressive resistance of these mixtures with WPFA was not significant.

The soils used for this study did not have any plasticity but it is important to observe that the amount of organic matter of the stabilized soil was considerable high, what could be a potential obstacle for the strength increase.

Durability of the stabilised soil.

One of the common problems in some binders that can affect the durability of a stabilised soil is being exposed to a sulfate source (sulfate attack). This source may come from rain from the pavement surface, or from the ground water if the below soil is rich in sulfate (due to existence of capillary action in soil). It occurs when tri-calcium phase inside the binder (it can be Portland cement or any cementitious material), becomes in contact with water

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containing sulfate. Calcium oxide and aluminium oxide in the binder react with sulfate and water solution and this reaction leads to expansion. This phenomenon could also happen with WPFAs, since they have almost similar properties to cement.

To carry out the durability of the soil using WPFA, two types of experiment are carried out. Both experiments try to simulate the real-life scenarios or worst-case scenarios.

As stated in the Spanish Specifications for Roads and Bridges (PG3), an analysis of the free swelling of soil for in situ stabilization must be conducted, according UNE 103601 standard, Test for free swelling of soils in odometer device. The free swelling is described as the increase in height, expressed as a percentage of the initial value, which a soil specimen experiences when it is confined laterally, subjected to a vertical pressure of 10 kPa, and flooded with water.

Since the type of soil intended to analyze has considerable big size distribution and the fine particles do not have a plastic behavior, in order to study the key mechanical properties of the materials, two different non-standardized experiments were designed and performed. The first one consists on analyzing the materials' behavior under horizontally confined conditions to assess its vertical swell/shrinkage, when subjected to dryness/humidity cycles. The second one consists on a volumetric analysis under non-confined conditions to assess the volumetric changes when subjected to dryness/humidity cycles as well. Finally, the third one consists on a mineralogical XRD test to determine the main components of the raw materials and the components created due to their interaction, which may be harmful for the overall structure of the road.

Horizontally confined swelling experiment

This experiment is carried out to measure the displacement in vertical axle in a confined system using PVC molds. The goal is to pour the material inside the PVC mold and put the sample in contact with water in a bath. Then the sample will absorb water due to capillary soaking.

To carry out with the experiment, 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 (any water evaporation is avoided).

After applying the delay time, the material is poured into a cylindrical PVC mold and compacted in 3 layers with a vibrocompactor to obtain 2000 kg/m3 density. Once the demanded height is satisfied, a metal lid and small balls are placed inside it to have a uniform surface. Then the samples are cured at 20°C and 90% RH for 7 days.

To measure the displacement in the samples, a precise measurement device that can measure up to 0.1 μm is being used. The measurement device has 3 external sensors (3 around the edge of PVC) and 3 internal sensors (3 on the metal lid). The measurement device is placed on the sample Figure below and the height of the sample inside the mold is registered.

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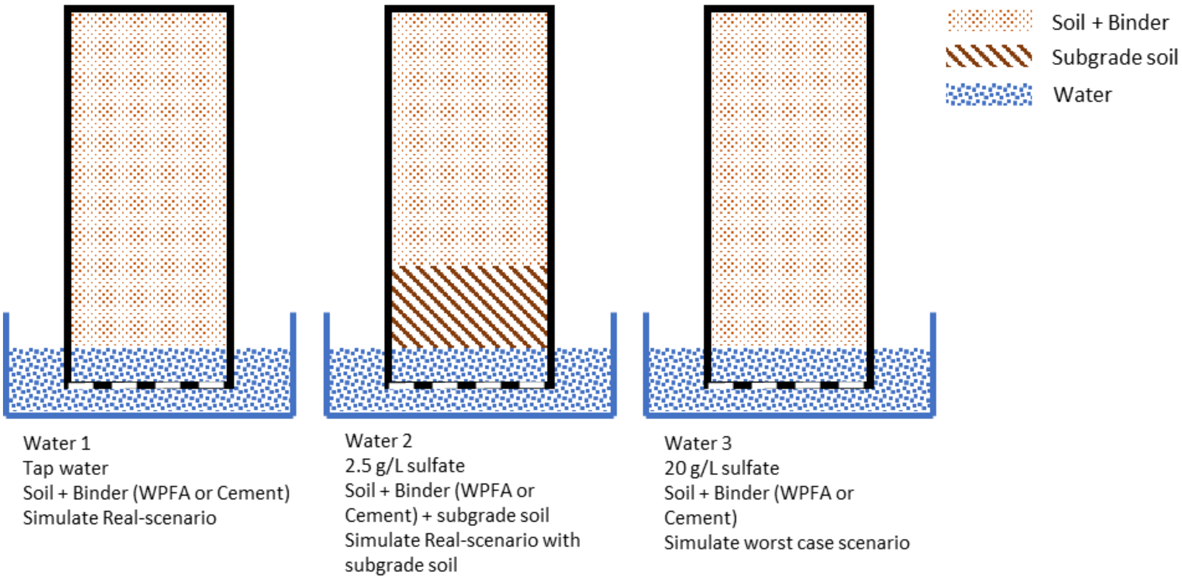

FIGURE 32. TEST SCHEME

Three different types of waters are used: tap water and water containing a sulfate concentration of 2.5 and 20.0 g/l and samples are kept at two different temperatures (5°C and 20°C).

Results:

The average displacement and weight per subgroup after 100 days since is shown in the table below. There was no swelling in the specimens; however, there was a small shrinkage. The weight of the specimens was increased until 60 days and after that, it kept constant over time.

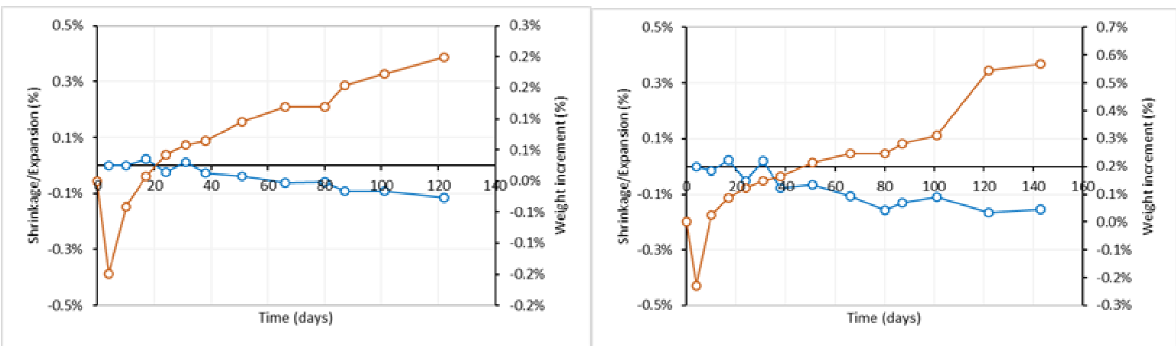

FIGURE 33. EXAMPLE OF DATA OUTPUT. WEIGHT AND DISPLACEMENT EVOLUTION, SOIL+CEMENT+20 G/LITER SO4 WATER (20°C) TEST SPECIMENS (P29, P30).

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Specimen type	*Average swelling (%)*	*Average weight increment*
Soil + WPA +Normal Water (20 °C)	- 0.124 %	2.477 %
Soil + WPA +Normal Water (5 °C)	- 0.056 %	1.707 %
Soil + Subgrade + WPA +2 g/liter SO4 water (20 °C)	- 0.082 %	0.507 %
Soil + Subgrade + WPA +2 g/liter SO4 water (5 °C)	- 0.083 %	0.366 %
Soil + WPA +20 g/liter SO4 water (20 °C)	- 0.068 %	3.423 %
Soil + WPA +20 g/liter SO4 water (5 °C)	- 0.018 %	2.871 %
Soil + Cement +Normal Water (20 °C)	- 0.092 %	1.342 %
Soil + Cement +Normal Water (5 °C)	- 0.051 %	1.049 %
Soil + Cement +20 g/liter SO4 water (20 °C)	- 0.106 %	1.435 %
Soil + Cement +20 g/liter SO4 water (5 °C)	- 0.033 %	1.140 %
Soil + Subbgrade + Cement+2 g/liter SO4 water (20 °C)	- 0.102 %	0.242 %
Soil + Subbgrade + Cement +2 g/liter SO4 water (5 °C)	- 0.012 %	0.246 %

TABLE 11. RESULTS. AVERAGE SWELLING AND WEIGHT INCREMENT AFTER 100 CURING DAYS

Unconfined volumetric test

This experiment is designed with the aim of measuring volumetric swelling in samples. The standard EN 13286-49 is indicated for a cohesive soil or a soil with enough fine particle fraction so that the experiment can be carried out. Additionally, it is indicated to use only the fine portion of the soil (smaller than 6.3 mm). Since the soil used in this study has most of the particles higher than 6.3 mm, the standardize test is not appropriate to evaluate swelling and so, the volumetric test described below is carried out.

Samples were prepared under the same conditions of the former experiment (construction placement conditions) with both WPFA and cement. Specimens are the placed inside an elastic membrane as shown in figure below. Then the samples are placed inside a moist room (at 20°C and 95% RH) to left to cure for 7 days. After curing, the specimens are placed on the tray with an absorbent cloth, so when saturated, the specimen could absorb water through capillarity. The water conditions used here are similar to those of the previous test (three types of water).

The humidity-dryness conditions for samples include one week leaving 12 samples in the tray in a moist room at 20°C and 90% humidity, and other 12 samples at 5°C, both with the

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50 ml water (allowing absorption from bottom) and then, two weeks of a drying stage, leaving them without any water and let them dry.

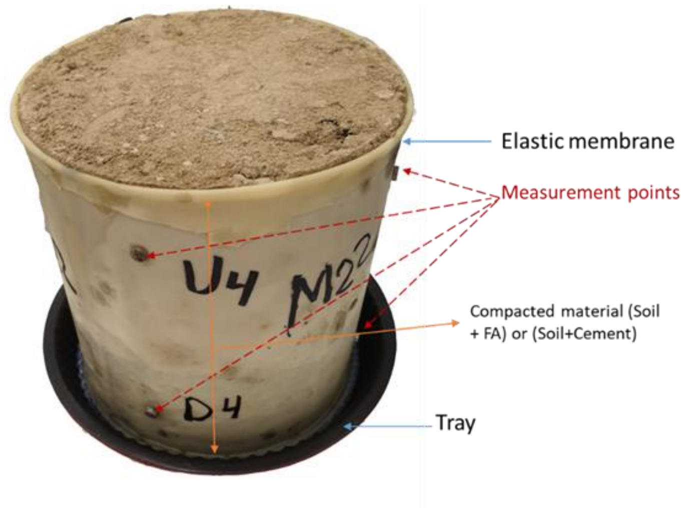
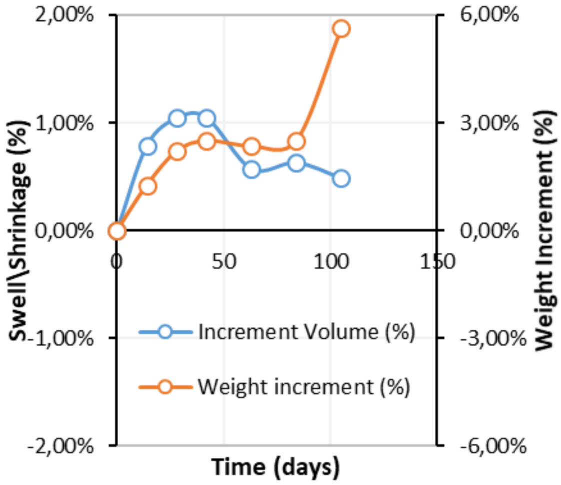


FIGURE 34. EXPANSION SAMPLE WITH ELASTIC MEMBRANE (L) AND MANUAL MEASUREMENT (R)

Results:

Unconfined volumetric test results have shown more swelling in some specimens; although great care should be taken with this data as, some results could be affected by the imprecision of the measurement procedure.



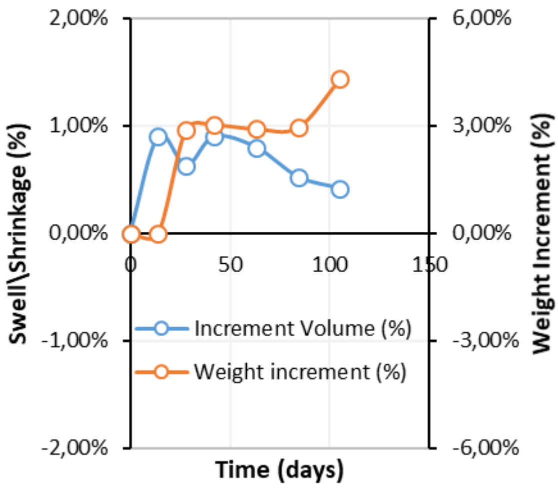


FIGURE 35. EXAMPLE OF DATA OUTPUT. INCREMENT VOLUME AND WEIGHT EVOLUTION, SOIL+CEMENT+20 G/LITER SO4 WATER (5ºC) TEST SPECIMENS (M3, M4).

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Specimen type	*Average volumetric change*	*Average weight increment*
Soil + WPA +Normal Water (20 °C)	+ 1.05 %	+ 0.44 %
Soil + WPA +Normal Water (5 °C)	- 0.09 %	+ 3.89 %
Soil + Subgrade + WPA +2 g/liter SO4 water (20 °C)	+ 0.45 %	+ 0.24 %
Soil + Subgrade + WPA +2 g/liter SO4 water (5 °C)	- 0.01 %	+ 2.44 %
Soil + WPA +20 g/liter SO4 water (20 °C)	+ 1.21 %	+ 1.07 %
Soil + WPA +20 g/liter SO4 water (5 °C)	+ 0.45 %	+ 4.97 %
Soil + Cement +Normal Water (20 °C)	+ 0.51 %	+ 1.12 %
Soil + Cement +Normal Water (5 °C)	+ 0.25 %	+ 2.17 %
Soil + Cement +20 g/liter SO4 water (20 °C)	+ 1.23 %	+ 0.87 %
Soil + Cement +20 g/liter SO4 water (5 °C)	- 0.15 %	+ 1.92 %
Soil + Subbgrade + Cement+2 g/liter SO4 water (20 °C)	+ 1.12 %	+ 2.10 %
Soil + Subbgrade + Cement +2 g/liter SO4 water (5 °C)	- 0.50 %	+ 2.57 %

TABLE 12. RESULTS. AVERAGE VOLUMETRIC CHANGE AND WEIGHT INCREMENT AFTER 100 CURING DAYS

X-ray diffraction analysis of stabilised soil in presence of sulfates

This study is conducted to advance and then analyse the minerals that are created in the soil containing WPFA and cement in different ages and temperatures (14, 30, 90 and 180, 270 and 360 days at two different temperatures, 5°C and 20°C) in contact under a sulfate source.

In this step, the mineral evolution is studied to determine the expansive minerals or evolution of minerals that can be produced in stabilized soil at different ages. The mineral evolution test can be used to compare and identify the different minerals produced or new produced minerals inside the matrix of these mixtures while becoming in contact with a sulfate source. DRX is able to determine and verify the swelling in the stabilized soil.

In order to analyse the material with the XRD machine, a preliminary treatment was needed which consisted in grinding down the materials to a particle size smaller than 63 μm with the aim of accelerating the future chemical reactions that would take place. This step was performed only with the soil and the subgrade soil, since WPFA and cement were already in the desired particle size.

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After obtaining the desired particle size for all the materials, the materials themselves and combinations of them were collected in small pots as shown in the figure below.

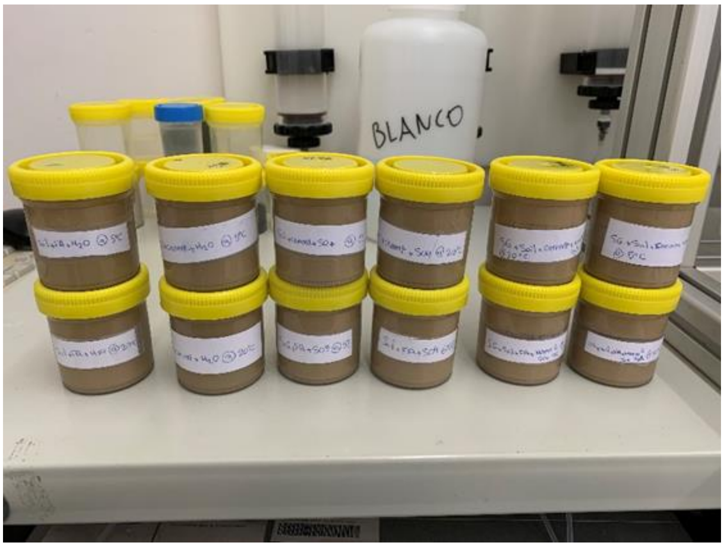

FIGURE 36. MATERIAL STORAGE MIXED WITH DIFFERENT WATER TO PERFORM XRD TEST

A complete set of analysis were performed in order to identify the original mineralogy of each original material, the stabilised soil and the stabilised soil under the former experimental sulfate waters and curing conditions.

Conclusions

Firstly, for the test specimens made up just with soil, the same amount of sulfates and at same temperature, when compared one by one, it can be observed that they have a similar XRD spectrum intensity in the ettringite angle, indifferently if they were prepared with cement or waste paper fly ash.

Secondly, for the test specimen made up with the subgrade lower layer, since it is a material rich in sulfate, the formation of expansive material, such as ettringite, is highly favourable.

Moreover, there is a big difference between the test specimens made up with cement and WPFA. It has been proved that the WPFA specimens, since they have a higher calcium and aluminium content, in contact with the high amount of available sulfates, show a higher intensity peak of ettringite than the ones made with cement.

Another reason why the formation of ettringite in the cement specimens is not that intense is that the used cement is a type IV cement. This type of cement has a low clinker content and the additional amount of added pozzolans prevents from sulfate attack.

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4. Soil – cement layer

4.1. Location

The soil-cement pilot case has taken place within the A31 – A33 highway connection, an ACCIONA´s construction project so-called La Font de la Figuera Bypass. In detail, it is located in a service highway of this relevant junction that communicates the inland with the North and South Mediterranean shoreline.

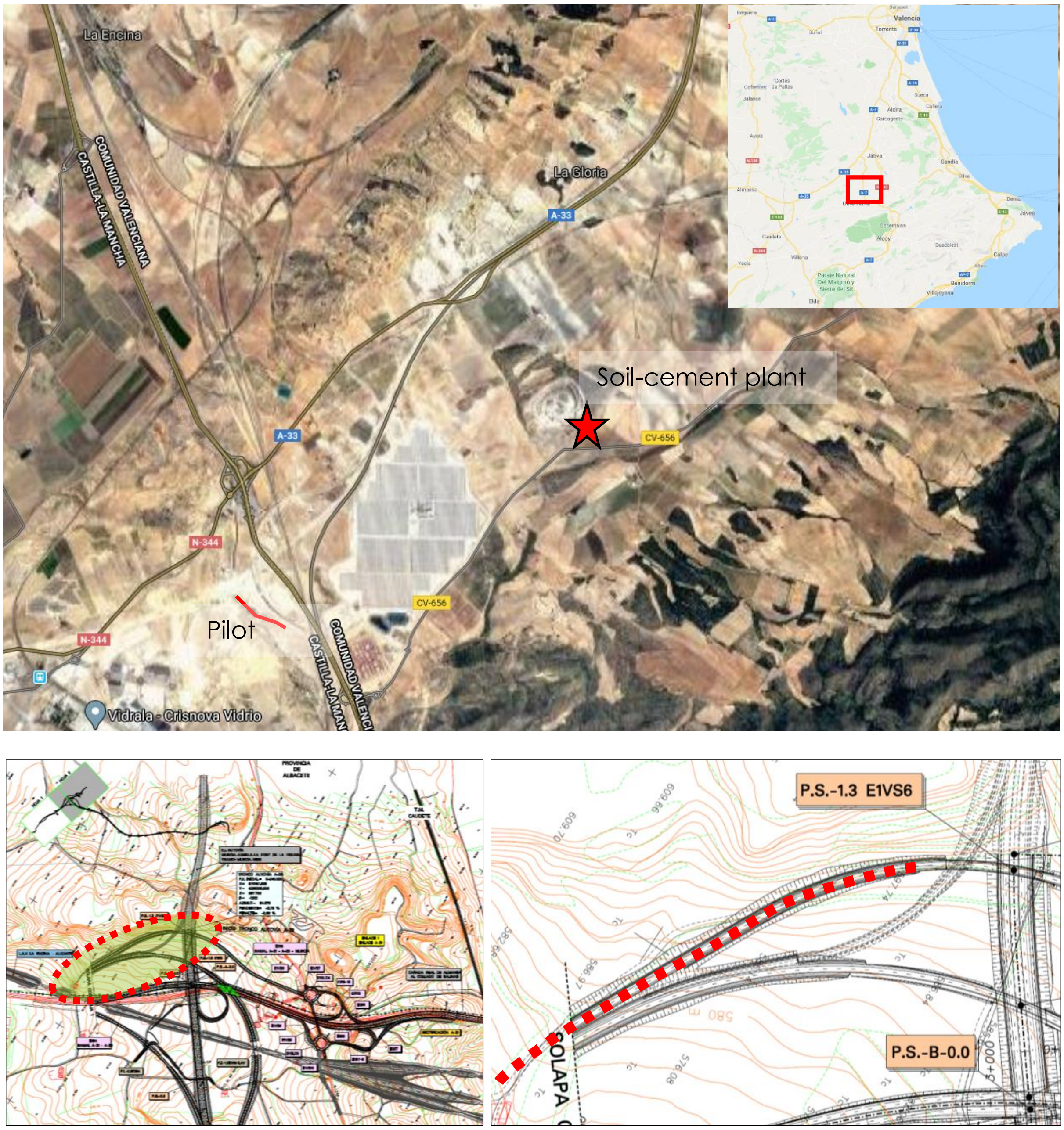

FIGURE 37. PILOT LOCATION SCHEME

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4.2. Pilot design

According to the construction Project, the cross-section of this service road is the type 232 of Standard 6.1 IC of the Spanish Highway Instruction. That is a cross-section compound of 15 cm of bituminous mixtures over 20 cm of soil-cement and supported by a formation-level type E3 (E_{V2}>300MPa Standard UNE 103808). As mentioned, the action was carried out on that layer of soil cement, replacing completely the cement with fly ash.

In the rest of the length of that route, it was executed using traditional soil cement as a reference for the comparison with the test section.

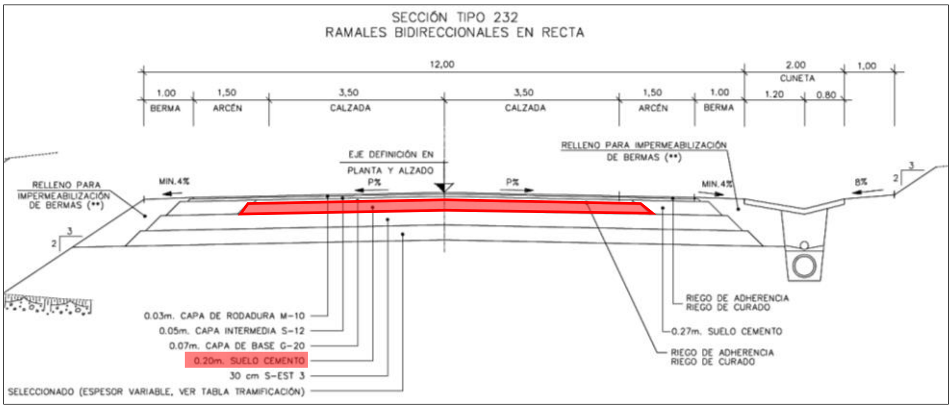

FIGURE 38. SOIL-CEMENT OF THE CROSS-SECTION

The granular material used was the same that the work uses to form the layers of soil cement. This comes from the Cantalar quarry, in the vicinity of the work.

Samples were taken in the quarry in two different fractions (0-32 and 0-6mm), as used in their facilities, and laboratory tests were performed. The starting sample was a mixture of 90% of the fraction 0-32mm with 10% of the fraction 0-6mm.

In relation to the characterization of the aggregate for use in soil-cement, all the requirements were checked for the granular material of Article 513 of PG-3 "Materials treated with cement (soil-cement and gravel-cement)". It fitted perfectly within the SC40 grading envelope, its organic matter content is less than 1%, soluble sulfates (SO_3) less than 0.5%, its Liquid Limit less than 30 and a Plasticity Index less than 12 (non-plastic material).

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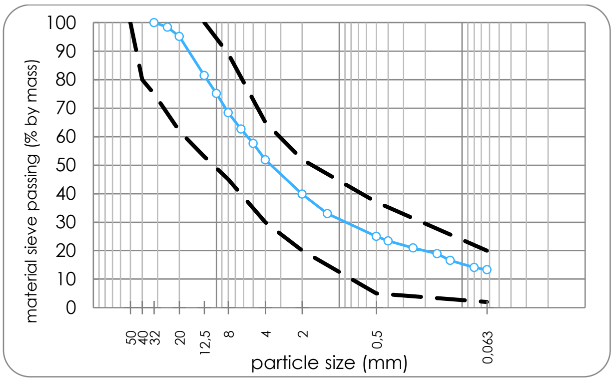

FIGURE 39. GRADING ENVELOPE OF SC40 SOIL-CEMENT AND PARTICLE SIZE DISTRIBUTION OF CANTALAR GRADED AGGREGATE

TABLE 13. SOIL-CEMENT TECHNICAL REQUIREMENTS ACCORDING TO THE PROJECT AND COMPARISON WITH WPFA-SOIL IN FONT DE LA FIGUERA

CHARACTERISTIC	UNIT	STANDARD	MATERIAL TYPE	
			SC	WPFA-SOIL TYPE SC
Binder content	% by mass of dry soil	-	≥ 3	5 – 5.2
Compressive strength at 7 days	MPa	UNE-EN 13286-41	≥ 2.5 ≤ 4.5	Fulfilled
Density (Modified Proctor test)	% of maximum density	UNE 103501	≥ 98	Fulfilled
Particle size distribution (of the original soil/aggregate)	-	UNE-EN 933-1	Grading envelope SC40	Fulfilled
Soluble sulphate content (of the original soil)	% by mass of dry soil	UNE 103201	> 0.5%	null
Organic matter content (of the original soil)	% by mass of dry soil	UNE 103204	≤ 1	0.17
Plasticity index of treated material	-	UNE 103103 + UNE 103104	Liquid limit < 30 Plasticity Index < 12	Non-plastic

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Layer thickness	cm	-	≥ 20 ≤ 30	20
Workability period	hours	UNE-EN 13286-45	Full width procedure: W_{pc} ≥ 3 Lane by lane procedure: W_{pc} ≥ 4	≥ 4
Stabilised-soil moisture at compaction	% by mass of dry components	UNE 103300	-1% / +0.5% of Modified Proctor test optimum moisture result	±1,5% but fulfilling target density in all cases
Transverse pre-cracking distance	m	-	≥ 3m ≤ 4m	3.5 m
Curing and surface protection of the stabilised layer	-	PG-3, art.:532	Bitumen emulsion curing coat within 3 hours of finalisation	Immediately after final compaction
Traffic ban after execution	-	-	To light traffic: 3 days To heavy traffic: 7 days	More than 7 days

Once the granular starting material was considered suitable, the soil cement working formula was defined with the content of binder and moisture capable of reaching 98% of its maximum dry density (Modified Proctor), resistances between 2.5 and 4.5 MPa at 7 days old.

In the case of the use of cement, the work has already defined its working formula at 3%, which was also tested in order to obtain a pattern. In the case of the use of WPFA ash, a series of remoulded specimens were manufactured varying the ash and moisture content until the formula was optimized. The following information summarizes the tests until the definitive working formula is found.

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TABLE 14. REFERENCES OF DENSITY AND HUMIDITY OF THE DIFFERENT DOSAGES

	Not treated	3% CEM IV/B 32,5	4% WPFA	6% WPFA	8% WPFA
Maximum dry density and optimum water content (*UNE 103501*)	2,241 t/m³ 5,9%	2,242 t/m³ 6,3%	2,172 t/m³ 7,6%	2,156 t/m³ 7,4%	2,103 t/m³ 7,1%

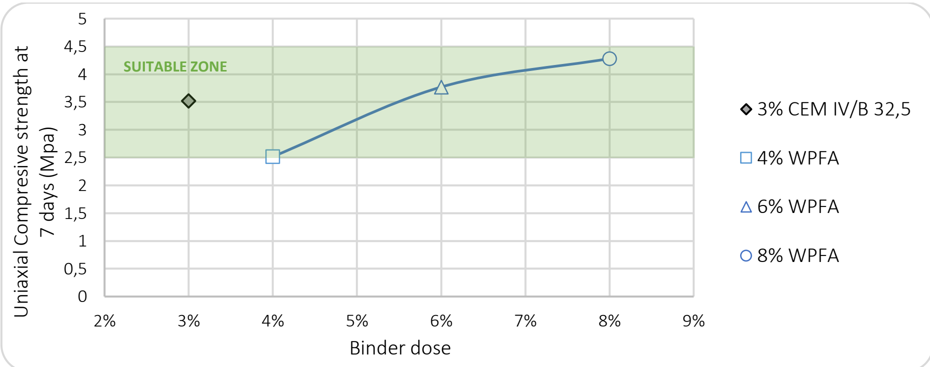

FIGURE 40. UCS$_7$ OF DIFFERENT BINDER DOSES TESTED (100% OF DENSITY REFERENCE)

The upper graph shows the average results of uniaxial compressive strength at 7 days of age, on families of three specimens manufactured at different dosages in an automatic compactor. The dimensions of the cylindrical specimens were 152.5mm in diameter and 177.8mm in height and, for the first trial, were compacted with the maximum dry density and optimum humidity of their respective reference Modified Proctor tests. All dosages tested under these compaction conditions met the resistance requirements for a soil-cement.

Because of the uncertainty of the first trial with this alternative soil-cement and the possible variations of humidity and dosage of the binder in the worksite, the objective resistance was increased by 20% at the laboratory level (3 MPa instead of the 2.5 MPa at 7 days). Attention was also paid to achieving a stiffness material similar to the standard SC adjacent to the test section (3.15 MPa at 7 days). With this, the successful working formula was achieved by adding 5% of WPFA.

In addition, to find out the influence of the density/humidity parameters on the stiffness of the material, additional tests were carried out varying its dry density and its moisture content by ± 1% on its optimum humidity during compaction. With the trend lines obtained from the point clouds generated by these tests, the value of its UCS$_7$ was set with a degree of compaction of 98%, the minimum density required by the PG-3 for this type of material.

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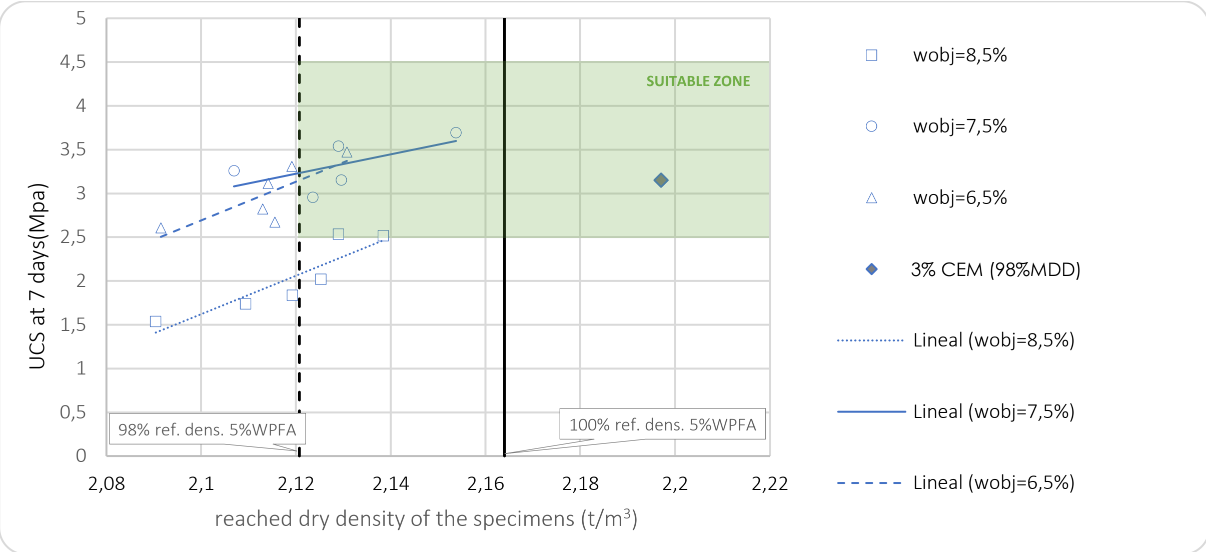

FIGURE 41. DENSITY/MOISTURE CONTENT INFLUENCE OF GRADED AGGREGATE + 5% WPFA SPECIMENS

One can appreciate the proper performance of the WPFA-stabilized soil type SC compacted at the optimum moisture or one point below, but the resistance drop is sharp when the material is compacted in the wet branch of the Proctor. This point was taken into account during the execution of the section.

In view of these results, the working formula on the sample tested in the laboratory was established:

- Maximum dry density (M.P.) = 2,164 t/m³ [98% MDD = 2,121 t/m³]
- Optimum wáter content (M.P.) = 7,5%
- **WPFA dose = 5%** w/w of the graded aggregate
- UCS reached at 7 days in specimens compacted at minumum density required = 3,23 MPa

4.3. Pilot execution

The commissioning work was done during October 2019 with a favourable climate.

Previously, a silo of the soil-cement plant was loaded with fly ash and dosing tests were completed with this additive. Relevant adjustments were made in the plant to achieve the material with the required working formula since as ash has a lower bulk density than cement and the greater dosage. In total, 105 tons of fly ash were employed in the demonstrator.

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FIGURE 42. SOIL-CEMENT PLANT: ASH-SOIL DETAIL ON CONVEYOR BELT AND TRUCK LOADING

The production was intermittent due to maintenance of the plant or holiday on these dates, but, in no case, was it related to ash. The total production of WPFA-soil was 2297.4 tonnes. The extended layer had a length of 591 meters.

The layer was transversely pre-cracked with saw every 3.5m after compaction. Forced fissures were sealed with bituminous emulsion and the surface was protected with a bituminous curing coat.

FIGURE 43. APPEARANCE OF THE PRE-CRACKING TEST SECTION (LEFT) AND THE PILOT COVER CURING EMULSION (RIGHT)

Exhaustive quality control was conducted on the material along the 591 meters of the section, particularly focused on the humidity of the material that came from the plant and over the reached densities after compaction. In summary, the following checks were made:

- 2 additional compaction tests (Modified Proctor)

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TABLE 15. WFPA-SOIL DENSITY DEFERENCE DURING PILOT EXECUTION

Origin sample	Maximum dry density (P.M.)	Optimum Moisture (O.M.)
km 1+290	2,12 t/m³	10,7 %
km 0+940	2,13 t/m³	9,2 %
REFERENCE (average)	2,125 t/m³ Minimum acceptable (98%): 2,083 t/m³	10 %

- 123 density/moisture measurements with nuclear gauge

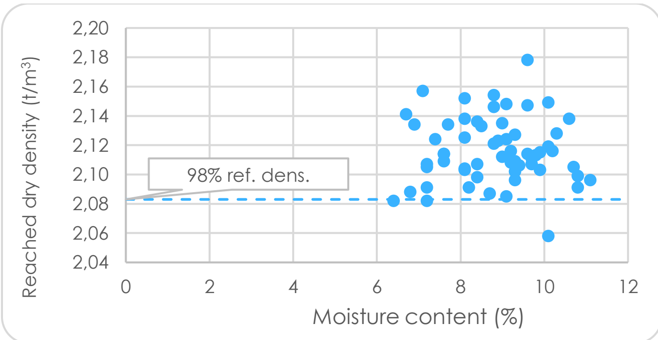
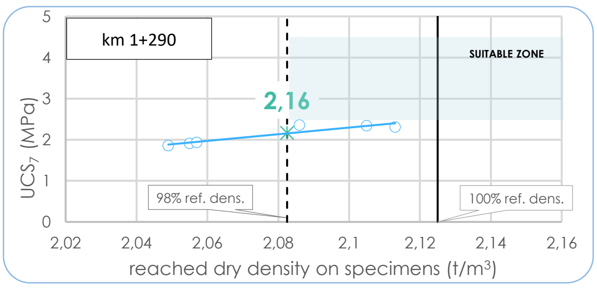
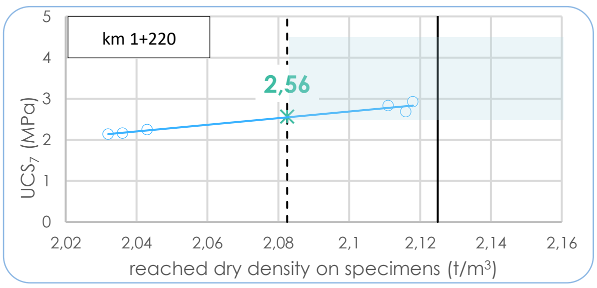


FIGURE 44. DENSITY/MOISTURE RELATIONSHIP ON FINISHED WFPA-SOIL LAYER

- 45 remoulded specimens for UCS_7 tests





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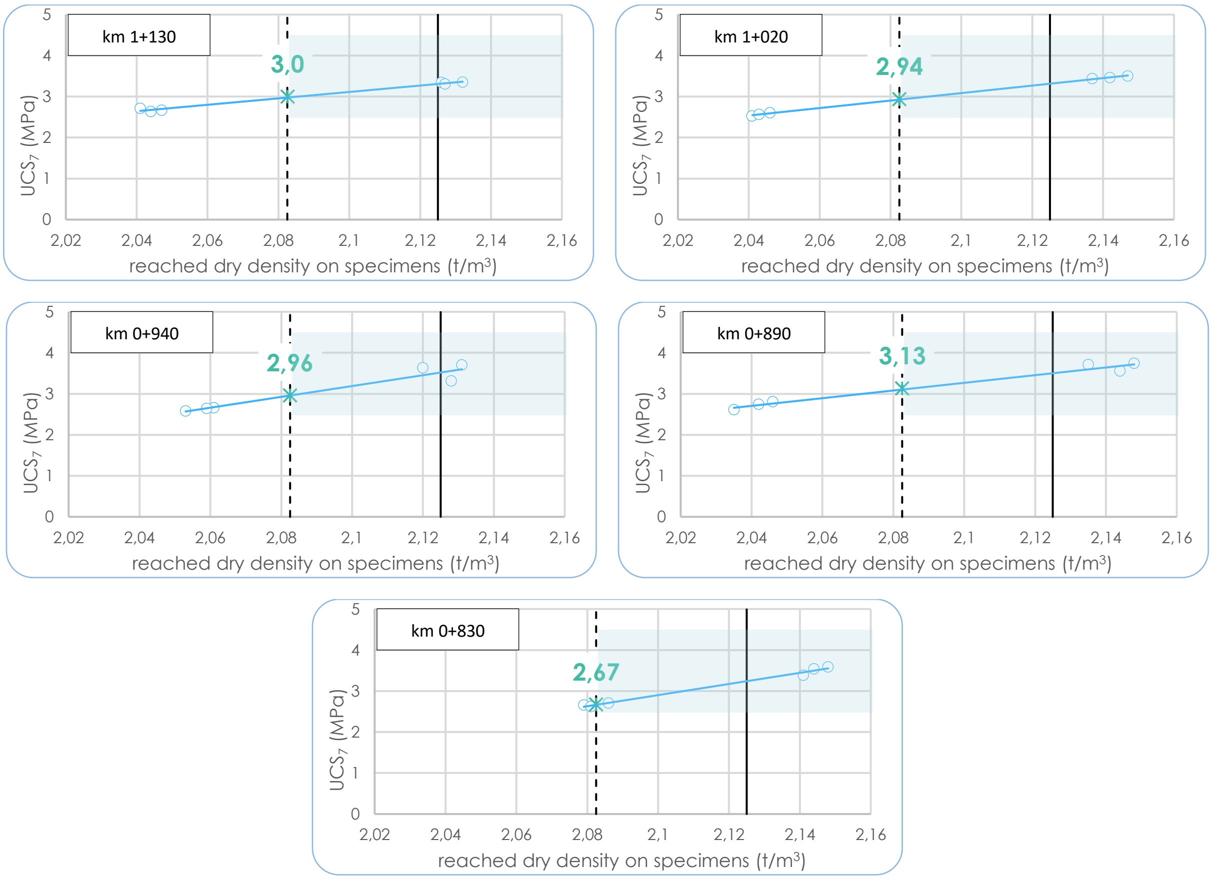

FIGURE 45. STIFFNESS QUALITY CONTROL ON SPECIMENS TAKEN FROM DIFFERENT POINT OF THE PILOT

These results show the correct performance of the material. Due to the start-up of the plant and its preliminary adjustments for the first meters of the demo, the first family of specimens does not meet the resistance requirements (>2.5 MPa) at the laboratory level. However, when comparing the trend line of its density/UCS_7, it is noted that on-site, average densities were reached in that environment of 2.12 t/m^3, indicating that it would reach the 2.5 MPa demanded.

4.4. Monitoring

This pilot is the less sensitive from the environmental point of view as it was interpreted in the preliminary environmental risk analysis, as the soil-cement layer containing WPFA is protected in its base and its cap, near impermeable asphalt layers, forming a "sandwich like" configuration, impeding the direct contact and avoiding the potential leaching from this layer, so, minimizing the potential risks to the media. This is due to the type of construction method:

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- The ash arrives to the construction site directly to the soil cement plant. The truck unload the ash into the soil-cement plant silo by pumping in a closed circuit, in a industrial controlled environment, so that, no dust is emitted in the process.
- The plant blends the WPFA, the soil and the precise water getting a homogeneous mix ready to be transported by truck to the site. In these conditions, there is no dust during transportation and placement.
- The soil cement layer is placed between a bituminous emulsion layer on top of the embankment and it is completely covered by the road base, consisting of 15 cm of sealing asphalt pavement. Finally, the road shoulders, keeping the layer isolated from water entrance and protected from atmospheric conditions, cover both sides of the layer.

Considering these facts, it has been stated that there is no risk of dust emission so the type of environmental monitoring performed in the former pilots does not make sense for this one.

The environmental monitoring will be based in the leaching performance of preserved specimens manufactured with the placement conditions and preserved in climatic chamber until for leaching tests under different conditions.

Given the fact that the pilot was finished by mid-October, there are no data available yet from this pilot.

4.4.1. Technical monitoring.

Technical monitoring will consist on an anlysis of the UCS at different curing ages to test the evolution over the long term and in situ testing basically consisting of tests.

These tests must be performed once the service road will be finished, which is expected by the end of March.

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5. Conclusions

After the exhaustive laboratory and field testing and pilots execution, it is proved the correct technical performance for WPFA-stabilised soils basis on standard stabilised-soil types of Spanish regulations. In all cases, the total amount of traditional binder (cement or lime) was entirely replaced by WPFA successfully.

The commissioning of S-EST2, S-EST3 and SC was carried out with the same machinery and procedures of the traditional stabilised soils without any relevant effects in terms of productivity once it entered into continue production. That is, after the initial start-up and dosing adjustments.

It was found that the setting of the WPFA-soil occurs more slowly but efficiently, which increases its workability term and, possibly, the distancing of its pre-cracking or, even, being able to do without it. This aspect will be reviewed in future research along with studies of openness to traffic on these types of mixtures.

The most significant precaution on this material is its sensitivity to excess water during compaction, which drastically reduces its resistance if the ash supply is very tight.

Economically, the savings on the unit of work is significant by eliminating the cost of the cement involved. But there is another indirect saving: the replacement of cement by fly ash decreases the reference density of the material once compacted, which leads to a higher yield of the latter. At equal tonnage leaving the plant, it yields more soil-ash than soil cement, volumetrically. At the laboratory level, it is estimated that the soil-ash yields 3.6% more. These savings could lead to a reduction of around 30% of the original cost in the work unit.

Environmentally, this type of execution reduces the consumption of raw materials and GHG emissions to the atmosphere that is produced due to the manufacture of cement, being no potential risky for the humans and ecosistems, if proper mixing, handling and use during the construction process is followed. In addition, it fosters a Circular Economy model by taking advantage of a byproduct produced in industry and favours its commitment of "Zero Waste".

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