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OPTIMIZATION OF HIGH-SPEED RAILWAY TRACK USING BITUMINOUS SUB-BALLAST

Progress report of project PDTC/ECM/70571/2006-2009

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"OPTIMIZAÇÃO DE VIAS-FÉRREAS DE ALTA VELOCIDADE MEDIANTE O USO DE SUB-BALASTRO BETUMINOSO"

RELATÓRIO DE PROGRESSO DO PROJECTO PDTC/ECM/70571/2006 – 2009

"OPTIMIZATION OF HIGH-SPEED RAILWAY TRACK USING BITUMINOUS SUB-BALLAST"

PROGRESS REPORT OF PROJECT PDTC/ECM/70571/2006 – 2009

"OPTIMISATION DE GRAND VITESSE DE CHEMIN DE FER AU MOYEN DE SOUS-BALLAST DE BITUME"

RAPPORT D'ACTIVITES DE PROJECT PDTC/ECM/70571/2006 – 2009

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1 | INTRODUCTION

The first high-speed lines in Europe were opened to commercial operation more than 20 years ago. Their construction meant a technological revolution in the railway field, forcing the establishment of new criteria for designing those lines.

Nowadays, these principles are still the dominant element of the high-speed lines design, characterised mainly by a granular ballast and sub-ballast configuration, although the design speeds have been increasing gradually, which raises the rate of deterioration of the line and requires an increase in maintenance.

In this frame, the main objective of the present project is to improve the structural design of the high-speed lines (up to 350 km/h) in order to reduce its maintenance costs by means of the incorporation of a bituminous sub-ballast layer, instead of the classical section, which only includes granular setting beds.

Previous experiences in this field are found particularly in Italy, where the bituminous sub-ballast layer was implemented during the construction of the first Italian high-speed line, in some sections of the “Direttissima” Rome-Florence, as a substitute of cement bound layer. Its good performance has justified the adoption of this solution in all designed high-speed lines until the present time. Also in some high-speed ballasted tracks in Japan a thin layer of bituminous sub-ballast has been applied. Nevertheless, in both cases there are no published studies on the technical-economic interest of this solution.

The objective of this Project is to address the technical and economical feasibility of a high-speed line with bituminous sub-ballast layer. Therefore, as a first step of this research, a set of structural sections were designed for high speed lines with bituminous sub-ballast, to study their response and to compare them with the classical section, using unbound granular sub-ballast. A laboratory trial based on physical model is being set up to perform experimental tests for structural characterization. It aims to contribute to the improvement of the structural design of high speed railway tracks in order to reduce their maintenance costs through the incorporation of a new material: the bituminous sub-ballast, instead of the traditional granular sub-ballast.

This report focuses on the laboratory trial set up. It addresses the characterisation of materials that can be used in railway substructure with asphalt sub-ballast.

For this purpose, the following tasks were undertaken:

a) Design and construction of a physical model of large dimensions representing various types of railway substructures;

b) Laboratory characterisation of selected materials – soils, granular materials and bituminous mixtures (asphalt)- to be used in the physical model;

c) Tests performed on the physical model, at different levels, in order to evaluate the performance of the structure.

The physical model, which is being built at Laboratório Nacional de Engenharia Civil (LNEC), will be representative of various types of railway substructures, both with granular and asphalt sub-ballast. These substructures will be instrumented and further submitted to loading tests in order to evaluate layers stiffness and their permanent deformation behaviour. The materials applied in the construction of the physical model are also being tested for evaluation of their basic physical and mechanical properties. For carrying out the experiment, an instrumentation plan and an experimental program have been established.

2 | LNEC'S PHYSICAL MODEL: INSTRUMENTATION AND EXPERIMENTAL PROGRAM

2.1 General presentation of testing facility

The physical model is being built in a test pit structure at LNEC, which was modified to serve the purposes of this study. It is divided into two sections, one of which presents a square area of 4.0 × 4.0 m^2, and a depth of 2.80 m, with concrete floor and walls (concrete pit section). Laterally there are two concrete chambers 1.10 m wide, which can act as tanks, allowing water level variations inside the pit. The other section is rectangular with a 4.0 × 6.0 m^2 area and 2.60 m depth (Fortunato, 2005). In order to ensure a homogeneous subgrade for all the test sections, the existing materials were excavated from the test pit and replaced with new ones.

For this study, four different infrastructure solutions will be constructed (Cell 1 to 4), as shown in Figure 1. The structures adopted are presented in 2.2.

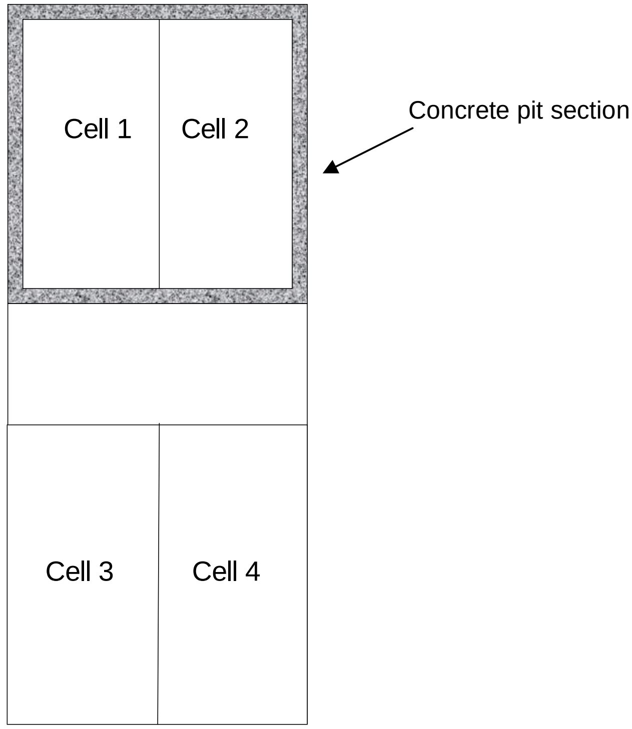

Figure 1 - Plant of the Test Pit

The testing facility is equipped with a reaction structure for load tests that consists of a steel beam, which enables loads applications up to 150 kN. This reaction beam is mobile, runs on two rails and can be used all along the test pit (see Figures 2 and 3). This structure was restored and upgraded, in order to work properly during this Project, according with the testing requirements and railway sections location.

Figure 2 - Overview of the tests pit and reaction beam

Figure 3 - Reaction beam

Figures 4 to 6 show the two sections of the tests pit and the excavation carried out.

Figure 4 - Excavating works in the rectangular section

Figure 5 – Excavating works in the concrete pit section

Figure 6 - Fully excavated sections

2.2 Railway substructures test sections

Four different railway substructures will be tested in order to represent several railway structures: a conventional one, using granular sub-ballast and three non-conventional, using asphalt sub-ballast. These were selected in order to provide reliable comparisons between conventional railway substructure and three distinct non conventional structures using asphalt sub-ballast. The structures selected for the four test sections are presented in Figures 7 to 10.

Test section 1 represents the conventional substructure and test sections 2 to 4 are designed using asphalt sub-ballast layers. Test sections 1 and 2 are being placed in the concrete pit section, within 2.0 x 4.0 m^2 cells each, while the other two are placed in the second tests pit section, within 2.0 x 6.0 m^2 cells each.

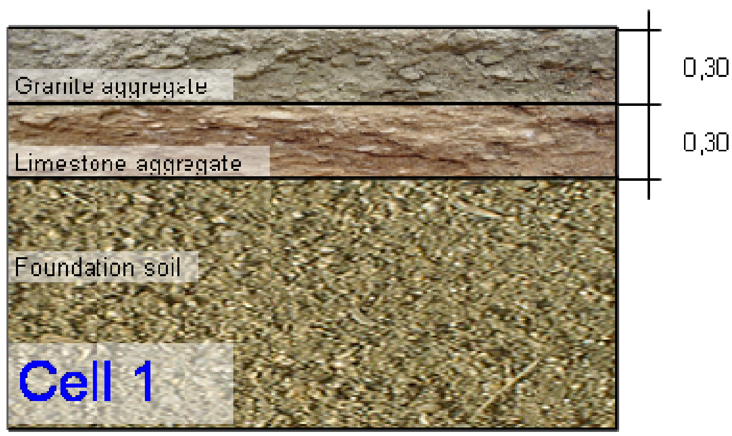

Figure 7 - Test section 1

Figure 8 - Test section 2

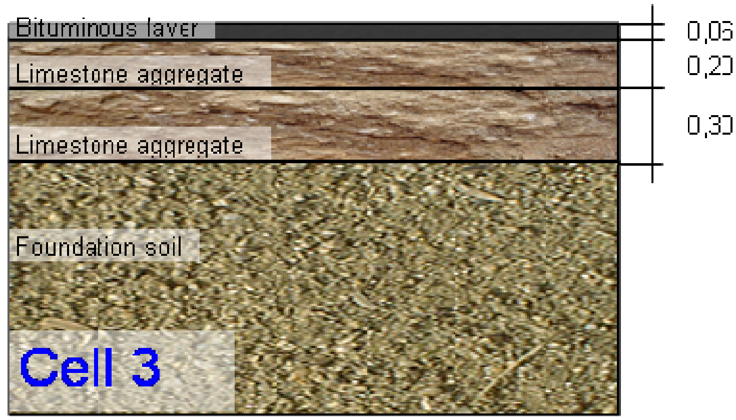

Figure 9 - Test section 3

Figure 10 - Test section 4

2.3 Instrumentation plan

Displacement transducer systems were designed and implemented at LNEC, to be placed at various interfaces of railway substructure layers.

Figures 11 and 12 show details of these transducers and their connection cables. The devices will be positioned in two directions horizontally, to measure the tensile strains and vertically, to measure the compressive strains.

Figure 11 - Displacement transducer system detail

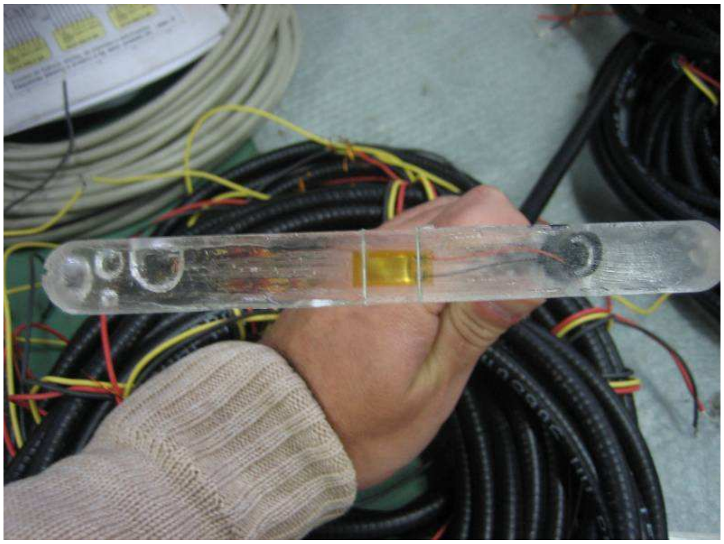

Figure 12 - Top view of the displacement transducer

2.4 Experimental program

The performance of the railway is significantly influenced by the quality of the substructure. Usually resilient behaviour is considered to be related with an equivalent modulus, while long-time behaviour is depending on the vertical permanent deformation of the layers Therefore, the stiffness of the layers and their permanent deformation will be determined in the test pit. For this purpose Falling Weight Deflectometer (FWD) tests and repeated Plate Load Tests (PLT) will be performed at the top of each section.

The repeated Plate Load Tests will be used to analyse the long-term behaviour (vertical permanent deformation) of the layers (Figure 13) under different levels of cyclic loads. The stresses induced by the PLT, do not reproduce the stresses rotation (Figure 14) that occurs under real load situation, however this is considered to be an efficient method to evaluate the vertical permanent deformation.

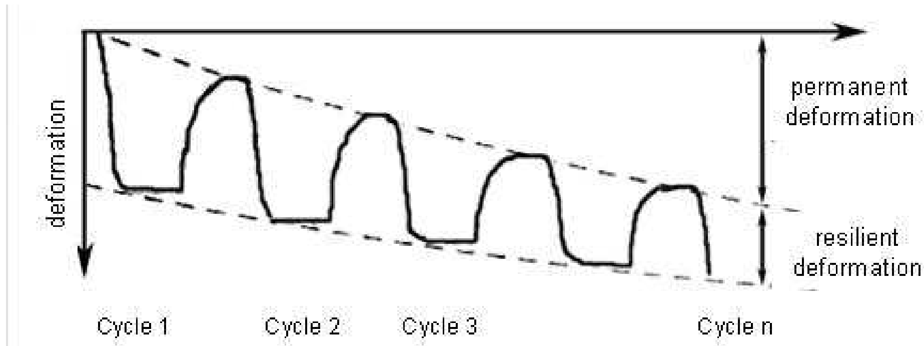

Figure 13 – Accumulation of permanent deformations with repeated cyclic loading (Fortunato, 2005).

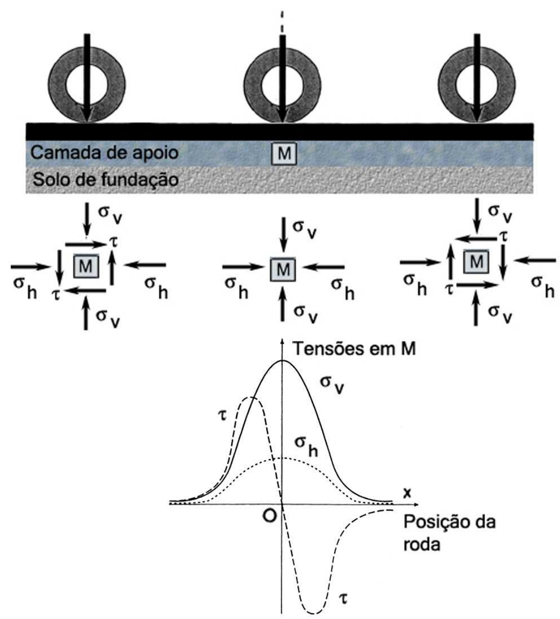

Figure 14 – Load induced stresses in granular materials (Fortunato, 2005)

Falling Weight Deflectometer (FWD) (Figure 15) will be used to determine the resilient behaviour of the substructure.

Figure 15 - Falling Weight Deflectometer (FWD)

Aiming at developing an efficient monitoring methodology for continuous assessment of railway infrastructure condition, tests with the Ground Penetrating Radar (GPR) (Figure 16) will be also performed on the physical model. The application of the GPR together with loading tests will enable the evaluation of the infrastructure condition during construction and later on, during simulation of loads induced during operation.

Figure 16 - Ground Penetrating Radar (GPR)

A brief characterization of the materials used in the different layers of the railways substructures modelled at LNEC are presented herein.

3.1 Materials

3.1.1 Soils

The soils to be placed in the subgrade layers are silty sands, classified as A-2-4 (AASHTO classification). Samples were collected for quality control and laboratory tests in order to define the adequacy of their use in the subgrade layers. Table 1 presents the results obtained. Figure 17 shows the grading curves of subgrade soils.

Table 1 – Laboratory tests results - Subgrade Soils

Sample	LL (%)	LP (%)	IP
AM1	27.1	17.5	9.6
AM2	22.8	NP	NP
AM3	24.0	16.3	7.7

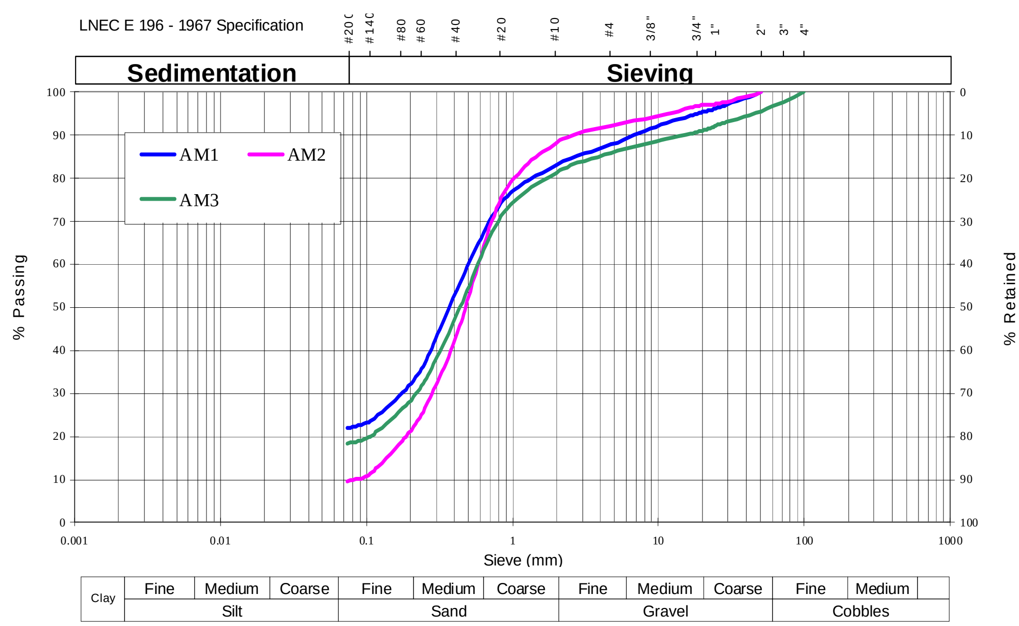

Figure 17 – Grading curve of the Subgrade Soils

3.1.2 Granular materials

The materials to be used in the sub-ballast and capping layers are well graded crushed granite and limestone aggregates, from two National quarries.

The granite material used as sub-ballast fulfils the specifications required by the Technical Instruction REFER IT.GEO.006 (see Table 2).

Table 2 – Physical and mechanical characteristics for sub-ballast material specified in IT.GEO.006

Grading	31.5 mm	90 - 100
	20.0 mm	70 - 90
	16.0 mm	62 - 85
	8.0 mm	46 - 66
	4.0 mm	32 - 52
	2.0 mm	24 - 40
	0.5 mm	11 - 24
	0.25 mm	8 - 19
	0.063 mm	4 - 8
Coefficient of uniformity C_U		CU ≥ 6
Coefficient of curvature C_C		1 ≤ Cc ≤ 3
Percentage of crushed and broken surfaces in coarse aggregates (NP EN 933-5)		< 20 %
Resistance to fragmentation of coarse aggregate, Los Angeles coefficient (NP EN 1097-2)		LA≤ 25%
Resistance to wear of coarse aggregate, micro-Deval coefficient (NP EN 1097-1)		MDE≤ 18%
LA + MDE		< 40%
Water absorption (NP EN 1097-6)		≤1E-04 m/s
Plasticity Index		NP
Liquid Limit		NP
Methylene Blue		MB g/kg x #2mm% <1

For quality control, three samples were collected from each quarry and laboratory tests were performed. Tables 3 and 4 present the results of the tests carried out. Both materials are non plastic.

Table 3 - Laboratory tests results of limestone aggregate

	LA	MDE	EA	MB	MB'	γ_{dmax}	W_{opt}
Sample	(%)	(%)	(%)	(g/kg)	(g/kg)	(g/cm^3)	(%)
1C	27	13	59	2.800	0.841	2.27	6.4
2C	27	12	63	2.840	0.836	2.28	6.6
3C	27	13	69	2.240	0.794	2.25	7.5

Legend:

LA – Los Angeles - resistance to fragmentation of coarse aggregate;

MDE – Micro Deval - resistance to wear of coarse aggregate;

EA – Equivalent sand;

MB – Methylene Blue;

MB' – Methyene blue value corrected per sample;

γdmax – maximum dry unit weight (Modified Proctor);

Wopt – optimum water content (Modified Proctor).

Table 4 - Laboratory test results for granite aggregate

	LA	MDE	EA	MB	MB'	γ_{dmax}	W_{opt}
Sample	(%)	(%)	(%)	(g/kg)	(g/kg)	(g/cm^3)	(%)
1G	22	8	56	0.650	0.196	2.23	7.2
2G	23	9	66	0.610	0.233	2.23	7.0
3G	23	10	63	0.860	0.322	2.23	7.8

Same legend as Table 4:

Figures 18 and 19 show the grading envelope of IT.GEO.006 for sub-ballast material and the grading curve determined in laboratory of limestone and granite aggregates, respectively. In terms of size, the materials have coefficients of uniformity significantly above 6 and coefficients of curvature between 1 and 3. The average values of the permeability coefficient are 1.1x10-5 cm/s and 2.6x10-4 cm/s for the granite and limestone, respectively.

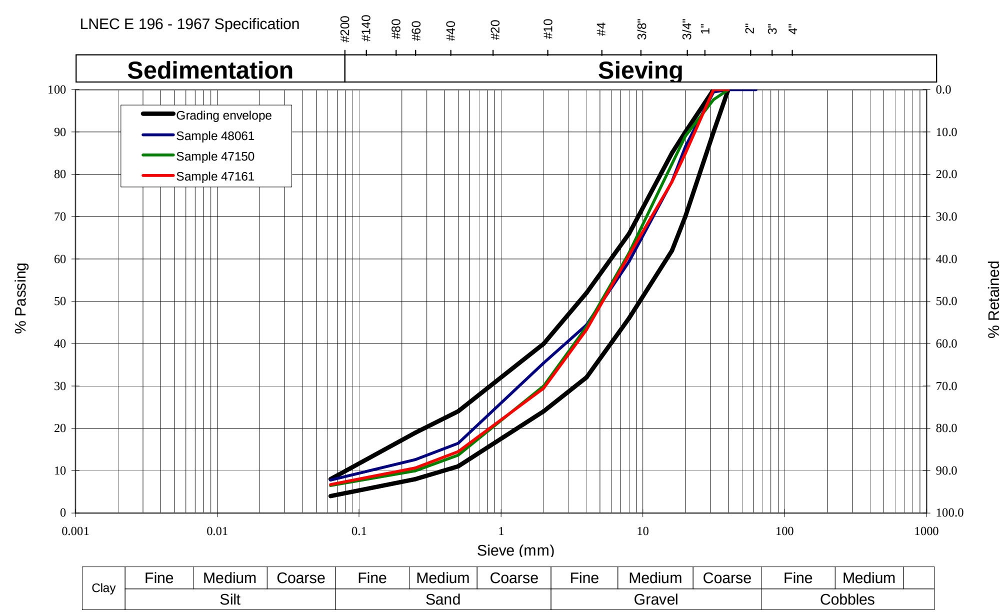

Figure 18 – Grading curve of IT.GEO.006 and of limestone aggregate

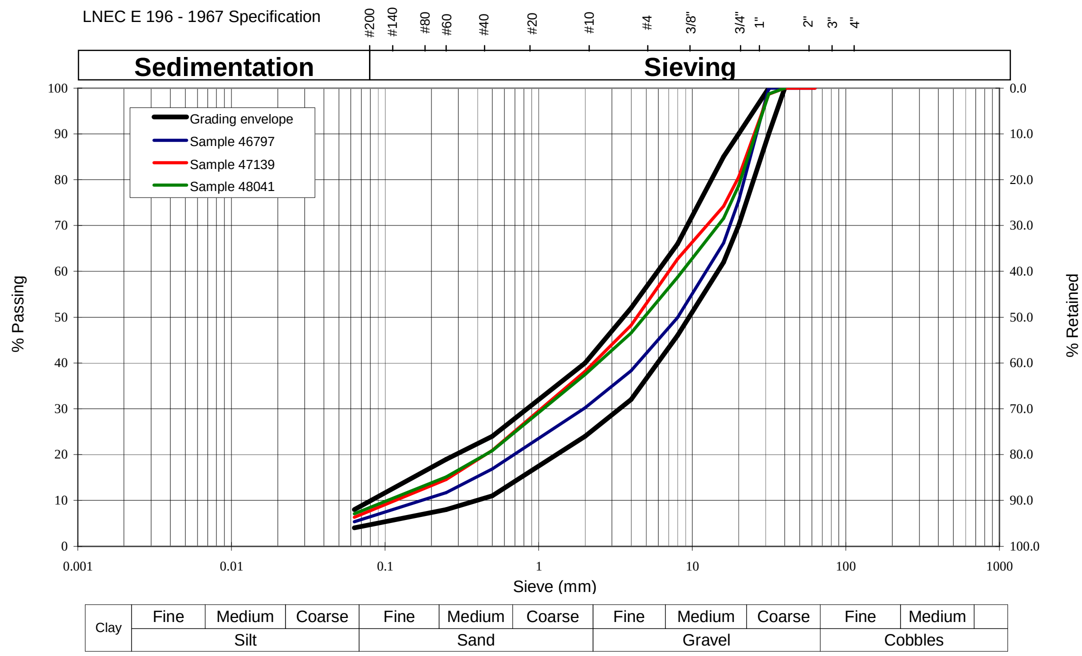

Figure 19 – Grading curve of IT.GEO.006 and of granite aggregate

3.1.3 Dielectric constant measurement

The GPR is a non-destructive equipment that performs an almost continuous measurement of the layers condition beneath the surface, through electromagnetic wave propagation. Nevertheless, the results can vary significantly according to material type and condition, mainly due to variations in the water content. Thus, for an efficient application, it is necessary to characterise the materials used in railway substructure, as well as their electromagnetic properties for different water contents.

These matters were studied during a dissertation for a Master Degree (Pedrosa, 2009). Within this study, not only the dielectric characteristics of materials were addressed, but also the testing methodologies to be applied for railway characterisation with GPR (frequency, test density, gain range and gain window, etc.). Tests were performed on experimental sections (see Figures 20 e 21) constructed at LNEC for the dielectric constant measurement of granite and limestone granular materials to be used on railway substructure sections. The results obtained for both LNEC's GPR antennas (1 Ghz and 2 Ghz) are presented in Table 5.

Figure 20 - Experimental site - Troxler measurements

Figure 21 - GPR measurement – metal plate calibration

Similar dielectric measurements will be performed at the top of the four railway test sections, both on traditional and asphalt sub-ballast solutions, in order to contribute, together with the loading tests results, to a better characterization of the materials.

Table 5 - Tests on experimental site: wave propagation speed, layer thickness and dielectric values

Material	Antennas frequency	Layer thickness (m)	Wave propagation speed (m/ns)	Dielectric value
Granite aggregate	1 GHz	0.32	0.107	7.86
	2 GHz		0.107	7.86
Limestone aggregate	1 GHz	0.29	0.098	9.37
	2 GHz		0.098	9.37

3.1.4 Asphalt mixtures

The asphalt mixtures that will be applied in the various sections previously defined are of the type AC 20 base 50/70 (MB). This type of asphalt mixture was chosen because it is usually applied in paving works and it is assumed to satisfy structural and functional requirements for a sub-ballast layer.

Table 6 presents the requirements of the Portuguese Road Administration (EP) for aggregates to be used in the asphalt mixtures in road base and binder courses (EP, 2009), taking into account NP EN 13043. Table 7 shows the requirements for the asphalt mixtures, considering the European Standard EN 13108-1.

Table 6 - Requirements for aggregates for use in the asphalt mixtures

Properties		AC 20 50/70 (MB)
Grading	31.5 mm	100
	20.0 mm	90-100
	12.5 mm	57-86
	4.0 mm	34-49
	2.0 mm	26-41
	0.5 mm	12-26
	0.125 mm	4-14
	0.063 mm	2-7
Fines quality (NP EN 933-9)		MBF10
Shape of coarse aggregate – Flakiness índex (NP EN 933-3)		FI20
Percentage of crushed and broken surfaces in coarse aggregates (NP EN 933-5)		C 100/0
Resistance to fragmentation of coarse aggregate, Los Angeles coefficient (NP EN 1097-2)		LA40
Resistance to wear of coarse aggregate, micro-Deval coefficient (NP EN 1097-1)		MDE25
Particle density (NP EN 1097-6)		Declared
Water absorption (NP EN 1097-6)		≤ 2 %
Bulk density (NP EN 1097-3)		Declared
Resistance to thermal shock (NP EN 1367-5; NP EN 1097-2)		Declared
Affinity of coarse aggregates to bituminous binders (EN 12697-1)		Declared

Table 7 - Requirements for asphalt mixtures (EP, 2009)

Properties		AC 20 50/70 (MB)
Marshall values (EN 12697-34) (specimens compaction – 75 blows – EN 12697-30)	Maximum stability	Smax15
	Minimum stability	Smim7.5
	Maximum flow	F4
	Minimum flow	F2
	Marshall quotient	Qmin2
Voids in mineral aggregate (VMA), min. (EN 12697-8)		VMAmin14
Voids content, Vm (EN 12697-8)		Vmin3.0 - Vmax6
Water sensitivity, ITSR (EN 12697-12) (specimens compaction – EN 12697-30; 75 blows, 15ºC)		Declared
Resistance to permanent deformation (EN 12697-22) (small size equipment, procedure B, on air, 60ºC)	Wheel tracking slope	Declared
	Maximum deformation	Declared
Binder content, min		Bmin3.5

Laboratory mix design of the asphalt mixtures is being carried out using the Marshall method (EN 12697-34), following the normal practice in Portugal.

The optimum binder content will result from: the average values of binder contents leading to the maximum bulk density of compacted samples (EN 12697-6); from the average of the limits of the percentage of voids (EN 12697-8); the value corresponding to the maximum Marshall stability (EN 12697-34); and the value corresponding to minimum flow (EN 12697-34).

In addition, a study to characterize both the resistance to permanent deformation (EN 12697-22) and the water sensitivity (EN 12697-12) will take place on three asphalt mixtures: one with the optimum binder content determined by the Marshall method, one with a binder content 0.5% below the optimum value and one with a binder content 0.5% above the optimum value previously determined.

Laboratory characterization of asphalt mixtures will also include the execution of repeated load tests, namely four-point bending tests for determination of stiffness and fatigue resistance and triaxial cyclic compression tests for resistance to permanent deformation.

3.2 Quality control

During the construction of the several layers, compaction and moisture content measurements are being performed using the sand cone method (LNEC E 204-1967) and the nuclear probe method (ASTM D 6938), with nuclear equipment.

Together with these devices that are usually used for construction control, a new equipment is being used for compaction and moisture measurements. This equipment, known as Electrical Density Gauge (EDG), is shown in Figure 22. This represents an electrical measuring method that could constitute an alternative to the nuclear probe method (ASTM WK21805).

Figure 22 - Electrical Density Gauge (EDG)

For the calibration of the electrical test device, experimental tests were made on soils specimens placed on a uniaxial compression chamber (500 mm diameter) and on tests pit soils, which measured the density and the water content. Figures 23 and 24 present some aspects of the tests performed with EDG.

Figure 23 – Tests performed with the EDG on the Chamber DU 50

Figure 24 – EDG tests performed at LNEC tests pit

Given space restrictions in the LNEC tests pit, the compaction equipment to be used during construction is limited to light compactors. Therefore, in order to achieve the desired compaction characteristics the construction has to be carried out in layers of 0.10 to 0.15 m thickness.

During construction, the control of layers´ stiffness will be assessed through load tests performed with Portable Falling Weight Deflectometer and GeoGauge (ASTM 6758). At the top of the test sections, the Falling Weight Deflectometer (ASTM D 4694-96) will also be used.

4 | FINAL CONSIDERATIONS

This Project was motivated by the need to improve the performance of railway lines, enabling the design of more durable high speed tracks, and to reduce the maintenance costs of existing lines through the application of asphalt in sub-ballast layers.

With this purpose, a physical model is being built, in which four different railway substructures solutions are being implemented, in order to represent several railways structures: a conventional one using granular sub-ballast and three non-conventional, using asphalt sub-ballast layers.

The materials used for the construction of these structures are the following:

- A-2-4 (AASHTO classification) subgrade soil;
- Well graded crushed granite and limestone aggregates for sub-ballast and capping layers;
- AC 20 base 50/70 (MB) for asphalt sub-ballast.

Laboratory characterization of materials was performed in order to enable a proper application and the quality control during the construction of the physical model. Also, tests were performed on experimental sections constructed at LNEC for dielectric constant measurement of granite and limestone sub-ballast materials.

An instrumentation plan was developed, that includes the installation of displacement transducers at various interfaces of railway substructure layers for the measurement of the strains that occurs during tests. The displacement transducers structures, as well as the data acquisition system, were designed at LNEC.

A testing plan was defined in order to characterise the behaviour of different substructures and to enable the comparison among different solutions in terms of performance. This includes measurements of stiffness and permanent deformation, at the top layer of the four experimental railway substructures.

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