MECHANICAL BEHAVIOUR OF ASPHALT MIXTURES TO BE USED IN RAILWAY INFRASTRUCTURES

Freire, A. C., Civil Engineering Ph. D. - LNEC - acfreire@lnec.pt

Lopes, M. G., Civil Engineering Ph. D. - ISEL - glopes@dec.isel.ipl.pt

Mendes, Susana, Civil Engineering M.Sc. - ISEL - 29334@alunos.isel.pt

ISBN 978-88-902409-0-4

ABSTRACT

Most transport infrastructures, including road and airport pavements, include bituminous mixtures which allow a good performance and an adequate durability under ordinary service conditions.

Due to the need to improve the performance of railways, allowing a more durable high-speed lines and a maintenance cost reduction, several studies to promote the use of new materials, mainly through the incorporation of bituminous mixtures as sub-ballast layer have been developed, instead of the classical section, which only includes granular setting beds.

The present work aims to characterize the mechanical behaviour of bituminous mixtures in order to be applied in railway infrastructures.

As a methodology to study the mechanical behaviour of the bituminous mixtures, laboratory repeated loading tests were performed, namely four-point bending tests (4PBT) to determine stiffness and fatigue behaviour, and cyclic triaxial compression tests to evaluate the permanent deformation behaviour.

The fatigue behaviour of the studied bituminous mixtures was evaluated by the 4PBT, with controlled strain and the application of a sinusoidal loading with different frequencies, according to the European Standard EN 12697-24.

The permanent deformation behaviour of the bituminous mixtures was analyzed with the cyclic triaxial compression test, by subjecting the samples to a static confinement stress through the application of vacuum and applying a rectangular cyclic axial pressure stress, according to the European Standard EN 12697 -25.

For this study several samples were cored from a physical model built at LNEC’s test pit, built in order to test different unconventional railway substructures, namely using bituminous mixtures as sub-ballast layer.

The results obtained showed that the bituminous mixture AC20 base 50/70 (MB) applied in the sub-ballast layer is suitable for application in transport infrastructure because it presents an adequate performance to fatigue and permanent deformation. Through the tests carried out it was also possible to understand the importance of volumetric characteristics, especially the bulk density to a good behaviour of bituminous mixture.

Keywords: Bituminous mixtures, transport infrastructures, mechanical characterization, repeated loading tests, cyclic triaxial tests, fatigue tests.

INTRODUCTION

The traditional railway substructures are usually characterized mainly by granular layers, although having a good mechanical behaviour, they can be infeasible due to the current structural and functional criteria of high-speed transport, implying a constant maintenance with inherent high costs.

To analyze the structural behaviour of high-speed rail lines with different structural solutions, a research study was developed in LNEC involving a physical model, in which four different railway substructures solutions were 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 characterization of the bituminous mixtures, applied to the sub-ballast layer, included triaxial cyclic compression tests and also wheel-tracking tests to evaluate the permanent deformation behaviour and repeated load tests, namely four-point bending tests (4 PBT) to determine stiffness and fatigue behaviour. The knowledge of these mechanical properties is of major importance to the formulation of bituminous mixtures, the design of a structure or the establishment of a proper solution regarding the rehabilitation of a transport infrastructure.

This paper reports and analyzes the results of the mechanical characterization of the asphalt mixture applied to the sub-ballast layer. This includes the evaluation of stiffness, fatigue resistance and permanent deformation.

PHYSICAL MODEL

The physical model used is intended to represent four different types of railways infrastructures (figure 1): one using conventional granular sub-ballast (Cell 1) and three non-conventional using bituminous sub-ballast layers (Cells 2, 3 and 4).

The cell 1 which comprehends the conventional solution with granular sub-ballast comprises a granite aggregate layer with 30 cm thick and a limestone aggregate layer also with 30 cm thick. The cell 2 comprises a limestone aggregate layer 30 cm thick and a bituminous layer with 12 cm thick. Cell 3 comprises two layers of limestone aggregate with respectively a 30 cm thick and a 20 cm thick. In this cell the bituminous layer has only 6 cm thick.

Finally cell 4 comprises a limestone aggregate layer with 20 cm thick, and a bituminous layer with 14 cm thick.

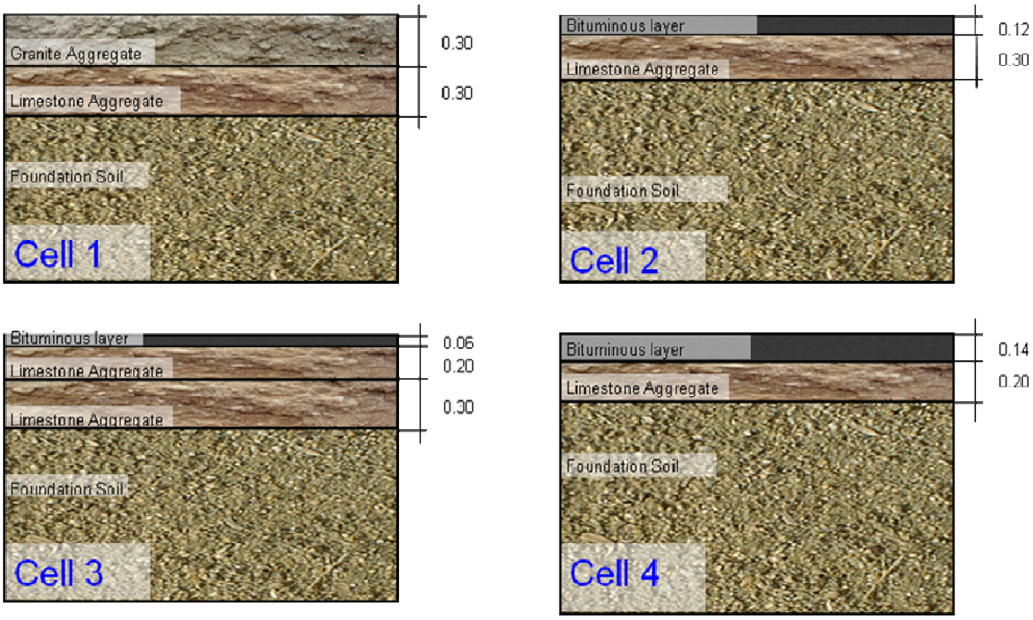

Figure 1 Cells structure (adapted from Fortunato et al, 2011)

BITUMINOUS MIXTURE CHARACTERIZATION

The bituminous mixture applied at the bituminous sub-ballast installation is a AC20 50/70 base (MB) type. The selection of this type of mixture resulted from the fact that its application in usual for road paving, and is expected to accomplish structural and functional sub-ballast layer characteristics.

For mechanical characterization of the bituminous mixture applied, prismatic and cylindrical specimens were compacted in laboratory. On the other hand, specimens were collected from the bituminous sub-ballast layer of cells 2, 3 and 4 (figure 2): in a first stage seven specimens (with red colour in the figure) of each cell were extracted in other to assess the properties of the mixture and for fatigue resistance and stiffness evaluation. At a later stage more six specimens (with blue colour in the figure) were extracted from each cell for triaxial cyclic compression tests.

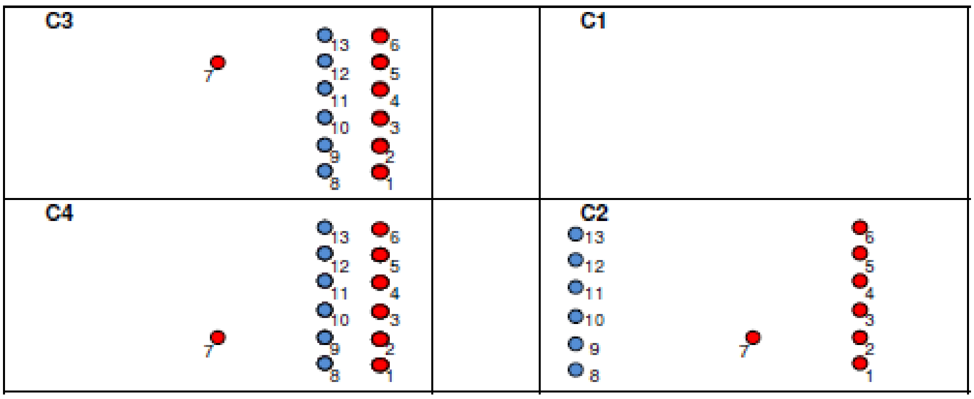

Figure 2 Location of the extracted samples in different cells (Mendes, 2011)

During the application of the bituminous mixtures, samples of the uncompacted material were collected for latter laboratory characterization. Cores were also performed on bituminous layers in order to verify the compaction and bulk density, as well as the layer thickness. Laboratory tests were performed for bituminous mixtures characterization.

Table 1 shows the tests carried out with samples of the bituminous mixture compacted in laboratory, compacted *in situ* and with uncompacted material collected during the application of the bituminous mixtures.

Table 1 Laboratory tests (Mendes, 2011)

Type of mixtures	Test	Standard
Uncompacted asphalt mixtures	Determination of soluble binder content Particle size analysis	NP EN 12697-1 NP EN 933-1
Compacted asphalt mixture in laboratory	Four-point bending tests - Stiffness Four-point bending tests – Resistance to fatigue Wheel-tracking test Indirect tension test	EN 12697-26, annex B EN 12697-24, annex D EN 12697-22, method B, in air EN 12697-26, annex C
Compacted asphalt mixture *in situ*	Determination of the dimensions Determination of bulk density Marshall Test Determination of the water sensitivity Triaxial cyclic compression test Indirect tensile test	EN 12697-29 NP EN 12697-6 (B) and EN 12697-5 (A) NP EN 12697-34 EN 12697-12 EN 12697-25, method B EN 12697-26, annex C

TEST RESULTS AND ANALYSIS

Grading

On the uncompacted asphalt mixture sample after extraction of bituminous binder, the particle size analysis based on EN 12697-2 and NP EN 933-1 standards was carried out on the aggregate mixture retrieved, through the sieving analysis. The grading curve of the aggregate mixture recovered from the uncompacted asphalt mixture applied to the sub-ballast layer is shown in figure 3. In the same figure is also indicated the grading envelope defined in the requirements of the Portuguese Road Administration (EP) (EP, 2011) for the AC 20 base mixtures, showing that the grading curve falls within the limits of the specified grading envelope.

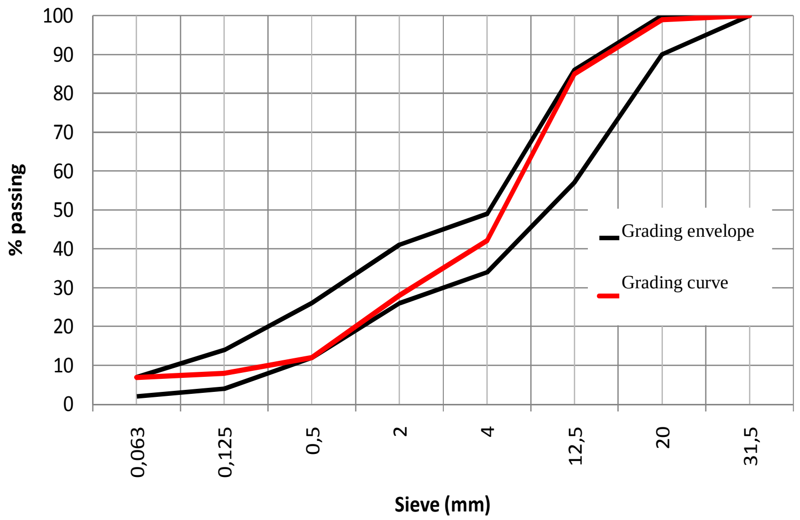

Figure 3 Grading curve of the aggregate mixture (Mendes, 2011)

Binder content

The asphalt mixture applied in the various sections previously defined is of the type AC20 base 50/70 (MB).The binder content of the asphalt mixture was determined according to NP EN 12697-1 "Bituminous mixtures. Test methods for hot mix asphalt. Part 1: Soluble binder content." by method B 1.5 - extraction by centrifugation with the quantification of the amount of residual mineral matter in the binder extract by the method 1 in clauses C.2.

The binder content value obtained (3.5%) is the minimum value specified in the requirements of the Portuguese Road Administration (EP) (EP, 2011), for the type of mixture under study.

Voids content

The void characteristics of bituminous specimens were determined according to European Standard EN 12697-8. Figure 4 shows the mean values and respective standard deviations obtained for voids content of the samples extracted from various cells of the pit and test specimens compacted in laboratory. The figure also shows, in gray colour, the limits considered in the requirements of the Portuguese Road Administration (EP) (EP, 2011) for this type of bituminous mixture (3% to 6%).

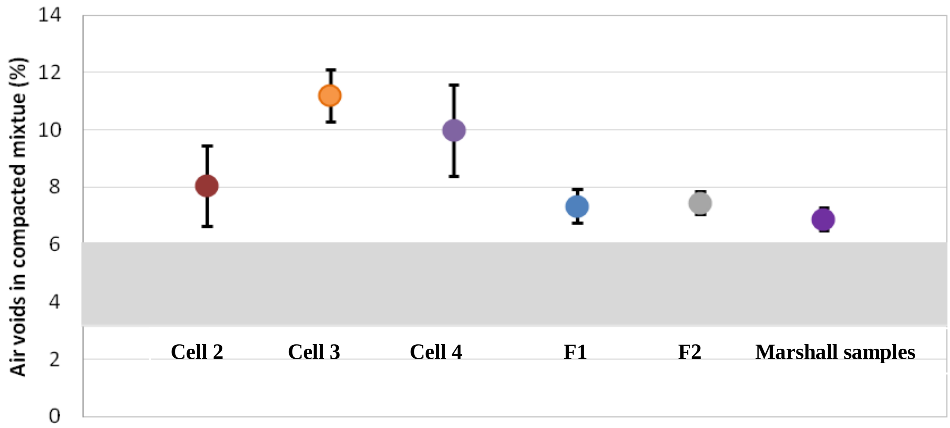

Figure 4 Samples mean and standard deviation voids content (Mendes, 2011)

From the values shown in figure 4, all samples exhibit voids content outside of the specified range for this type of asphalt mixture. It is further understood that the values of the voids content of the samples extracted from cells C2, C3 and C4 are higher than those of the samples compacted in laboratory (F1, F2 and Marshall Test specimens), which may eventually result from the difficulty in performing a properly compacting on the asphalt mixtures applied to the cells due to the small dimensions of the test pit.

Marshall Test

The Marshall test results (performed according to NP EN 12697-34) for specimens collected from the cells 2 and 4 are shown in Table 2.

Table 2 Marshall characteristics (Mendes, 2011)

Specimens	Average stability (kN)	Average deformation (mm)	Marshall quotient (kN mm^{-1})
Cell 2	9.4	6.4	1.5
Cell 4	6.3	6.7	0.9

The results show some variability due to the difference in voids content of the specimens collected from cell 2 and 4 (respectively 8% and 10%).

Water sensitivity

The evaluation of the water sensitivity of the bituminous specimens was conducted in accordance to Method A of EN 12697-12 standard. The results obtained are shown in Table 3.

It can be concluded that the mixture has a good behaviour of water sensitivity, since indirect tensile strength ratio (ITSR) is greater than the value specified in the standard (80%).

Table 3 Water sensitivity test results (Mendes, 2011)

Sample	Properties	Dry specimens	Wet specimens
AC20 base 50/70	Average geometrical bulk density (kg m^{-3})	2282	2277
	Average value of indirect tensile strength - ITS (kPa)	2180	2200
	Indirect tensile strength ratio - ITSR (%)	100	

Resistance to fatigue

The fatigue resistance of the asphalt mixtures was determined according to standard EN 12697-24. The test conditions adopted consisted in applying a repeated sinusoidal load with a 10 Hz frequency, with controlled strain. The test temperature was 20° C, the test was conducted for four strain levels (600, 400, 200 and 100 µm) with two replicates per level. The fatigue life law obtained for each of the sets specimens, F1 and F2, and it is shown in Figure 5.

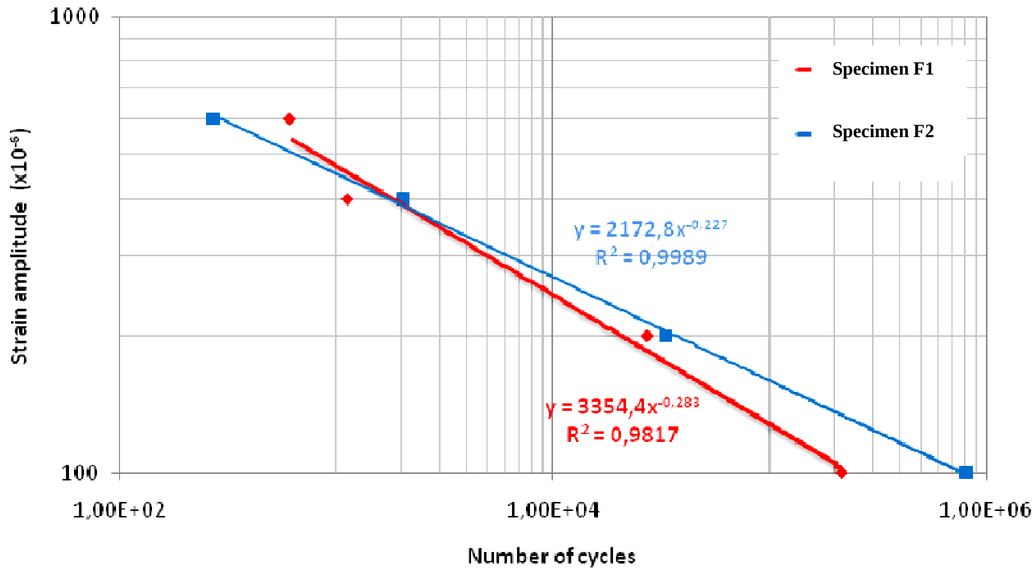

Figure 5 Fatigue law of bituminous mixture - specimens F1 and F2 (Mendes, 2011)

From figure 5 it can be concluded that the asphalt mixture under study has a fatigue resistance within the range considered normal for that type of mixture.

Stiffness module

The stiffness module of the bituminous mixture applied to the sub-ballast layer was carried out by indirect tension tests according to the EN 12697-26 standard, annex C, and by four-point bending tests (4PBT), according to EN 12697-26 standard, annex B. The test conditions applied to the specimens subjected to indirect tension involve a preload with repetition of charge value, for 10 cycles in order to perfume the adjustment of the system of load charge. The test was performed according to two diametric perpendicular directions and the value of stiffness module was computed by mean value of the two tests. The test results, at temperatures of 10ºC and 20° C are shown in Table 4.

Table 4 shows the influence of temperature on the values of stiffness module, i.e., lower stiffness module at higher test temperatures. Also the influence of the compaction characteristics of the bituminous mixture, expressed by the voids content, also affect the stiffness module, observing a reduction in the stiffness module for the specimens with higher voids content, as it is the case of the samples (5B and 6B) extracted from the cell 4 (C4) in comparison with to specimens A and B compacted in the laboratory.

Table 4 Indirect tension test results (Mendes, 2011)

Samples	Temperature (ºC)	Bulk density (kg m^{-3})	Voids content (%)	Stiffness module (MPa)
C4-5B	10	2325	7.6	11053
C4 6B		2256	10.3	15451
A		2349	6.6	27080
B		2335	7.2	25135
C4-5B	20	2325	7.6	8016
C4 6B		2256	10.3	7652
A		2349	6.6	15744
B		2335	7.2	17050

The test conditions adopted for the four-point bending test (4PBT) in accordance with EN 12697-26 standard, Annex B, consisted of a repeated sinusoidal loading, and a maximum traction strain of 50 µm. The tests were performed at 20 ° C in order of increasing frequency, having been applied 1, 4, 8, 10, 30 Hz and again 1 Hz. At each frequency 100 cycles were applied, excepting at the frequency of 30 Hz where 200 cycles were applied. Figure 5 shows the evolution of the stiffness module of the bituminous mixture according to the frequency of loading for the specimens F1 and F2.

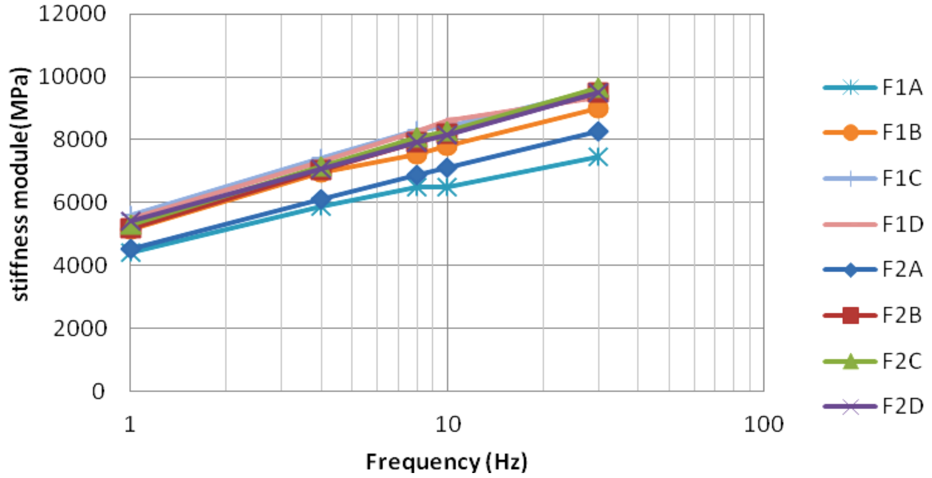

Figure 5 Stiffness module of the bituminous mixture versus frequency for specimens F1 and F2 (Mendes, 2011)

Figure 5 shows that the stiffness module of specimens F1 and F2 increase with the increase in the frequency. The values of stiffness modules for 8 Hz and 10 Hz are similar.

Permanent deformation behaviour

The permanent deformation behaviour of the bituminous mixtures applied to the layer of the sub-ballast was analyzed with the cyclic triaxial compression test, by subjecting the samples to a static confinement stress through the application of vacuum and applying a rectangular cyclic axial pressure stress, according to EN 12697 -25 standard (method B) and the test conditions specified in the NP EN 13108-20.

The test temperature was 40° C and before the test a pre-load of 5 kPa (0,02 (σ_B+σ_C)) was applied during 120s. The cylindrical specimen was subjected to a cyclic axial load of 200 kPa, the load was a rectangular charge with 1 s loading and 1 s load rest. Also, it was subjected to a constant confinement lateral pressure of 50 kPa created through the application partial vacuum. The test was carried out for a total of 10,000 cycles.

The test results are shown in Figure 7 through the creep curves that relate the axial strain of the specimen during the test with the number of cycles.

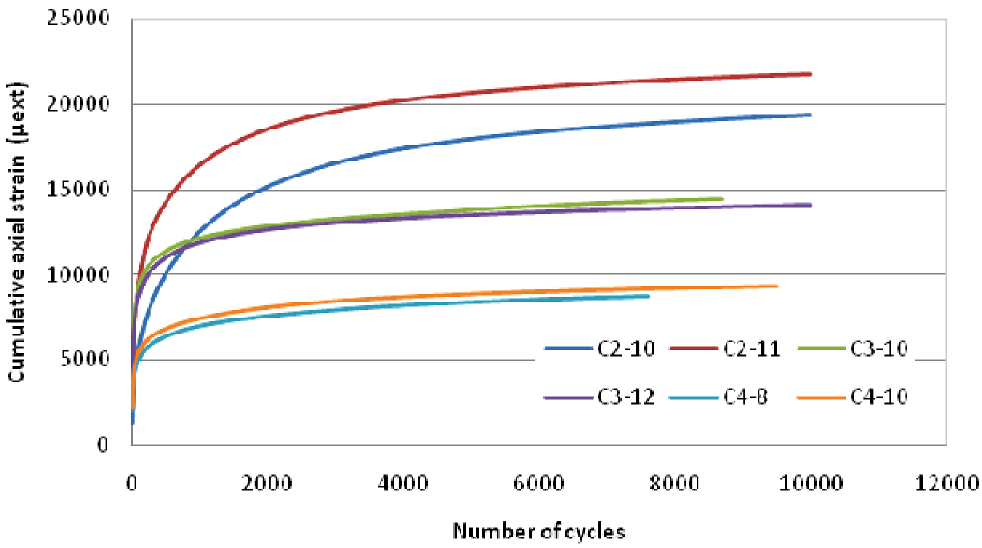

Figure 7 Permanent deformation of bituminous cored specimens under cyclic triaxial compression test (Mendes, 2011)

As shown in Figure 7, in any of the specimens tested it was not achieved the phase of rupture of the specimen. From the figure it is also possible to conclude that the specimens collected in cell 2, with smaller voids content, have higher strain values in comparison with specimens collected from cells 3 and 4, showing a worse behaviour to permanent deformation, eventually as a result of grater evolution of the axial strain during the initial phase. The variability on the obtained results for the same type of asphalt mixture, but with different values of voids content, may be an indicative of the need for more tests to characterize the mixture, eventually with specimens of different voids content.

The wheel tracking test was used to determine the resistance to permanent deformation, according to EN 12697-22 standard, method B, in air. The test was carried out at the temperature of 60° C, as stated in NP EN 13108-1, and at a load charge of 10,000 cycles on the two samples simultaneously. The test ended after 10,000 cycles and did not reach the rut depth of 20 mm, one of the criterions for stopping the test described in the applied standard. Two samples (WT1 and WT2) were subjected to testing: sample WT1 with dimensions 305×305×54 (mm), presented a immersed bulk density of 2257 kg m^{-3} and a voids content of 10.3%; sample WT2 with dimensions 305×305×51 (mm), presented a immersed bulk density of 2318 kg m^{-3} and a voids content of 7.8%.

Table 5 shows the test results for the wheel-tracking slope in air (WTS_{AIR}) and for the mean proportional rut depth (PRD_{AIR}) of the tested samples.

Table 5 Wheel tracking test results (Mendes, 2011)

Samples	WTS_{AIR} (mm/10^3 cycles)	PRD_{AIR} (%)	Mean rut depth (mm)
WT1	0.07	5.7	3.0
WT2			

Figure 6 shows the evolution of the permanent deformation obtained during the tests. From Figure 6 it appears there is a high influence of the voids content of the samples in the obtained deformation values. It can be noticed that WT1 sample, with a higher voids content value, has slightly higher deformation than the WT2 sample. Also, in the initial phase of permanent deformation curve the deformation is higher for WT1 sample, which may explain the greater rut depth value displayed.

The values obtained fall within the range expected for a bituminous mixture of this type. Considering the categories presented in the EN 13108-1 standard for the obtained parameters, it can be asserted that the bituminous mixture under study falls in the categories WTS_{AIR} of 0.80 and PRD_{AIR} of 7.0.

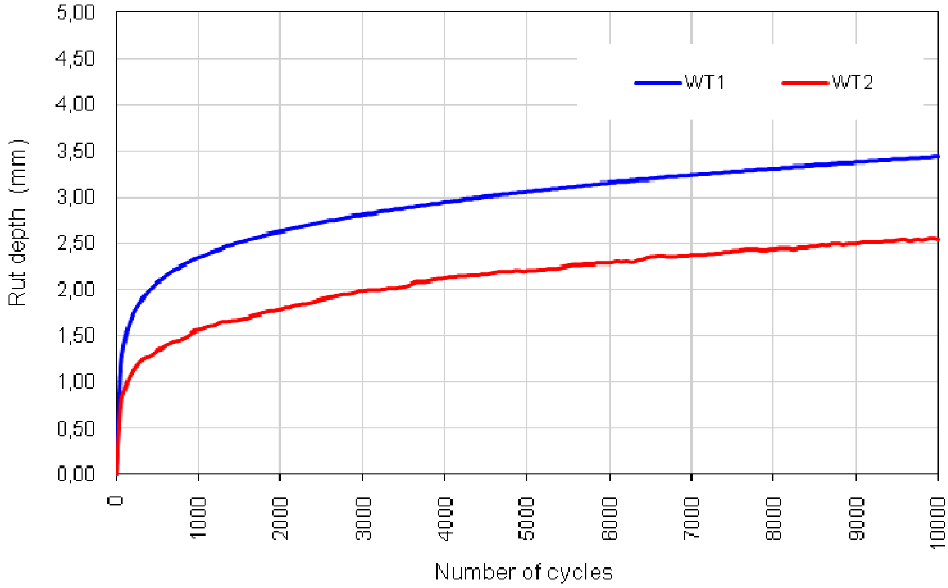

Figure 6 Permanent deformation of bituminous samples under wheel tracking test (Mendes, 2011)

CONCLUSIONS

This article presents the main results obtained on the mechanical characterization of an asphalt mixture type AC20 base 50/70, applied in the sub-ballast layers. For this purpose specimens were compacted in the laboratory and specimens were collected from a physical model constructed in order to analyze the structural behaviour of railway infrastructure. To determine the stiffness module four-point bending tests (4PBT) and indirect tension tests were performed on specimens compacted in the laboratory and specimens collected after application. The fatigue behaviour of bituminous mixture was evaluated using the four-point bending tests (4PBT), performed on specimens compacted in the laboratory. In what regards the permanent deformation behaviour, wheel-tracking test tests and cyclic triaxial compression test were carried out.

The results of the various tests have enabled the following conclusions, considering its application in sub-ballast layers:

- The voids content of the specimens of asphalt mixture presented high values, above the limits initially foreseen. This was the case of the samples compacted *in situ* due to the difficulty of asphalt mixture compaction due to the reduced size of the test pit where the material under study was applied;
- The water sensitivity of the bituminous mixture was not affected by the voids content, having been achieved an excellent value in of the indirect tensile strength ratio, if compared with other results obtained in similar tests (Freire, A. C. *et al*., 2009; Batista, F.A., Antunes, M. L., 2009);
- The stiffness module values obtained by indirect tension tests were significantly higher than those obtained by four-point bending tests (4PBT), despite being different tests. From the analysis of the results of the indirect tension test was possible to established that the specimens compacted in laboratory show higher stiffness module in comparison with the ones compacted *in situ*, a fact which is related to the difference observed in the values of voids content obtained for the specimens compacted in laboratory. Also, it was possible to state that an increase in temperature reduces the stiffness modulus as a result of the visco-elastic behaviour of the mixture.

- The fatigue resistance of the bituminous mixture tested was revelled as compatible with the usually observed in such type of mixtures.
- The behaviour of the permanent deformation of the bituminous mixture tested was revelled as compatible with that of this type of mixtures. In assessing the behaviour of permanent deformation, through the cyclic triaxial compression test, specimens which showed higher voids content values have lower permanent deformation. Moreover, in many tests carried out have shown the influence of the voids content on the results.

ACKNOWLEDGEMENTS

The financial support of GALP for the physical model construction, the rehabilitation of the testing facility and testing equipment is acknowledged.

REFERENCES

Batista, F.A., Antunes, M. L. (2009). "*Ensaios de comparação interlaboratorial para avaliação da sensibilidade à água de misturas betuminosas compactadas*". Report DT/09, LNEC, Lisboa.

EN 933-1:1997."*Tests for geometrical properties of aggregates. Determination of particle size distribution. Sieving method"*, CEN, Brussels.

EN 12697 – 12: 2008. "*Bituminous mixtures. Test methods for hot mix asphalt. Part 12: Determination of the water sensitivity of bituminous specimens"*,CEN, Brussels.

EN 12697 – 22: 2003 + A1: 2007. "*Bituminous mixtures. Test methods for hot mix asphalt. Part 22: Wheel Tracking"*, CEN, Brussels.

EN 12697 – 24: 2004 + A1: 2007. "*Bituminous mixtures. Test methods for hot mix asphalt. Part 24: Resistance to fadigue"*, CEN, Brussels.

EN 12697 – 25: 2005. "*Bituminous mixtures. Test methods for hot mix asphalt. Part 25: Cyclic compression test*", CEN, Brussels.

EN 12697 – 26: 2004. "*Bituminous mixtures. Test methods for hot mix asphalt. Part 26: Stiffness"*, CEN, Brussels.

EN 12697 – 29: 2002. "*Bituminous mixtures. Test methods for hot mix asphalt. Part 29: Determination of the dimensions of a bituminous specimen"*, CEN, Brussels.

EP (2011). "Caderno de Encargos Tipo Obra.14.03 – Pavimentação. Estradas de Portugal S. A", EP, Almada.

Fortunato, E., Fontul, S. and Costa, C. (2011). "*Optimização de vias ferroviárias de alta velocidade mediante o uso de sub-balastro betuminoso*", Project PDTC/ECM/70571/2006: Caracterização experimental das propriedades dos materiais e leis constitutivas – Final Report, Report LNEC 57/2012 DT/NIF.

Freire, A. C., Antunes, M. L., Maricato, S., Moura, J. (2009). "*Estudo do comportamento de misturas betuminosas resistentes aos carburantes*", XV Congresso Ibero-Latino Americano do Asfalto, Portugal.

Mendes, S. (2011). "*Caracterização mecânica de misturas betuminosas a aplicar em infra-estruturas de transportes*", Master thesis, Instituto Superior de Engenharia de Lisboa.

NP EN 12697-1:2005. "*Misturas betuminosas. Métodos de ensaio para misturas betuminosas a quente. Parte 1.* Determinação da percentage de betume", IPQ, Portugal.

NP EN 12697 – 6: 2003 + A1: 2010. "*Misturas betuminosas. Métodos de ensaio para misturas betuminosas a quente. Parte 6: Determinação da baridade de provetes betuminosos"*, IPQ, Portugal.

NP EN 12697 – 34: 2004 + A1: 2010. "*Misturas betuminosas. Métodos de ensaio para misturas betuminosas a quente*. *Parte 34: Ensaio Marshall*", IPQ, Portugal.