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Assessment of stiffness and fatigue tests in Portugal

L. Picado-Santos & A. Almeida
Department of Civil Engineering, University of Coimbra, Coimbra, Portugal

J. Pais
Department of Civil Engineering, University of Minho, Guimarães, Portugal

M. L. Antunes & F. Batista
Department of Transports, LNEC, Lisboa, Portugal

ABSTRACT: In the last decade, quality control of asphalt mixtures for pavement construction on the main Portuguese national road network used, most of the time, four-point bending beam tests (4pb) results as a reference. Stiffness modulus and fatigue laws established with samples prepared in the laboratory are usually used as a reference for behaviour/quality control analysis of the samples coming from the construction site. There is however, with this procedure, not only a problem of real world representation but also a question of the compatibility of results coming, again most of the time, from different laboratories using different equipments. Trying to address the second problem, this paper presents the results obtained from four-point bending tests carried out in three different laboratories in Portugal, owning three different 4pb equipments, concerning the performance characterization of a typical Portuguese base course asphalt mixture. The paper finally discusses the variability of the results obtained and underlines the main inferences that could be extracted.

1 INTRODUCTION

Asphalt mixtures applied in construction works on the Portuguese national motorways network are often subjected to a "performance based" type of quality control.

For the majority of the situations, the reference laws for characterising the deformation behaviour and fatigue resistance are established using 4pb tests over laboratory prepared beams fabricated with material samples coming from production plant. It often happens that the laboratory where the reference laws were established is not the laboratory that controls the quality of the materials performing 4pb tests on beams collected at the construction site and compares the results with those reference laws.

This paper addresses the differences that can be found among three different laboratories, all of them with an extensive participation on asphalt mixtures quality control processes during the last decade, when obtaining the mechanical characteristics (stiffness modulus and phase angle) and fatigue resistance of a typical Portuguese base course asphalt mixture.

The discussion of the results will help to understand if the differences found make it necessary to produce a new orientation for Portuguese performance assessment of asphalt mixtures.

2 CONDITIONS USED ON THE STUDY

2.1 *Type of 4pb Equipments*

One of the equipments is of the “Cox” type with the horizontal translation freedom at the supports established with ball bearings. Separate bending frames in which the beams are clamped by servo motors ensure the required rotation freedom at the supports. Although the two inner supports are connected to each other they can move independently of each other. There is a stop at the end of the frame to avoid that the beam may slide away. An absolute deflection with respect to the move less main frame is measured using a ‘bridge’ resting on the outer reference supports. The deflection sensor measures the deflection in the centre of the beam. The beam dimensions are limited to the typically 65x50 mm^2 cross section. Because the equipment is normally used for low frequencies (< 10 Hz) no corrections are needed nor applied for the influence of mass inertia forces on the bending.

The second equipment is a Cooper Technology equipment, referred to as “CRT-SA4PT-BFAT”, which uses servo pneumatic technology and a digital data acquisition and control system. The loading system is able to apply a repeated sinusoidal signal at a given frequency. The distance between inner clamps is 118.5 mm, and therefore the distance between the outer clamps is 355.5 mm.

Finally, the third equipment is a self made design. The requirements for the translation and rotation freedoms at the supports are fulfilled by “rollers” (bearings) used between the beam and the supports. Also a lubricant is used to minimize friction. The clamping is achieved by pneumatic actuators with a constant force. A PID process control with a feed-forward speed loop is used. The frequency is limited from 0.1 to 10 Hz. The deflections are measured in an absolute way. The length between the two outer supports can be varied between 270 and 450 mm and the distance between the two inner supports from 110 to 150 mm. The maximum width for the beams is 90 mm and the height is limited to 80 mm. The back calculation formulas are based on the formulas for the pseudo-static case. In view of the limited frequency range no corrections have to be applied for the influences of moving masses.

2.2 *Asphalt Mixture*

A typical Portuguese standard for base course (or binder course) hot mix asphalt concrete was used as a reference. This type of mixture is usually used with a 10 cm thickness limit on a pavement. This reference matches the new Portuguese provisional standard for asphalt concrete (IPQ, 2008) which resulted froma European standard with the same reference (EN 13108-1).

The blend of limestone aggregates used was the following: 5% of filler; 41.5% of 0/5 (mm); 23.5% of 5/15 (mm) and 30.0% of 15/25 (mm). This blend allowed the grading showed in Figure 1 for the mixture.

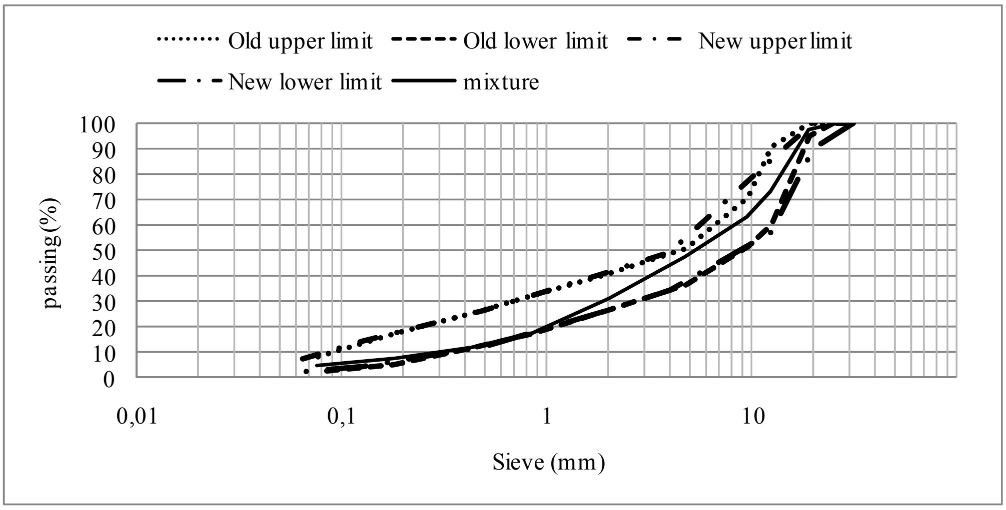

Figure 1. Grading curve of the asphalt mixture used printed with the limits of the blend used in Portuguese technology

The former blend limits (“Old” in the legend) used in Portuguese technology until 2008 as well as the new blend for asphalt concrete according to the new Portuguese standard (IPQ, 2008) which is in line with the European standard is also shown in Figure 1.

A virgin 50/70 (millimetres/10) penetration bitumen was used to produce the mixture. The bitumen content was 4.2% which resulted from a previous composition study (Baptista and Picado-Santos, 2007) made with other objectives.

The beams for the tests (435x65x50 mm^3) were obtained by cutting roller compacted slabs (435x500x50 mm^3) which had had a consistent 3% of void content. The three laboratories received 14 beams each. In Table 1 the bulk specific gravity average and four variability indicators are shown for the three sets of beams. It can be said that the three sets presented consistent results in terms of bulk specific gravity. This and the fact that all the beams had similar dimensions was enough to admit that the three sets have the necessary homogeneity to proceed with the tests.

Table 1. Bulk specific gravity (kg/m^3) average and four variability indicators for the three sets of beams, one for each laboratory

Indicator	Set 1	Set 2	Set 3
Average	2383	2381	2384
Standard deviation	6,8	10,6	11,1
Max value	2395	2397	2400
Min value	2372	2353	2360
Variation coefficient	0,29%	0,45%	0,46%

2.3 *Test Conditions*

It was decided the use of two test temperatures, 20ºC and 40ºC, to analyse the deformation behaviour (stiffness modulus and phase angle). Temperatures close to 40 ºC adequately represent the upper level of Portuguese service temperatures on flexible pavements at a depth of 10 cm (Picado-Santos, 2000 and Freire et al, 2006). The temperature of 20ºC is often the reference temperature used in pavement design and for the quality control of the mixtures despite the fact that temperatures of around 25ºC for asphalt layers at a depth of 10 cm are the temperatures that represent service conditions in Portugal.

The strain used to perform the stiffness tests was 100 μm/m. The strain application uses a sinusoidal form with amplitudes of 50 μm/m plus -50 μm/m. The frequencies analysed were 1, 2, 4, 6, 8 and 10 Hz. The last one (and 6 and 8 Hz in less extent) usually is used to carry out quality control tests but it was agreed to analyse the whole spectrum ranging from 1 Hz to 10 Hz.

To establish the fatigue laws a 20ºC temperature was also set for the reasons abovementioned and because it is the most appropriate to perform fatigue analysis when compared with 40ºC.

The fatigue tests were carried out using three imposed strains, 200, 500 and 800, applied through a sinusoidal form with amplitudes that were half of the total imposed strain. The frequency used in each case was 10 Hz.

3 RESULTS AND DISCUSSION

3.1 *Stiffness Modulus and Phase Angle*

The results will always be identified per laboratory. Each one of the laboratories is identified by a number (1, 2 or 3) corresponding to the sets of beams with the same number as the label. Tables 2 and 3 show the results (average from 3 samples per figure for stiffness modulus and phase angle) for the test conditions selected. In the figures 2 to 5 the same results are shown in a more visual friendly form.

In general, the stiffness modulus increases with test frequency (high frequencies are known to correspond to higher load application speeds which means lower loading times). The opposite occurs for the phase angles. These results are typical for the whole range of temperatures and strain levels (Picado-Santos *et al.*, 2003). This trend was verified in the tests for the three laboratories despite the fact that some of the sets of results had a more evident evolution than others. It is notorious that the abovementioned general trend is clearer for the stiffness modulus than for the phase angle and for 20ºC than for 40ºC. This is not something unexpected because at 40ºC the asphalt mixture behaviour is more complex (non-linear) than at 20ºC and, as known, the form of determination of the phase angle is more influenced by this aspect.

Table 2. Stiffness Modulus and Phase Angle at 20ºC for the beams tested in the three laboratories

Frequency (Hz)	1		2		3	
	Stiffness (Mpa)	Phase Angle (degree)	Stiffness (Mpa)	Phase Angle (degree)	Stiffness (Mpa)	Phase Angle (degree)
1	5159	32	4604	32	4856	35
2	5765	29	5668	26	5809	27
4	7597	24	6760	22	7041	21
6	8486	21	7388	19	7709	18
8	8743	17	7828	17	8039	17
10	8980	15	8166	16	9243	17

Table 3. Stiffness Modulus and Phase Angle at 40ºC for the beams tested in the three laboratories

Frequency (Hz)	1		2		3	
	Stiffness (Mpa)	Phase Angle (degree)	Stiffness (Mpa)	Phase Angle (degree)	Stiffness (Mpa)	Phase Angle (degree)
1	956	40	244	61	448	53
2	1057	40	382	61	636	53
4	1083	42	605	61	977	50
6	1301	46	789	60	1289	46
8	1407	47	948	59	1543	45
10	1422	45	1090	58	1868	46

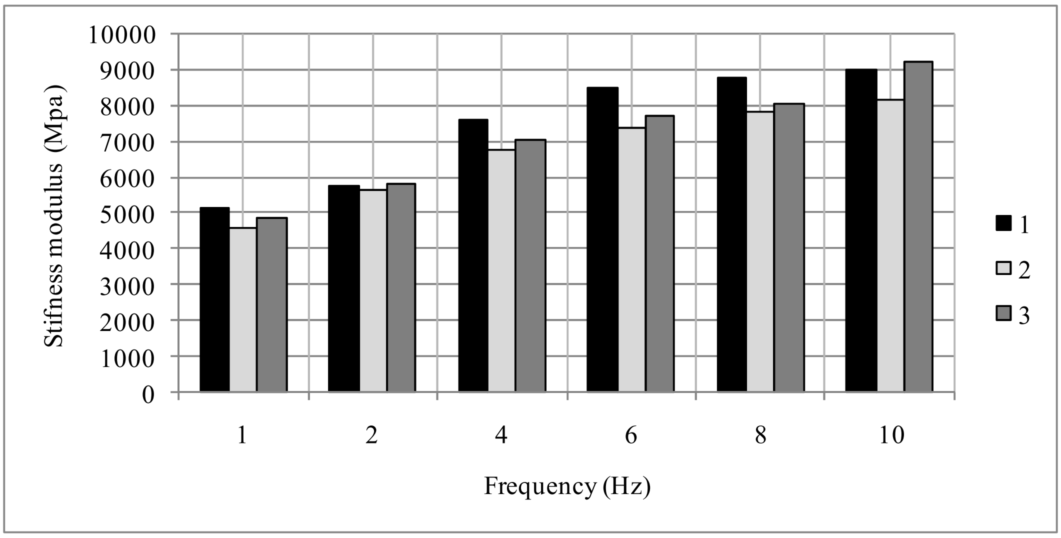

Figure 2. Stiffness Modulus at 20ºC for the beams tested in the three laboratories

Just looking at the stiffness modulus at the three higher frequencies (6, 8 and 10 Hz), because they are the ones mostly used when performing quality control analysis, Table 4 shows in the first two columns the differences between the laboratories in percentage of the lower value, consistently coming from laboratory 2, and also, in the last column, the difference between the laboratories 1 and 3 in percentage of the figure of the last one.

The main inference that can be exposed by these results is that a tolerance of at least 15% should be considered when analysing stiffness modulus results at relatively low test temperatures (around 20ºC). When using high test temperatures (over 30ºC probably) for the same purpose the whole process should be accomplish by the same laboratory and figures should be seen as relative and not absolute.

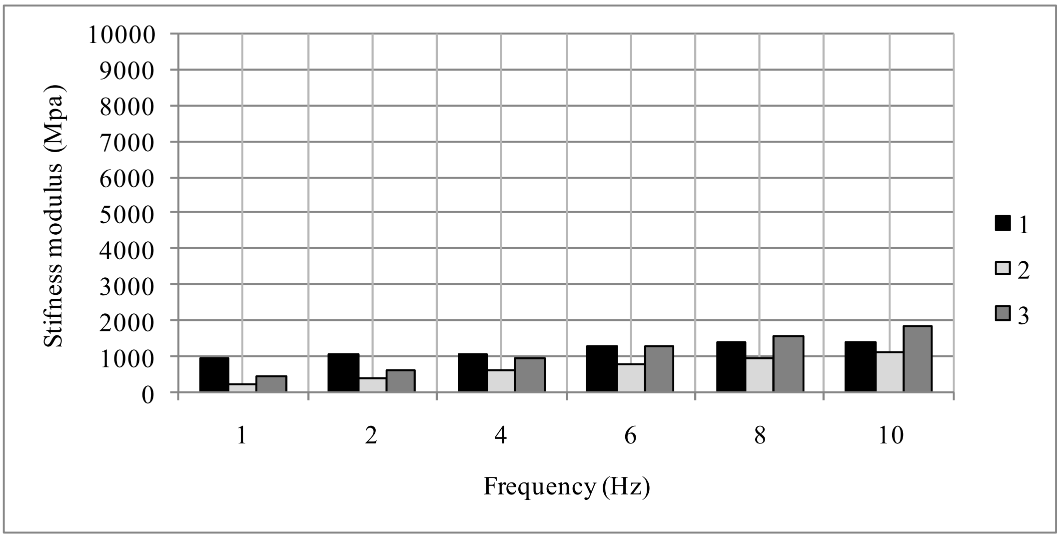

Figure 3. Stiffness Modulus at 40ºC for the beams tested in the three laboratories

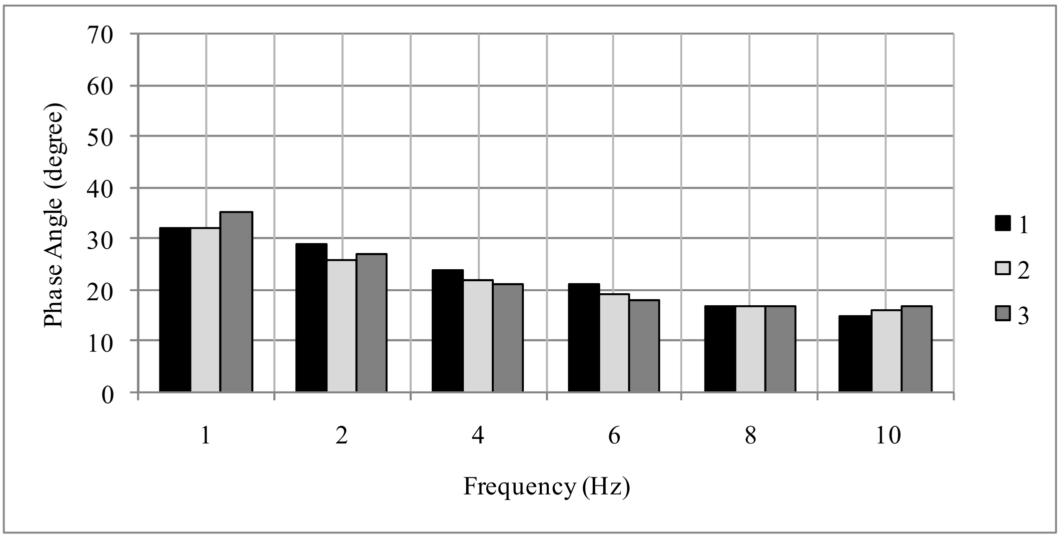

Figure 4. Phase Angle at 20ºC for the beams tested in the three laboratories

3.2 *Fatigue Analysis*

As known, fatigue life characteristics of asphalt mixtures, often translated by "fatigue laws", are represented most of the time by relationships between the applied strain and the number of load repetitions to failure. For design purposes those laws, after adjustments based on behaviour observation, could be aimed to relate the strain with the number of standard axle's repetitions to failure. When used as reference for quality control purposes, the fatigue laws are directly derived from laboratory fatigue tests, in general of the 4pb type.

This study presents fatigue laws derived from four-point bending tests performed in the conditions abovementioned and based on a classical approach, which assumes that the damage of specimen accumulates during testing until failure occurs. This is considered to happen when a certain stiffness decreasing is reached by the beam. It was assumed that failure occurs when asphalt mixture stiffness reduction is 50 % of its initial value.

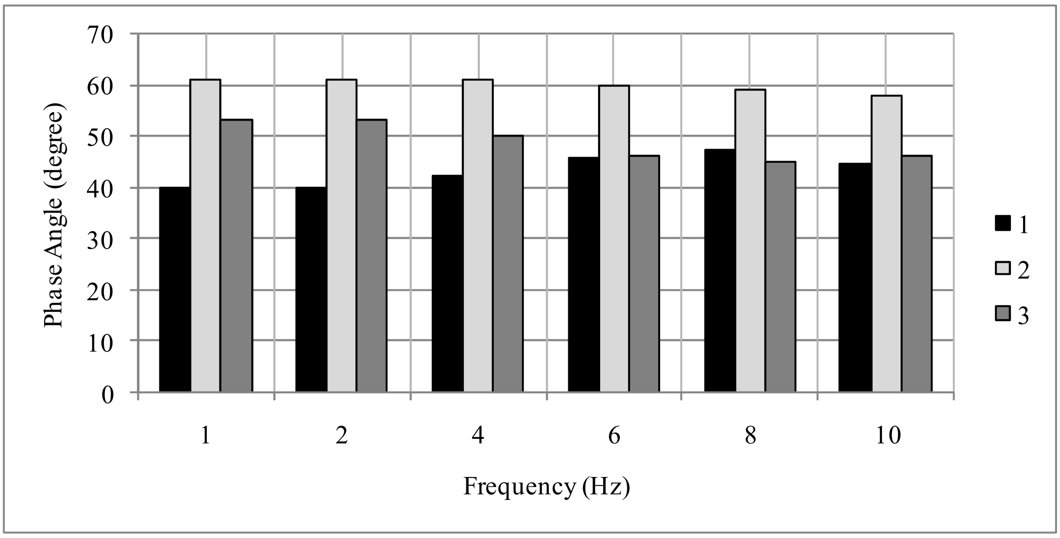

Figure 5. Phase Angle at 40ºC for the beams tested in the three laboratories

Table 4. Differences between laboratories for Stiffness Modulus at 20ºC and 40ºC

Temperat. (ºC)	Frequency (Hz)	Δ 1–2 (%)	Δ 3–2 (%)	Δ 1–3 (%)
20	6	15	4	10
	8	12	3	9
	10	10	13	-3
40	6	65	63	1
	8	48	63	-9
	10	30	71	-24

In figures 6 to 8 the fatigue laws obtained for the three laboratories are presented, also labelled as 1, 2 and 3. The figures also present the law equations and the determination coefficient which is good for the three cases.

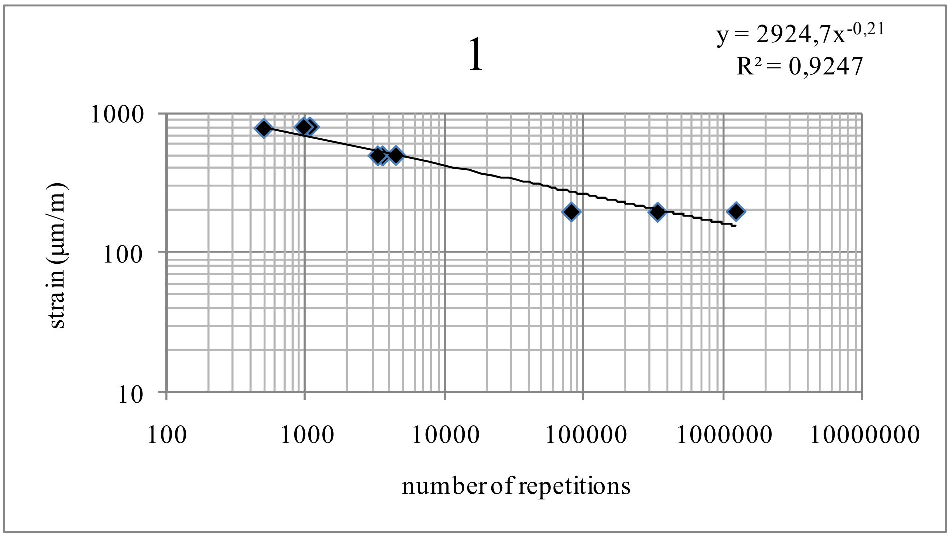

Figure 6. Fatigue law at 20ºC for the beams tested in laboratory number 1

The presented laws show a similar trend despite some differences with respect to equation coefficients. This fact is underlined by similar figures among the laboratories' results for strains at hundred thousand (ε_5), one million (ε_6) and 10 million (ε_7) load repetitions (Table 5). Probably the relatively low test temperature has a great deal of influence in this result as was seen for the stiffness modulus results but, this also means that for longer 4pb tests and temperatures around 20ºC, the differences among calibrated equipments are not significant in terms of fatigue results for this type of asphalt mixtures.

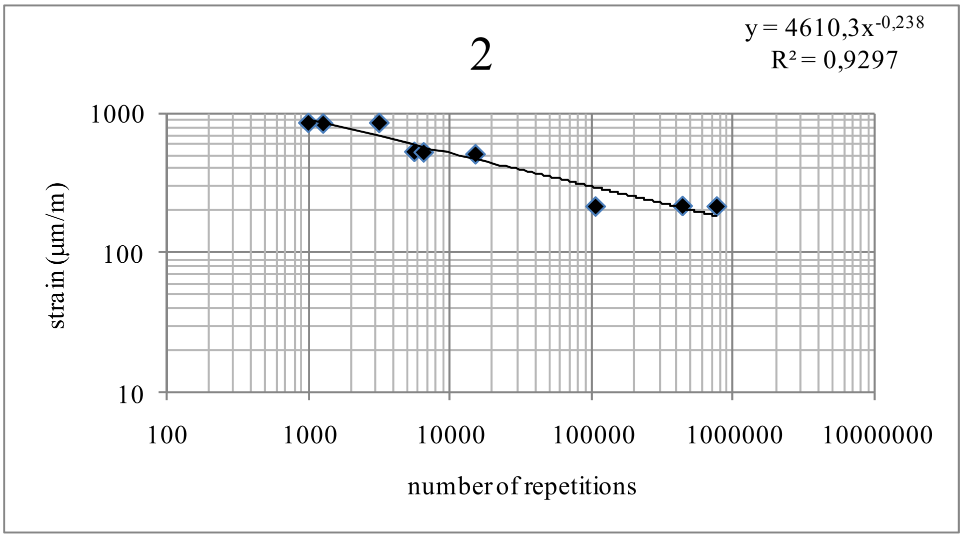

Figure 7. Fatigue law at 20ºC for the beams tested in laboratory number 2

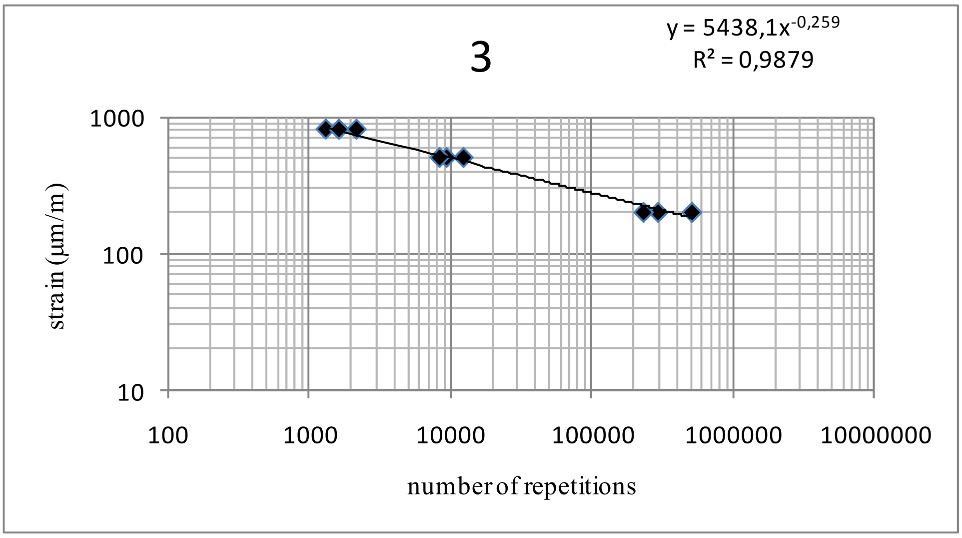

Figure 8. Fatigue law at 20ºC for the beams tested in laboratory number 3

Table 5. Strains at hundred thousand (ε_5), one million (ε_6) and 10 million (ε_7) load repetitions

	1	2	3
ε_5 (µm/m)	261	298	276
ε_6 (µm/m)	161	172	152
ε_7 (µm/m)	99	99	84

4 CONCLUSIONS

The work developed during this study allowed the following inferences:

- When performing the deformation characterization of an asphalt mixture (stiffness modulus) by the use of a 4 pb equipment, the type of equipment may have influence in the results.
- When addressing quality control using relatively low test (service) temperatures (around 20ºC) determination of the stiffness modulus could be made by any type of 4pb equipment but, the test "set conditions" used to obtain the reference values must be known in order to minimize discrepancies. Even doing this, an acceptance coefficient related to the reference values must be defined and this study has lead to a figure of +/- 15 to 20%.
- For the same test temperature situation mentioned above and for fatigue characterization, it can be said that any of the three 4pb equipment performing similar "set conditions" will provide similar results.
- When addressing quality control using relatively high test (service) temperatures (around 40ºC) the whole process should be accomplished by the same laboratory (same 4pb) equipment and stiffness modulus figures should be seen as relative and not absolute.
- Fatigue characterization at high test (service) temperatures is not a quality control issue, at least for Portuguese technology.

The authors are pretty much aware about the limitations of this study. It only can constitute an alert for Portuguese technology because of the limited range of analysis that could be achieved. Nevertheless, this alert underlines, on the one hand, the need for a more careful interpretation of the quality control results when using performance tests, namely when using 4pb equipments, and, on the other hand, the importance of establishing a periodic cross evaluation and calibration of the equipments used for that purpose in order to minimize discrepancies. The authors believe that this last suggestion is mandatory in order to have a reliable quality control evaluation throughout the country.

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