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Table of contents

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Evaluation of fatigue performance at different temperatures

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ABSTRACT: The fatigue performance of asphalt mixtures is used to predict pavement life to control the cracking in the asphalt layers. The design of an asphalt pavement is usually made for a specific temperature, what is intended to represent the pavement behaviour throughout a whole year. For damage analysis during a year, along which the pavement temperature constantly varies, it is necessary to calculate the fatigue performance of pavements at a wide range of temperatures. Thus, this paper presents the evaluation of the fatigue response of two asphalt mixtures, a conventional and an asphalt rubber mixture. Frequency sweep tests were also performed to evaluate the stiffness modulus. The fatigue test results showed that the fatigue life decreases when the test temperature decreases up to a certain value. After that value, the fatigue life increases when the test temperature decreases. To explain this phenomenon, this paper presents the preliminary tests carried out to measure the temperature inside the testing specimens to verify possible discrepancies between the climatic chamber temperature and the specimen temperature.

1 INTRODUCTION

The fatigue life of asphalt mixtures is used to predict the life of a pavement to control the cracking in asphalt layers. The laboratory tests used to predict fatigue life allow the development of fatigue models that correlate the fatigue life to the strain level at the bottom of the asphalt layers. When the fatigue life models are related only to the strain, they can be used for the temperature used in their development.

To analyze damage throughout a year or when applied at other pavement temperatures, it is vital to know the fatigue performance at different temperatures. In this case the fatigue life must be defined for a range of test temperatures or for a range of material stiffness. This last option is used in most fatigue models that relate the fatigue life to more than one parameter (strain level).

The development of these models is made at different test temperatures and the results are expressed for the different stiffnesses exhibited by the material at those test temperatures.

The existing results of fatigue tests (SHRP, 1994) allow to conclude that the fatigue life decreases when temperature decreases due to the visco-elastic behaviour of the bitumen which, at high temperatures behaves as a liquid and at low temperatures behaves as a solid. However, the Shell design method (Shell, 1978) drew some conclusions that indicate that the decrease of temperature may contribute to an increase in the fatigue life.

This paper presents the evaluation of the fatigue response of two asphalt mixtures, a conventional and an asphalt rubber mixture. Frequency sweep tests were also performed to evaluate the stiffness modulus. The fatigue test results showed that the fatigue life decreases when the test temperature decreases up to a certain value. After that value, the fatigue life increases when the test temperature decreases. To explain this phenomenon, this paper presents the preliminary tests that are being carried out to measure the temperature inside the testing specimens of a conventional mixture to verify possible discrepancies between the climatic chamber temperature and the specimen temperature.

2 TEMPERATURE MEASUREMENT

In a previous study by Minhoto et al. (2005) the temperature distribution throughout the pavement structure was obtained through field measurements by using a temperature-recording equipment (Datalogger associated with thermocouples).

During twelve months (from January 2004 to December 2004) pavement temperatures were measured at a certain pavement section, in which seven thermocouples were installed, at seven different depths: at surface, 27.5 mm, 55 mm, 125 mm, 165 mm 220 mm and 340 mm, in a pavement with a 0.125 m overlay layer and a 0.215 m cracked asphalt layer (Figure 1). The top thermocouple was installed at the pavement surface. The depths for the other six devices were chosen conveniently to provide a good representation of all the asphalt layers. Temperatures were recorded at every hour, every day throughout a year. The pavement instrumentation and the equipment used to record the pavement temperature are presented in Figure 2.

In Figure 3, the observed temperatures on the pavement surface, at the bottom of the overlay (0.125 m) and at the bottom of the existing asphalt layers (0.335 m) are presented. Typical summer (May to September) and winter temperature variations can be observed.

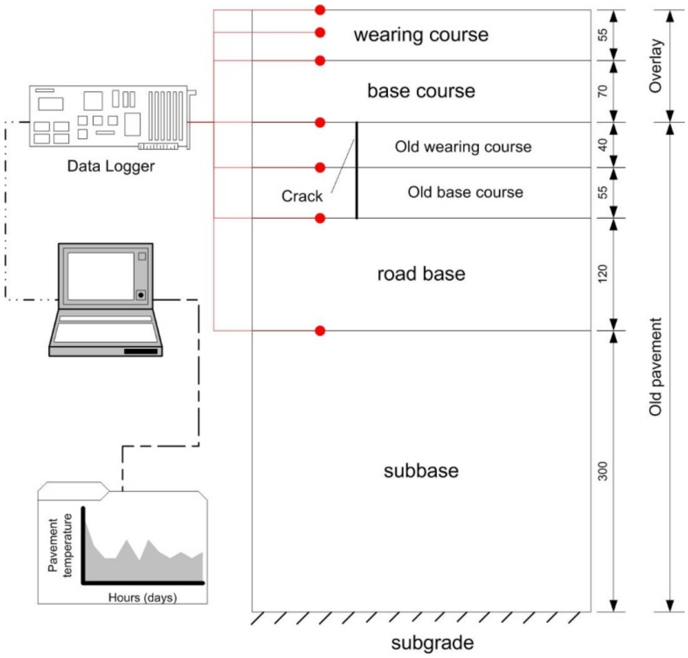

Figure 1. Pavement structure and locations (depths) for temperature measurement

Figure 2. Pavement instrumentation and data acquisition

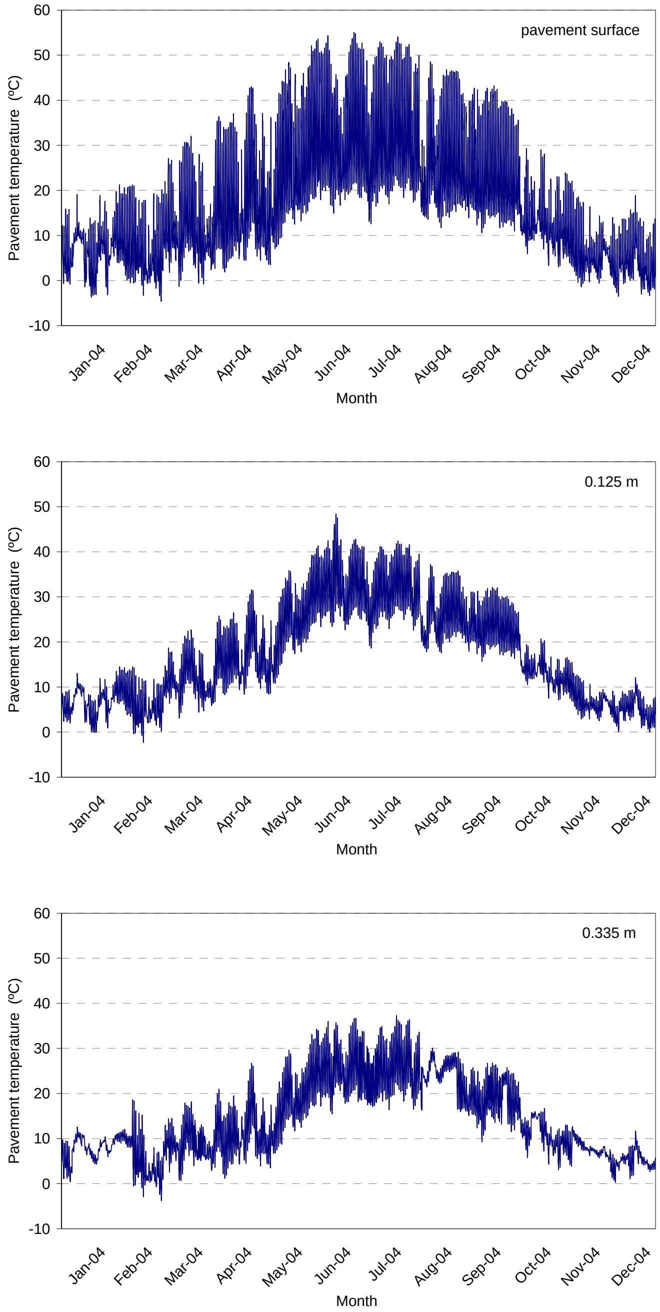

Figure 3. Pavement temperature during a year (Minhoto et al., 2008)

3 FATIGUE LIFE OF ASPAHLT MIXTURES

The stiffness and fatigue resistance of conventional and asphalt rubber mixtures were assessed using the four-point bending test in controlled strain, where the strain is kept constant and the stress decreases during the test. The tests were performed for four test temperatures of -5ºC; 5ºC, 15 ºC and 25ºC, involving a previous placement of the specimens in an environmental chamber during 2 hours to ensure that the specimen reaches the test temperature before being tested

The frequency sweep test was used to measure the stiffness and the phase angle of mixtures when subjected to different loading frequencies at each test temperature. In this study, seven frequencies were tested (10; 5; 2; 1; 0,5; 0,2; 0,1 Hz) in 100 cycles. The results of frequency sweep tests to determine the stiffness of the mixtures, conducted at several temperatures, are shown in Figures 4 and 5 for a conventional mixture and in Figures 6 and 7 for an asphalt rubber mixture. The stiffness modulus of both mixes increases with the decrease of both temperature and frequency, while the phase angle decreases with the decrease of temperature and frequency.

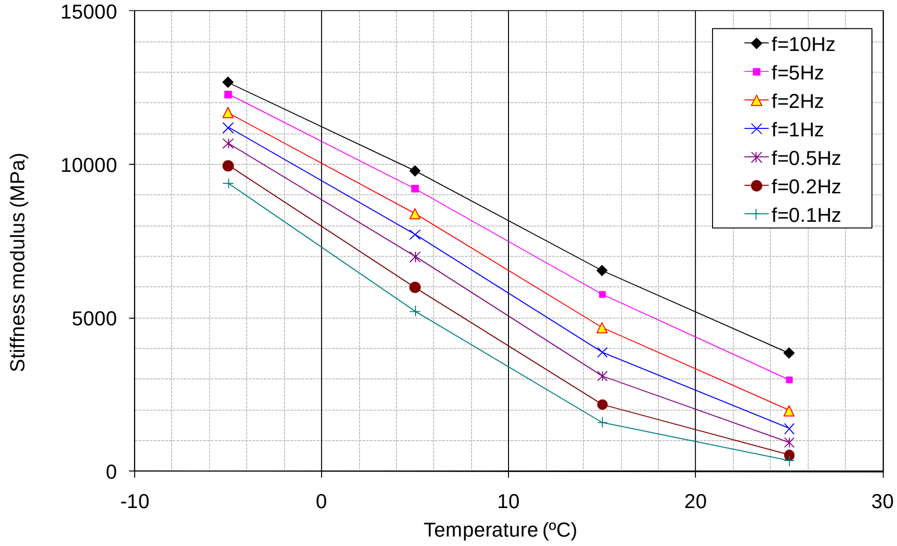

Figure 4. Stiffness modulus of the conventional mixture

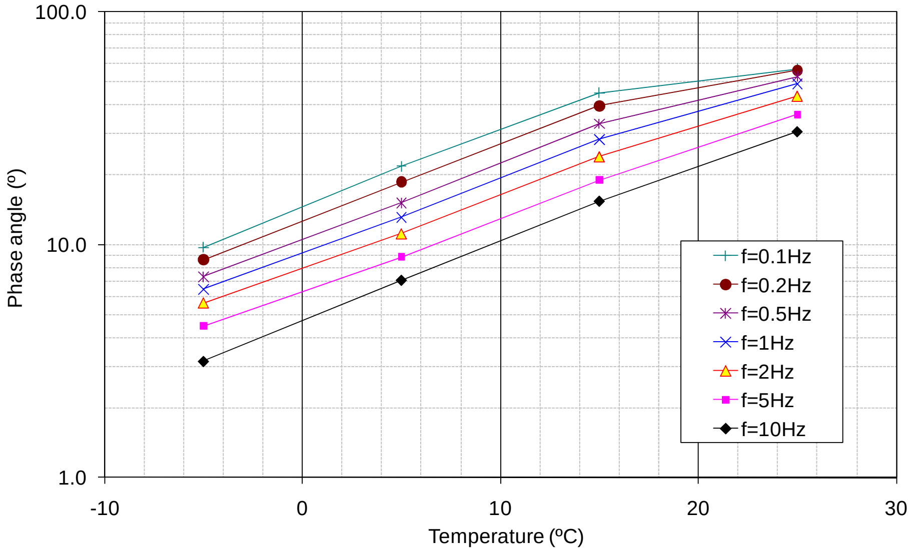

Figure 5. Phase angle of the conventional mixture

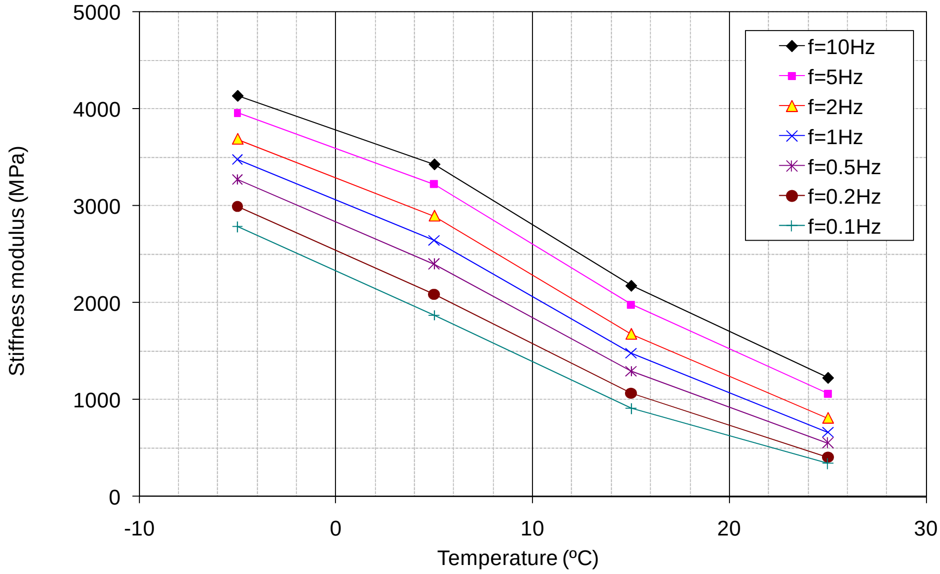

Figure 6. Stiffness modulus of the asphalt rubber mixture

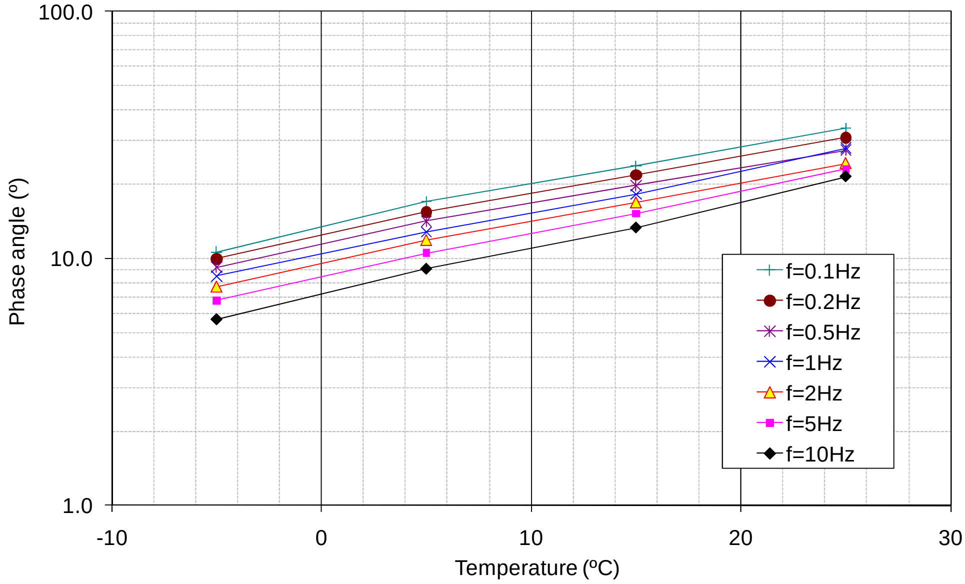

Figure 7. Phase angle of the asphalt rubber mixture

Flexural fatigue tests were conducted according to the AASHTO TP 8-94 (Standard Test Method for Determining the Fatigue Life of Compacted HMA Subjected to Repeated Flexural Bending). All tests were carried out at 10 Hz and at four different temperatures (-5ºC; 5ºC, 15ºC and 25ºC) with specimens with 50 mm high by 63 mm width by 380 mm long. Fatigue failure was assumed to occur when the flexural stiffness reduces to 50 % the initial value.

The fatigue tests were conducted in strain control by applying at least to 2 different strain levels and, for each one, 3 specimens were tested through a sinusoidal loading without rest periods. The results of the flexural fatigue tests conducted at several temperatures of the conventional mixture are shown in Figure 8; Figure 9 presents the results for the asphalt rubber mixture.

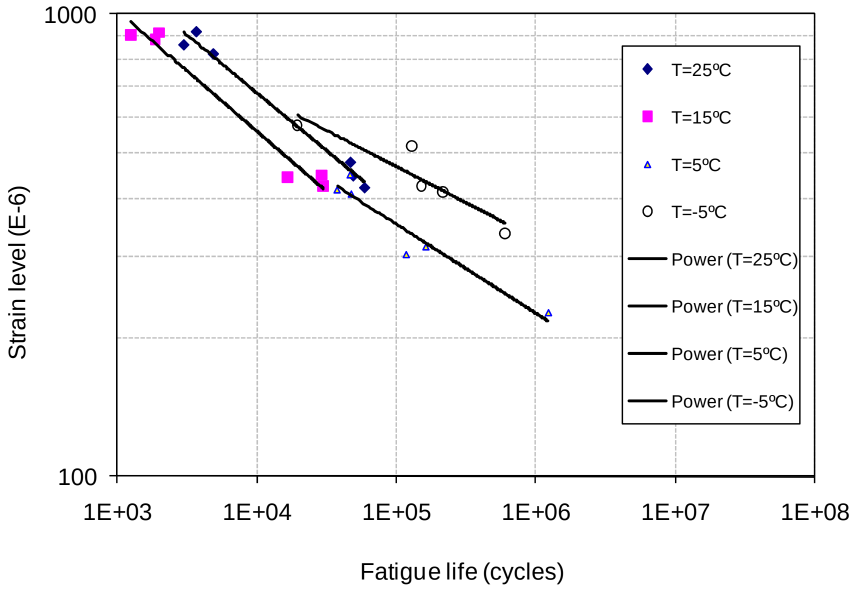

Figure 8. Fatigue life of the conventional mixture

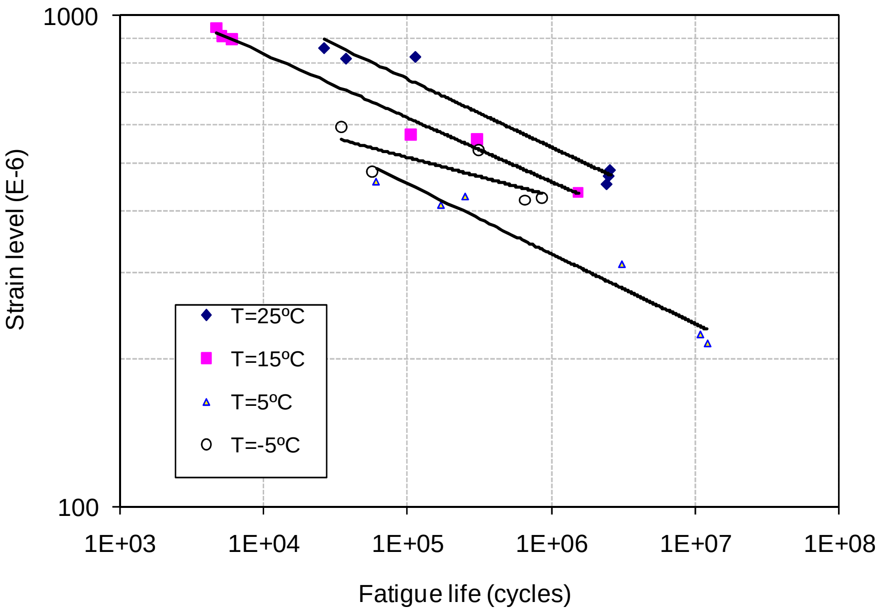

Figure 9. Fatigue life of the asphalt rubber mixture

The analysis of figures 8 and 9 reveals that, as expected, for test temperatures of 25ºC and 15ºC, the decrease of the test temperature in the asphalt mixture decreases its fatigue resistance, while for lower test temperatures of 5ºC and -5ºC, the trend is reversed. These results allow to conclude that there must be a temperature value at which the fatigue resistance shows a different behaviour, i.e., the fatigue life decreases when the test temperature decreases up to a certain value and, after that value, the fatigue life increases when the test temperature decreases.

The fatigue test results for the studied mixtures were compared to the fatigue resistance predicted by the Shell model (Equation 1):

$$N = \left(\frac{\varepsilon_t}{(0.856V_b + 1.08)S_{mix}^{-0.36}} \right)^{-5} \quad (1)$$

where N is the fatigue resistance, in terms of number of axles, ε_t is the strain level, S_{mix} (Pa) is the stiffness modulus and V_b (%) is the volume of the binder in the mixture.

The comparison between the testing results and the fatigue life predicted by the Shell model is presented in Table 1, for the conventional mixture, and in Table 2 for the asphalt rubber mixture. The comparison, referred to in both tables by the column "Error", presents the difference in the fatigue life obtained when testing to the fatigue life predicted by the Shell model.

The analysis of these tables allows concluding that small errors can occur in asphalt rubber mixtures when compared to conventional ones. A bigger error appears in the case in which it was expected a shorter fatigue life in laboratory. This can be observed at temperatures of 5ºC and -5ºC in the conventional mixture and at -5ºC in the asphalt rubber mixtures, i.e. those cases studied in laboratory in which it was observed that the fatigue life increased when the temperature decreased.

Table 1. Fatigue results of the conventional mixture

Specimen	Temperature (ºC)	Strain (E-6)	Stiffness (MPa)	Fatigue life test	Fatigue life Shell model	Error (%)
mcd-06	25	448	3440	4.9E+04	4.4E+04	11
mcd-01		858	3183	3.0E+03	2.0E+03	53
mcd-02		820	3602	4.9E+03	2.0E+03	148
mcd-03		916	2548	3.7E+03	2.1E+03	74
mcd-05		422	4033	5.9E+04	4.4E+04	33
mcd-05		479	2524	4.7E+04	5.5E+04	-15
mcd-12	15	448	5129	2.9E+04	2.1E+04	36
mcd-07		913	5004	2.0E+03	6.4E+02	214
mcd-08		882	6062	1.9E+03	5.4E+02	251
mcd-09		904	5752	1.2E+03	5.2E+02	140
mcd-10		424	7885	3.0E+04	1.3E+04	130
mcd-11		443	6316	1.7E+04	1.6E+04	7
mcd-18	5	302	12443	1.2E+05	3.1E+04	280
mcd-13		417	11322	3.8E+04	7.3E+03	420
mcd-14		450	8473	4.7E+04	8.5E+03	457
mcd-15		409	14029	4.8E+04	5.5E+03	771
mcd-16		226	11982	1.2E+06	1.4E+05	754
mcd-17		314	10777	1.6E+05	3.3E+04	391
mcd-24	-5	424	10666	1.5E+05	7.6E+03	1905
mcd-19		412	16536	2.2E+05	4.0E+03	5355
mcd-20		520	15084	1.3E+05	1.5E+03	8738
mcd-21		576	8238	2.0E+04	2.6E+03	650
mcd-22		335	11428	6.0E+05	2.2E+04	2678
mcd-23		341	10489	8.1E+05	2.3E+04	3395

4 FATIGUE PERFORMANCE AT DIFFERENT TEMPERATURES

The increase of fatigue life when temperature decreases is also contemplated in both the Shell Pavement Design Manual (Shell, 1978), (SPDM) and in the Strategic Highway Research Program, SHRP-A-404 (SHRP, 1994).

The Shell design method (Shell, 1978) draws some conclusions that may indicate that the decrease of the temperature can contribute to an increase of the fatigue life. The SPDM shows a set of typical results of relationships between the permissible fatigue strain and the stiffness of the mixture for various types of mixtures and the fatigue lives (Figure 10), suggesting the occurrence of the phenomenon above described.

Table 2. Fatigue results of the asphalt rubber mixture

Specimen	Temperature (ºC)	Strain (E-6)	Stiffness (MPa)	Fatigue life test	Fatigue life Shell model	Error (%)
ar-gg-05	25	485	1046	2.6E+06	1.7E+06	49
ar-gg-06		454	909	2.4E+06	2.4E+06	1
ar-gg-01		858	880	2.6E+04	1.0E+05	-74
ar-gg-02		817	1111	3.7E+04	1.3E+05	-71
ar-gg-03		472	1040	2.5E+06	2.0E+06	27
ar-gg-04		824	1152	1.1E+05	1.2E+05	-7
ar-gg-12	15	573	1808	1.0E+05	2.7E+05	-61
ar-gg-07		947	1853	4.7E+03	2.2E+04	-78
ar-gg-08		897	1798	6.1E+03	2.9E+04	-79
ar-gg-09		910	1829	5.1E+03	2.7E+04	-81
ar-gg-10		437	1453	1.5E+06	1.0E+06	47
ar-gg-11		562	2060	3.1E+05	3.0E+05	3
ar-gg-18	5	312	3698	3.1E+06	2.5E+06	25
ar-gg-13		428	3346	2.5E+05	5.1E+05	-50
ar-gg-14		459	3025	6.1E+04	3.6E+05	-83
ar-gg-15		411	3748	1.7E+05	6.2E+05	-72
ar-gg-16		225	2978	1.1E+07	1.3E+07	-15
ar-gg-17		216	3047	1.2E+07	1.6E+07	-22
ar-gg-24	-5	534	3881	3.1E+05	1.2E+05	157
ar-gg-19		427	4094	8.6E+05	3.7E+05	133
ar-gg-20		422	3722	6.5E+05	3.9E+05	66
ar-gg-21		483	3640	5.7E+04	2.0E+05	-71
ar-gg-23		593	3031	3.5E+04	7.1E+04	-52
ar-gg-05		485	1046	2.6E+06	1.7E+06	49

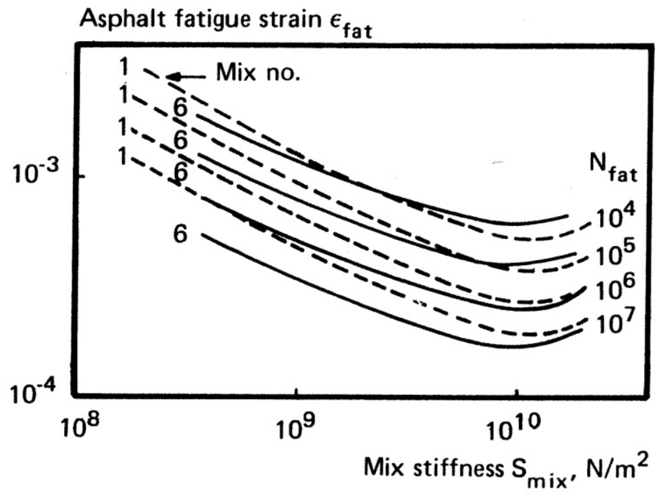

Figure 10. Fatigue properties (Shell, 1978)

This figure clearly shows that the increase of the mixture stiffness, S_{mix}, causes a decrease in the fatigue strain up to a certain amount of S_{mix}. At higher values of S_{mix} the strain appears to increase. Considering that the variation of S_{mix} is exclusively due to temperature variations, as noted in Figures 4 and 6, a similar phenomenon is observed.

The report SHRP–A–404 shows identical graphical illustrations representing a set of relationships between the fatigue life, in terms of the cycles to failure and the pavement temperature at the bottom of the asphalt layers and temperature gradients (Figure 11). Those relationships are parabolic and also suggest the occurrence of the phenomenon described above. The report SHRP–A–404 allows concluding that the fatigue life decreases as the temperature decreases due to the visco-elastic behaviour of the bitumen, which at high temperature behaviours as a liquid and at low temperature behaviours as a solid.

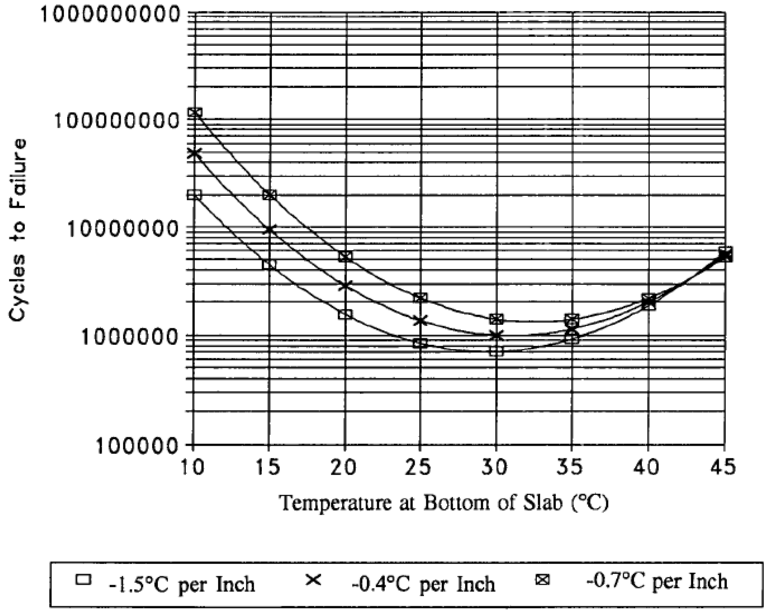

Figure 11. Fatigue life vs pavement temperature (SHRP, 1994)

From the laboratory fatigue test results performed in this work, a set of relationships between the fatigue life and stiffness modulus were developed, and where the phenomenon described in the SPDM can be observed. These relationships are illustrated in Figure 12, for a conventional mixture, and in Figure 13, for an asphalt rubber mix.

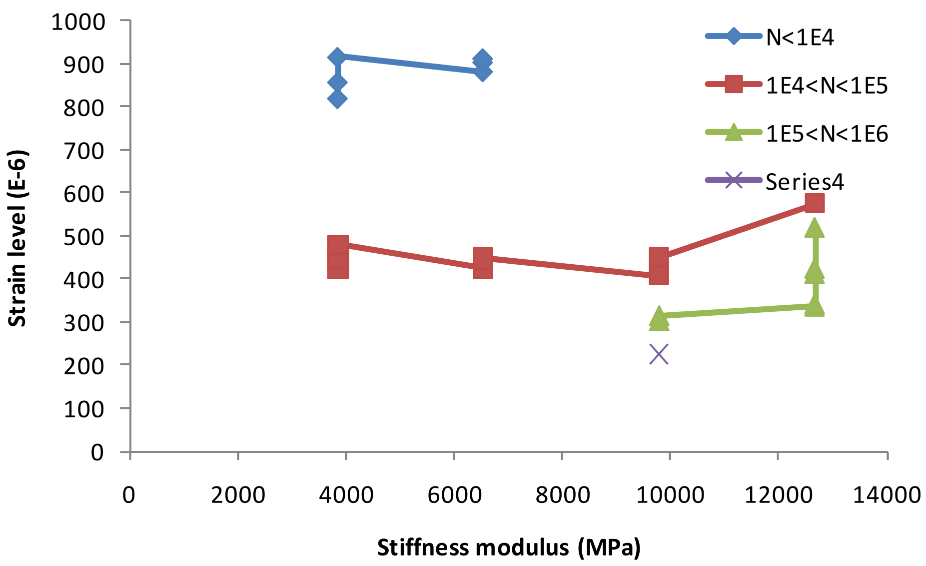

Figure 12. Relationship between fatigue life and stiffness modulus of the conventional mixture

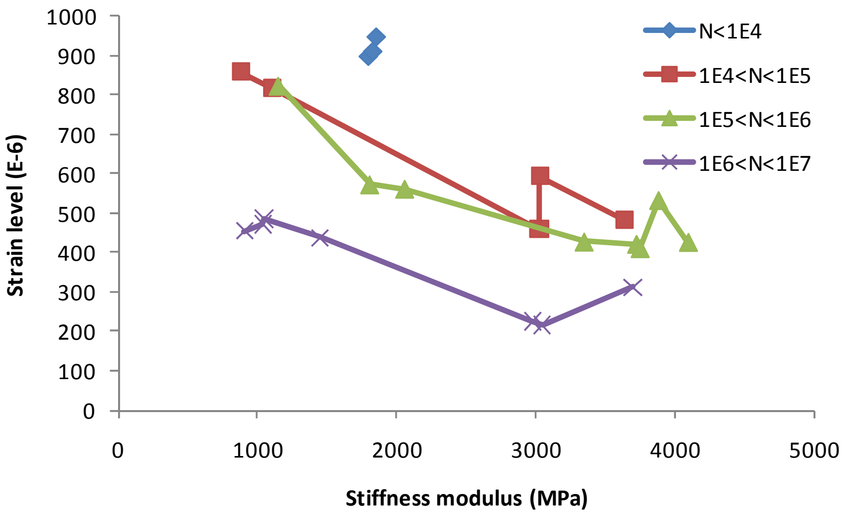

Figure 13. Relationship between fatigue life and stiffness modulus of the asphalt rubber mixture

5 CONTRIBUTION TO THE DISCUSSION

As a contribution to the discussion and a better understanding of this phenomenon, a series of fatigue tests was performed in order to characterize the thermal behaviour of testing samples, when subjected to a fatigue test. Thus, a set of typical test samples were obtained and prepared for the four point bending fatigue tests, performed at a constant temperature of 20ºC. Aiming at thermal measurements, a set of thermocouples were placed in each one, as observed in Figure 14.

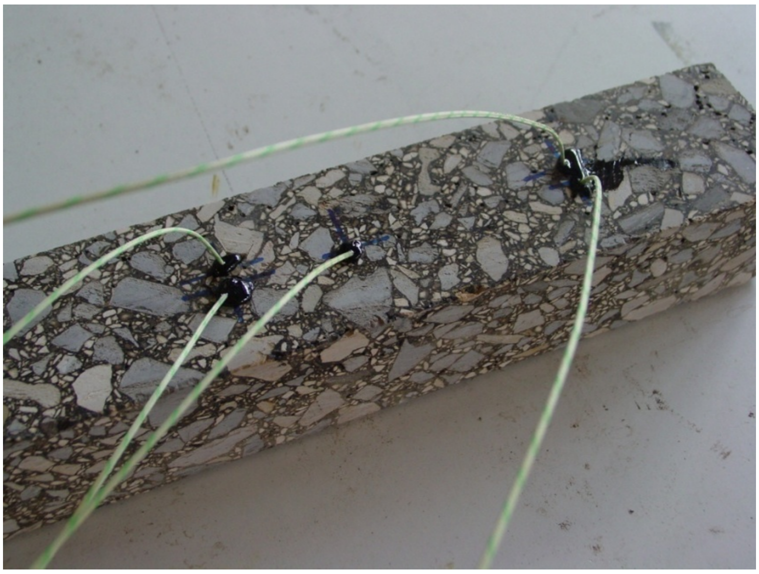

Figure 14. Test sample with thermocouples for temperature measurement

Three thermocouples were placed at the surface of the sample (one in the middle of the specimen, one under the inner clamp and another one between the inner and the outer clamp). Two more thermocouples were placed: one at mid-length of the sample and the other one between the inner and outer clamp.

The temperatures in the test sample, during the fatigue test, were obtained by using a device for the acquisition/recording of the temperatures, to which all the thermocouples were connected, as shown in Figure 15.

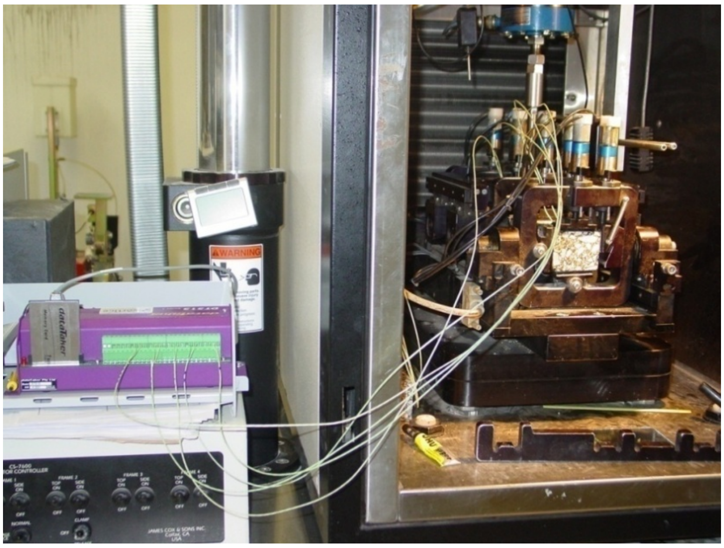

Figure 15. Test device to perform thermal-fatigue tests

To evaluate the temperature during the fatigue tests, 4 specimens were tested at 20ºC. One specimen was tested at a strain level of 800E-6, one at 400E-6 and one at 200E-6. The last specimen, with an almost null stiffness (a fatigued specimen was used for this purpose), was tested at 200E-6 and used as reference for the assessment of the dissipated energy in conditions of binding without stiffness.

The fatigue test results expressed in terms of dissipated energy are presented in Figure 16. The analysis of this figure allows concluding that, in the fatigue tests performed at a strain level of 800 μm, an increase of the dissipated energy occurs, when compared to the other test conditions.

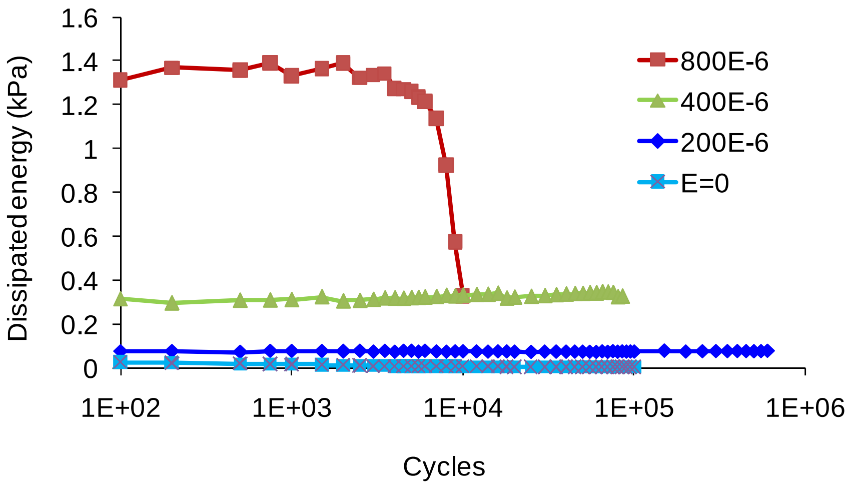

Figure 16. Dissipated energy during fatigue tests

In Figure 17, the temperature measured during the fatigue test at the mid-length of the beam, located on the surface and inside the specimen, is presented. Discrepancies between the climatic chamber temperature and the specimen temperature were observed, which may have influenced the results of tests. Furthermore, the temperature inside the testing specimens shows the same discrepancies with the climatic chamber temperature.

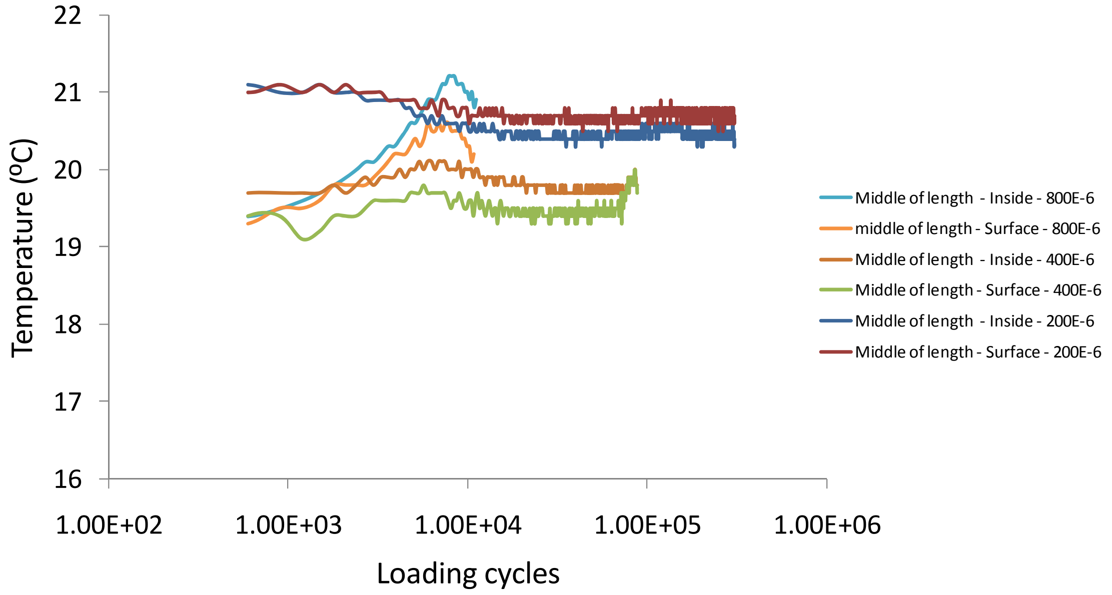

Figure 17. Temperature evolution with the fatigue test observed at mid- length of the beam

From the correlation between the graphs of the dissipated energy and the temperature, it is notorious that for larger strain levels larger dissipated energy is observed. These larger strain levels are responsible for larger dissipated energy as well as for an increase of the temperature inside the specimen which reduces its stiffness and affects its fatigue response.

As a result of those findings it seems important to highlight some key aspects that need to be considered in future characterizations of the fatigue resistance of mixtures: (1) extent to which the temperature variation observed in the sample can affect the stiffness of the mixture, as a result of the variation of the stiffness during the test temperature. (2) Moreover, to control the stiffness, it is important to consider the characterization of the evolution of the thermal state of the samples throughout the test and to explain its origin and mode of control.

It is fundamental to establish the relationships between the thermal state of the sample and the evolution of the fatigue test, by profiling a function of internal energy generation (Q(x,y,z,t)), described in terms of dissipated energy as a result of loading cyclic test. This function should ensure thermal equilibrium of the test system, namely, fulfilling the relation expressed in equation:

$$\rho C_p \frac{\partial}{\partial t} T(x,y,z,t) = k\,\nabla T(x,y,z,t) + Q(x,y,z,t) \quad (2)$$

where: x, y, z – spatial coordinates; t – time coordinate - time; ρ – material density; Cp – specific heat of the material at constant pressure; T(x,y,z,t) – spatial and temporal temperature distribution; k – thermal conductivity of material; ∇ - Laplace operator; Q(x,y,z,t) – internal energy generation.

To define the function Q(x,y,z,t), it is assumed that for each load cycle test the energy dissipated is given by the equation:

$$\Delta W_{2\pi}(x) = \pi \cdot \sigma(x) \cdot \varepsilon(x) \cdot \sin(\varphi)\, \rho C_p \frac{\partial}{\partial t} T(x,y,z,t) = k\,\nabla T(x,y,z,t) + Q(x,y,z,t) \quad (3)$$

where: $\Delta W_{2\pi}$ (x) – dissipated energy, in each fatigue load cycle; σ(x) – stress distribution as result of each applied load; ε(x) – strain distribution as result of each applied load.

6 CONCLUSIONS

This paper presents the fatigue response and stiffness modulus evaluations, at several test temperatures, of a conventional asphalt mixture and an asphalt rubber mixture. Those evaluations showed that, up to a certain value, the fatigue life decreases when the test temperature decreases, and after that value, the fatigue life increases when the test temperature decreases.

In the SHRP program (SHRP, 1994) and in Shell design method (Shell, 1978) some conclusions indicate an identical phenomenon. To explain that phenomenon, this paper describes the preliminary tests that are being carried out to measure the temperature inside the testing specimens to verify the consistency of the test. With this test it was concluded that there exist clear discrepancies between the climatic chamber temperature and the specimen temperature. This evidences some aspects that need to be further investigated, such as the extent to which the temperature variation observed in the sample can affect the fatigue resistance results and the characterization of the evolution of the thermal state of the samples throughout the test.

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