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Application of plateau value to predict fatigue life

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ABSTRACT: Fatigue resistance of asphalt mixtures represents an important parameter for pavement design. This fatigue resistance is calculated through laboratory tests which require some time depending on the strain level applied to the specimen. For very low strain levels, identical to the one installed in the pavement, one test may last more than one week depending on the testing frequency. The time needed for the development of the fatigue law may last longer. Recent developments introduced an energy approach, based on the ratio of dissipated energy change, which leads to a plateau value that requires short testing to predict the specimen failure. This paper presents the implementation of this approach to evaluate the fatigue resistance of Portuguese asphalt mixtures. Three asphalt mixtures were studied. The first mixture was tested using two strain levels and three specimens for strain level. The second mixture was tested using three strain levels and three specimens per strain level, whereas the last mixture was tested with 18 specimens, 6 per strain level. The approach seems to have potential to be used for fast evaluation of the fatigue response of asphalt mixtures.

1 INTRODUCTION

The design of a road pavement requires the knowledge of the material properties which, for the case of asphalt materials, are characterized by the stiffness modulus and the fatigue resistance. The fatigue resistance relates the number of load cycles to failure with the strain level applied to the mixture.

The most used standards used to evaluate the fatigue resistance of asphalt mixtures include the AASHTO T321-03 (AASHTO, 2003) and the European Standard (EN 12697-24, 2004). When evaluating fatigue resistance through four point bending beam tests, both standards define the specimen failure when the stiffness of the material is reduced by 50% of the initial stiffness.

To define a fatigue life law for an asphalt mixture, the European standard specifies the use of 18 specimens to be tested at 3 different strain levels with 6 specimens per strain level. For low strain level, what in the standard is defined when the fatigue is about 1 million loading cycles, the test lasts more than one day. For the other strain levels, the tests may last longer. The entire testing time to evaluate a fatigue law may last two weeks and, in certain cases, it can prolong about one month.

Recently, Shen and Carpenter (2007) introduced a method that can be used to evaluate the fatigue life of asphalt mixtures using short-time fatigue tests (without reaching the failure point). The method is based in an energy approach, using the Ratio of Dissipated Energy Change (RDEC) which leads to the definition of the Plateau Value (PV) that can be correlated to the fatigue life.

Due to the potentialities of this method to reduce the time needed to perform fatigue tests, this paper presents the application of this method for evaluating the fatigue life of some Portuguese asphalt mixtures.

2 ENERGY APPROACH

The ratio of dissipated energy change (RDEC) approach was introduced by Carpenter and Jansen (1997). This approach considers not all dissipated energy is responsible for material damage. Damage only comes from the relative amount of energy dissipation due to each additional load cycle, while the energy dissipated through passive behaviors such as plastic dissipated energy and thermal energy is not considered (Shen and Carpenter, 2007).

This RDEC can be calculated based on Equation 1. The typical cycle count between a and b for RDEC calculation is 100, i.e. b-a=100. Larger number such as 1000 or 10000 can be used when the DE change between every 100 cycle is too small to recognize. Such definition of RDEC provides a true indication of the damage being done to the mixture from one cycle to another by comparing the previous cycle’s energy level and determining how much of it contributed to damage (Shen and Carpenter, 2007).

$$RDEC_a = \frac{DE_a - DE_b}{DE_a \times (b-a)} \tag{1}$$

where:
a, *b* = loading cycle a and b, respectively;
RDECa = the average ratio of dissipated energy change at cycle a, comparing to cycle b;
DEa, *DEb* = dissipated energy at cycle a and b, respectively, which were calculated directly by fatigue testing program.

The typical RDEC vs.. loading cycles curve can be divided into three stages. As shown in Figure 1, it develops a plateau (stage II) after the initial period (stage I). This plateau period, an indication of a period where there is a constant percentage of input energy being turned into damage, will extend throughout the main service life until a dramatic increase in RDEC occurs, which gives a sign of true fatigue failure (stage III) (Shen and Carpenter, 2007).

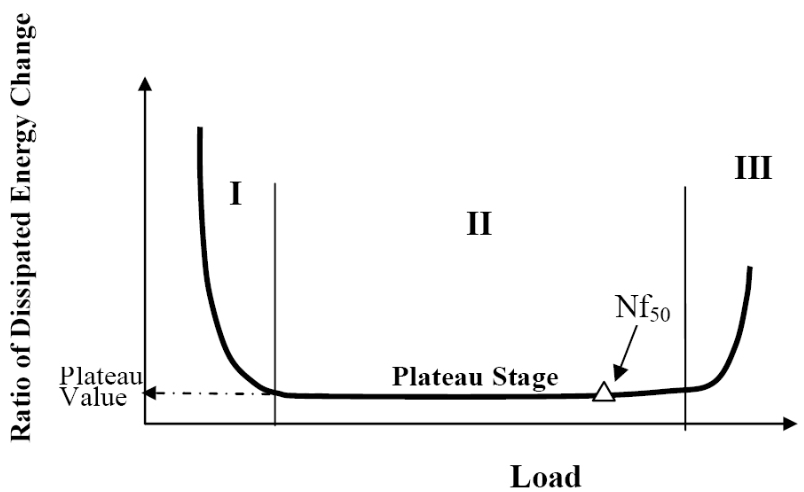

Figure 1. Typical RDEC vs.. Loading Cycles Plot and the Indication of PV (Shen and Carpenter, 2007)

The RDEC value at the 50% stiffness reduction point is defined as the plateau value, PV, which is also shown in Figure 1. Ghuzlan and Carpenter (2000) showed that the plateau value relates precisely to the true fatigue failure (stage III). Also, Shen and Carpenter (2005), found a unique relationship between PV and Nf50 (fatigue life at 50% stiffness reduction point) for different mixtures, loading modes, loading levels, and testing conditions (frequency, rest periods and temperature), defined by Equation 2.

$$PV = 0.4428 Nf_{50}^{-1.1102} \tag{2}$$

3 ASPHALT MIXTURES

The development of this study was based in the analysis of fatigue testing results from 3 different asphalt mixtures tested in laboratory by using a four point bending beam device. All mixtures have a dense graded aggregate gradation. The maximum aggregate size of the mixtures was: a.Mixture 1: 25 mm; b. Mixture 2: 14 mm; Mixture 3: 19 mm, as presented in Table 1, which also contains the binder type and content for each mixture.

Table 1. Mixture description

Mixture	Description	Binder type (pen)	Binder content (%)
1	0/25 dense graded asphalt concrete for base layers	35/50	4.5
2	0/14 dense graded asphalt concrete for top layers	40/50	5.5
3	0/19 dense graded asphalt concrete for binder layers	35/50	4.3

The fatigue testing results of the mixtures used in this study are presented in Table 2, expressed in terms of strain level and fatigue life. Mixture 1 was tested using 6 specimens (2 strain levels and 3 specimens in each strain level). Mixture 2 was tested using 9 specimens (3 strain levels and 3 specimens in each strain level). Mixture 3 was tested using 20 specimens and 3 strain levels. The name of each specimen is represented in the format: “mixture-specimen“.

The fatigue test results are represented in Figure 2 in terms of fatigue life lines, where it can be observed the excellent fit for power model (straight line in log-log scale), for both the mixtures tested with 2 and 3 strain levels. The models suggest that the use of the mid-strain level is not necessary to have a good approach in the definition of the fatigue model.

Table 2. Fatigue test results

Specimen	Strain	Fatigue life	Specimen	Strain	Fatigue life
1-a	7.05E-04	1.52E+04	3-01	7.24E-04	5.90E+03
1-b	7.18E-04	1.34E+04	3-02	7.22E-04	6.46E+03
1-c	7.21E-04	1.14E+04	3-03	6.33E-04	1.20E+04
1-d	3.12E-04	5.03E+05	3-04	6.27E-04	9.59E+03
1-e	3.18E-04	3.50E+05	3-05	3.26E-04	8.58E+04
1-f	3.25E-04	3.76E+05	3-06	6.19E-04	9.18E+03
2-a	7.27E-04	6.70E+04	3-07	6.35E-04	1.01E+04
2-b	7.18E-04	7.81E+04	3-08	3.26E-04	9.53E+04
2-c	7.14E-04	6.56E+04	3-09	6.32E-04	6.22E+03
2-d	5.17E-04	3.42E+05	3-10	1.66E-04	1.18E+06
2-e	5.14E-04	4.86E+05	3-11	3.14E-04	1.26E+05
2-f	5.20E-04	3.05E+05	3-12	3.16E-04	1.14E+05
2-g	9.20E-04	1.59E+04	3-13	1.62E-04	7.27E+05
2-h	9.10E-04	1.35E+04	3-14	6.30E-04	6.03E+03
2-i	8.98E-04	1.48E+04	3-15	6.19E-04	7.73E+03
			3-16	6.28E-04	9.17E+03
			3-17	3.22E-04	9.86E+04
			3-18	1.63E-04	1.53E+06
			3-19	1.65E-04	8.51E+05
			3-20	3.20E-04	9.48E+04

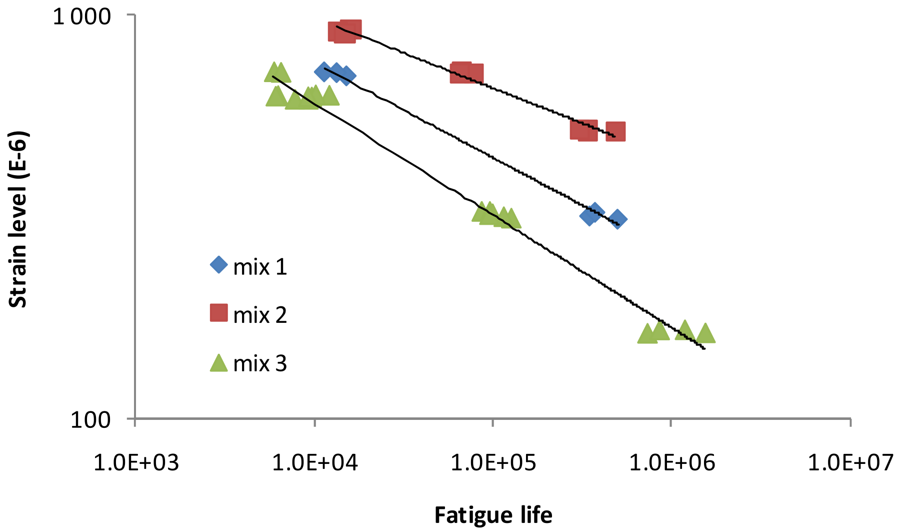

Figure 2. Fatigue life laws of studied mixtures

4 CALCULATION OF PLATEAU VALUE

The application of the ratio of dissipated energy change approach to predict fatigue life of asphalt mixtures needs the evolution of the dissipated energy per cycle during the fatigue test. Figure 3 depicts the plot of that dissipated energy against the loading cycles for specimen 1-c tested at 700E-6 strain level. This strain level can be considered as a high strain level for fatigue testing which produces, cycle after cycle, a considerable dissipation of energy during the fatigue test.

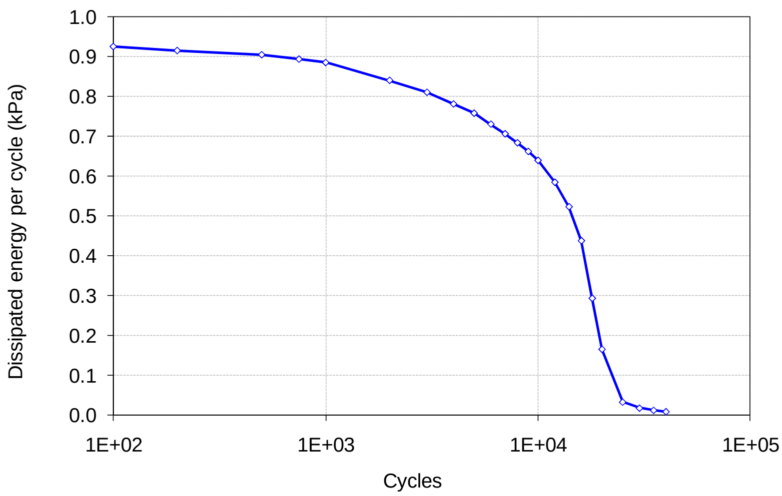

Figure 3. Plot of the dissipated energy for a high strain level

The ratio of dissipated energy change is calculated between two points. When calculated for all the recorded points the result is the plot represented in Figure 4. The stages indicated by Shen and Carpenter (2007) can be stated in the analysis of this plot, mainly stage II, where the ratio is constant during the test. Stage I can hardly be observed due to the fact that the first point was recorded at cycle number 100 because of the stabilization of the strain level. In spite of some variation in the ratio in stage II, it can be considered almost constant. After stage II, stage III can be easily observed.

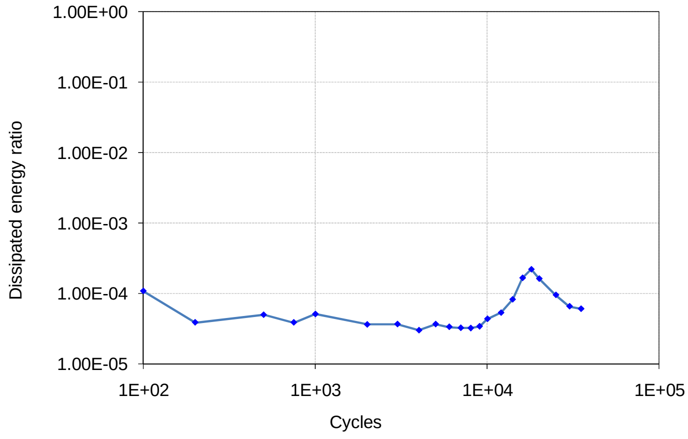

Figure 4. Plot of the ratio of dissipated energy change for a high strain level

The application of the ratio of dissipated energy change approach for very high strain levels, shown in Figure 5 through the example for specimen 2-g tested at 900E-6, presents a dissipated energy evolution with the loading cycles which is almost regular mainly before the failure (cycle number 16000). However, the RDEC (Figure 6) does not present the plateau value as expected.

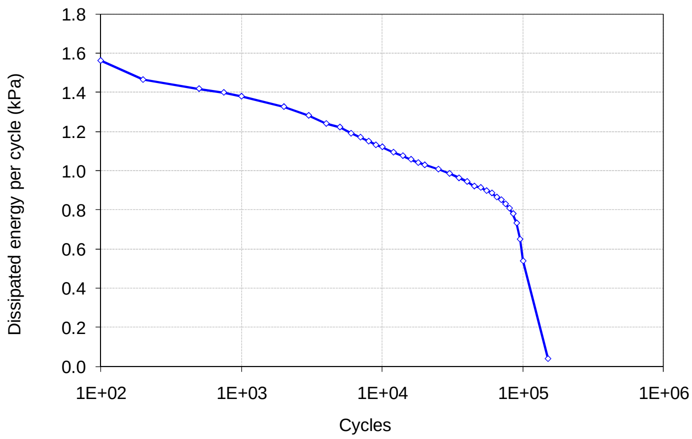

Figure 5. Plot of the dissipated energy for a very high strain level

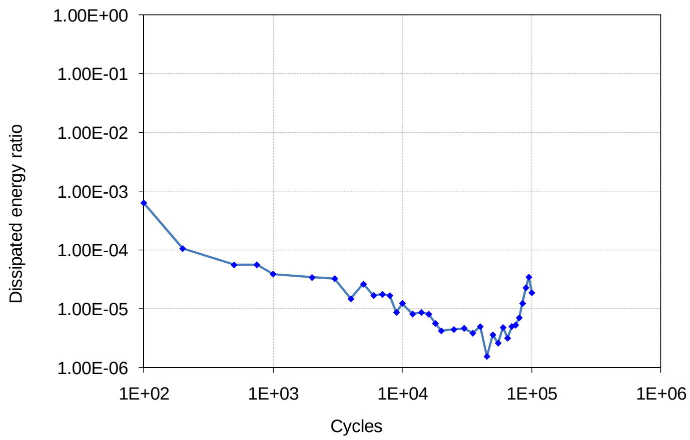

Figure 6. Plot of the ratio of dissipated energy change for a very high strain level

The application of the ratio of dissipated energy change approach for very low strain levels (165E-6), in which the evolution of the dissipated energy follows a trend presented in Figure 7, characterized by constant dissipated energy during the test, does not allow the calculation of the RDEC. For this case, the RDEC, presented in Figure 8, is, in most cases, negative because the dissipated energy sometimes increases from one cycle to another due to the variation of the strain applied by the testing equipment.

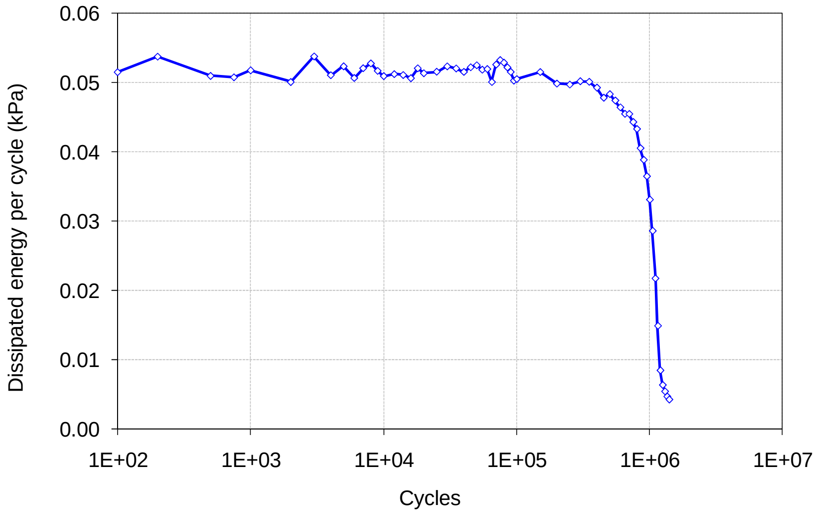

Figure 7. Plot of the dissipated energy for a very low strain level

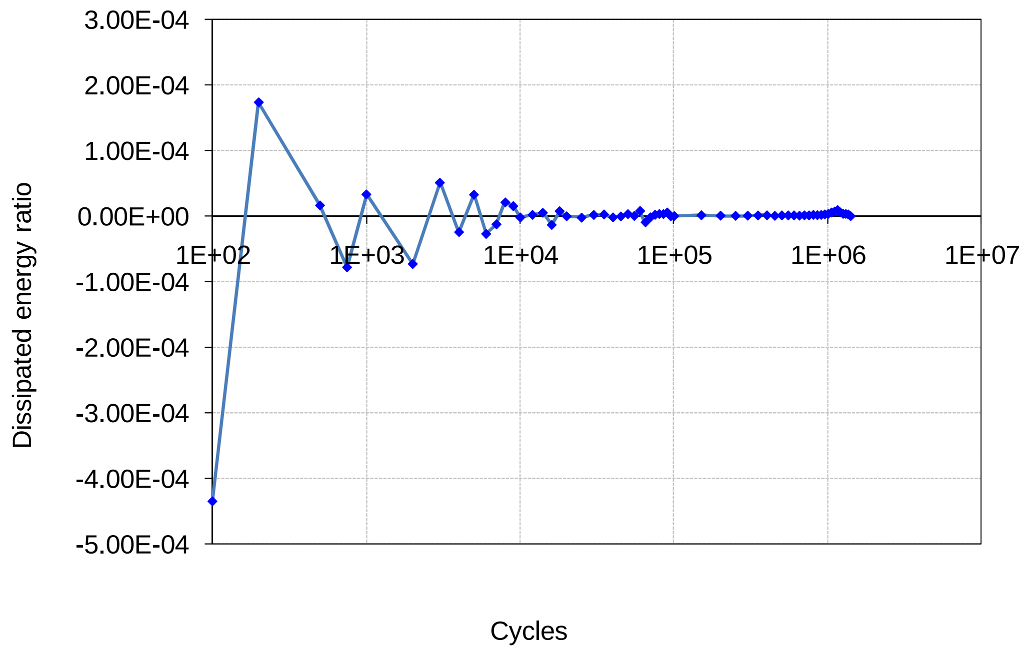

Figure 8. Plot of the ratio of dissipated energy change for a very low strain level

To solve these problems, the approach proposed by Shen and Carpenter (2007) defined that the interval for RDEC calculation can be larger than 100 and 1000 or 10000 loading cycles are proposed.

They also proposed a simplified RDEC approach where the dissipated energy must be fitted, by a power law relationship with the loading cycles to obtain the slope, *k*, of the model. This slope is used to calculate the RDEC and the plateau value as follows:

$$PV = -\frac{k}{Nf_{50}} \quad (3)$$

Using this simplified approach proposed by Shen and Carpenter (2007), the slope k of the power law model and the plateau value were calculated and presented in Table 3. The model fitted in the dissipated energy vs. loading cycles curve that was applied to the initial part of the data obtained from the laboratory tests, represents the part of the test where the RDEC will be constant.

However, the achieving of the slope k of the power law model faces some difficulties due to the shape of the dissipated energy vs. loading cycles curves, as it can be observed on the examples presented in Figures 5 and 7.

Nevertheless, the plot of the plateau value vs. the fatigue life, represented in Figure 9, indicates that the fatigue life can be predicted from the plateau value, although a large dispersion in the results may be observed. In this figure the model of Equation 2 is also represented. Nevertheless, the values obtained for the tested Portuguese mixtures are far from that model, what can be due to the power model from where the k was obtained.

Table 3. Slope of power law model and plateau value

Specimen	k	Plateau value	Specimen	k	Plateau value
1-a	-5.13E-02	3.38E-06	3-01	-6.22E-02	1.05E-05
1-b	-1.94E-02	1.45E-06	3-02	-5.75E-02	8.91E-06
1-c	-5.63E-02	4.94E-06	3-03	-5.00E-02	4.15E-06
1-d	-1.71E-02	3.41E-08	3-04	-4.88E-02	5.09E-06
1-e	-2.47E-02	7.05E-08	3-05	-5.06E-03	5.90E-08
1-f	-6.12E-03	1.63E-08	3-06	-4.05E-02	4.41E-06
2-a	-4.47E-02	6.68E-07	3-07	-3.78E-02	3.75E-06
2-b	-4.39E-02	5.63E-07	3-08	-1.50E-02	1.57E-07
2-c	-4.90E-02	7.47E-07	3-09	-3.99E-02	6.42E-06
2-d	-3.49E-02	1.02E-07	3-10	-1.29E-03	1.09E-09
2-e	-2.95E-02	6.07E-08	3-11	-1.00E-02	7.96E-08
2-f	-3.31E-02	1.09E-07	3-12	-4.45E-03	3.90E-08
2-g	-6.48E-02	4.07E-06	3-13	-2.65E-04	3.64E-10
2-h	-6.80E-02	5.05E-06	3-14	-2.54E-02	4.21E-06
2-i	-7.30E-02	4.92E-06	3-15	-1.86E-02	2.41E-06
			3-16	-2.08E-02	2.27E-06
			3-17	-2.60E-02	2.64E-07
			3-18	-4.83E-03	3.15E-09
			3-19	-2.79E-03	3.28E-09
			3-20	-7.11E-03	7.50E-08

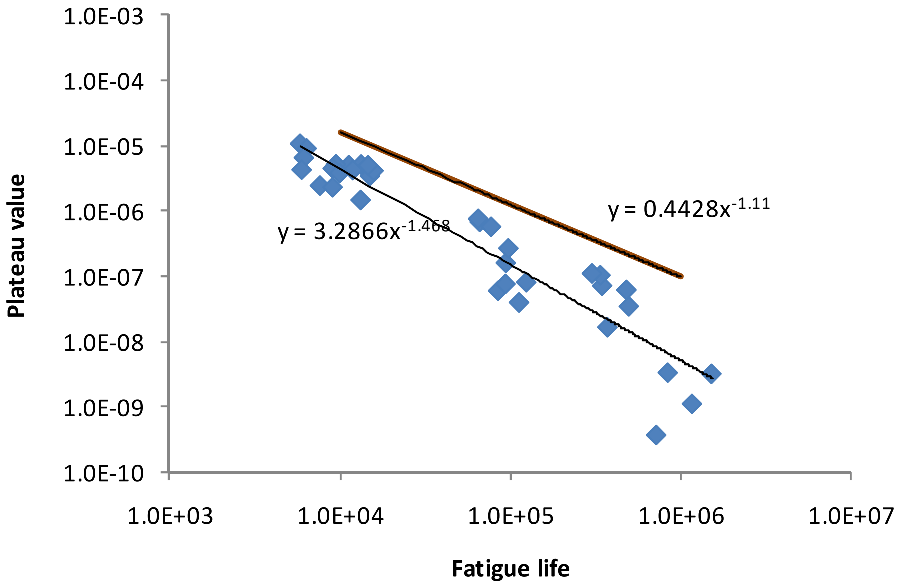

Figure 9. Plot of the plateau value as function of the fatigue life

To minimize the dispersion of the plateau value, the authors developed a method to calculate it based on the cumulative dissipated energy (sum of the dissipated energy per cycle up to the present cycle). Unlike the dissipated energy, the cumulative dissipated energy presents a regular trend with the loading cycles, as it can be observed in Figure 10.

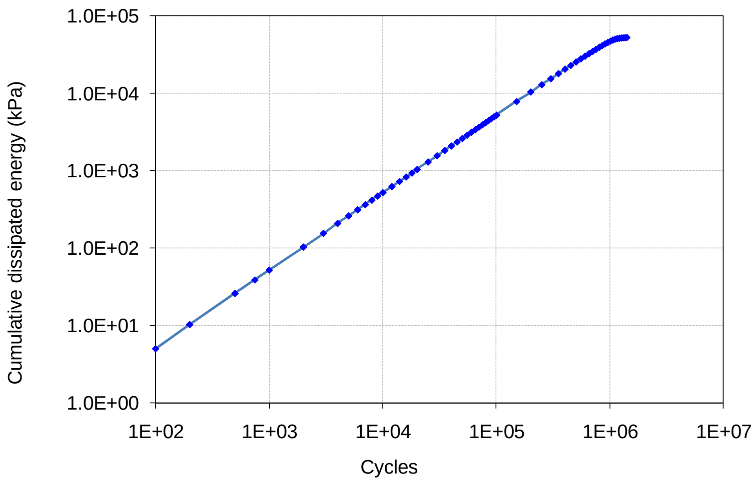

Figure 10. Cumulative dissipated energy

The proposed method calculates the dissipated energy for some specific loading cycles from the cumulative dissipated energy and it uses those values to calculate the RDEC. To ensure that the calculated dissipated energy decreases during the considered loading cycles, the authors defined the following ones: 1E3, 2E3, 5E3, 1E4, 2E4, 5E4 and 1E5. These loading cycles are approximately spaced in a logarithmic scale. The plateau value is defined as the average of the RDEC for the calculated loading cycles before the failure of the specimen. If the RDEC is negative that value is eliminated.

Applying the proposed method, the plateau value was calculated for all studied mixtures, the values of which are presented in Table 4. These values as well as the model of Equation 2 are represented in Figure 11 as function of the fatigue life.

Table 4. Plateau value

Specimen	Plateau value	Specimen	Plateau value
1-a	2.59E-05	3-01	6.21E-05
1-b	3.42E-05	3-02	5.84E-05
1-c	3.23E-05	3-03	2.93E-05
1-d	1.83E-06	3-04	3.87E-05
1-e	1.63E-06	3-05	6.31E-06
1-f	2.73E-06	3-06	4.10E-05
2-a	9.71E-06	3-07	3.55E-05
2-b	8.85E-06	3-08	4.67E-06
2-c	9.19E-06	3-09	8.41E-05
2-d	3.29E-06	3-10	2.55E-07
2-e	2.89E-06	3-11	2.18E-06
2-f	2.77E-06	3-12	3.54E-06
2-g	2.48E-05	3-13	9.49E-08
2-h	2.70E-05	3-14	8.32E-05
2-i	2.65E-05	3-15	4.94E-05
	2.59E-05	3-16	3.18E-05
	3.42E-05	3-17	2.78E-06
	3.23E-05	3-18	2.43E-07
	1.83E-06	3-19	3.64E-07
	1.63E-06	3-20	3.62E-06

The analysis of Figure 11 allows stating that the plateau value calculated by the method proposed by the authors can be used to predict the fatigue life of asphalt mixtures. It can also be observed that for high strain levels (low fatigue life) the plateau value follows a straight line in the log-log scale. For the other strain levels, the dispersion in the results presents a higher increase, but as the difference for the log-log model is small, it allows concluding that the proposed method seems to be suitable to predict the fatigue life.

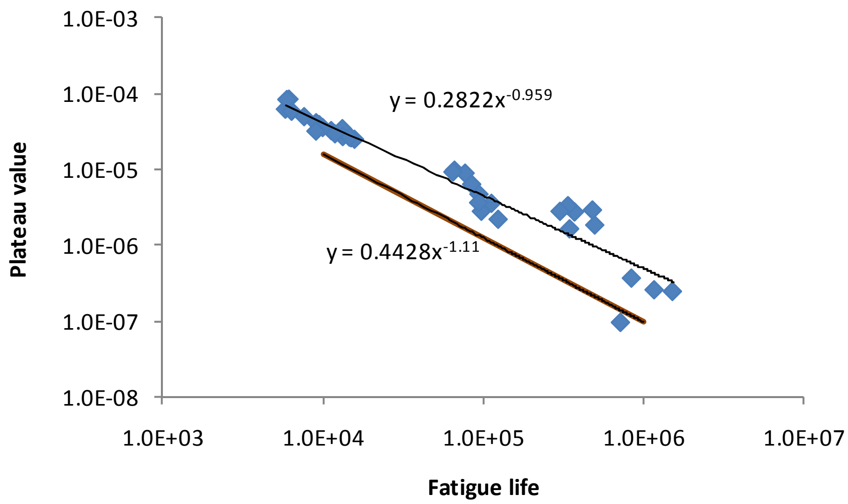

Figure 11. Plot of the plateau value as function of the fatigue life

The results obtained are encouraging to continue performing fatigue tests prior to the failure of the specimen. Nevertheless, further research must be conducted to validate the proposed method, mainly for fatigue tests performed at low strain levels. However, once the method seems to be suitable for high and mid strain levels, the fatigue life laws can be obtained for only these two strain levels.

5 CONCLUSIONS

This paper presented the procedure proposed by Shen and Carpenter (2007) to predict the fatigue life of asphalt mixtures based on the ratio of dissipated energy change and on the plateau value. Aiming at validating the model by Shen and Carpenter, it was applied to 3 Portuguese mixtures.

The analysis of the results obtained allowed concluding that the application of the method is not easy due to the evolution of the dissipated energy during the fatigue tests, mainly for low strain fatigue tests, where the dissipated energy remains almost constant during the process.

However, the plateau value follows a power law model with the fatigue life, but it presents a large scatter.

To solve the problem of the calculation of the plateau value, the authors proposed a method based on the analysis of the cumulative dissipated energy that leads to plateau values well correlated with the fatigue life, what allowed to perform fatigue tests prior to the failure of the specimen.

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