A dissipated energy comparison to evaluate fatigue resistance using 2PB

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ABSTRACT

Flexural fatigue due to repeated traffic loading is a process of cumulative damage and one of the main failure modes of flexible pavement structures. Typically, micro-cracks originate at the bottom of an asphalt concrete layer due to horizontal tensile strains. Micro-cracking starts to propagate towards the upper layers under repeated loading which can lead to pavement failure.

Different approaches are usually used to characterise fatigue resistance in asphalt mixtures including the phenomenological approach, the fracture mechanics approach and the dissipated energy approach. This paper presents a comparison of fatigue resistance calculated for different dissipated energy models using 2 Point Bending (2PB) at IFSTTAR in Nantes. 2PB tests have been undertaken under different loading and environmental conditions in order to evaluate the properties of the mixtures (stiffness, dissipated energy, fatigue life and healing effect).

Keywords: Flexural Fatigue, Dissipated Energy Methods, 2 Point Bending Tests.

1 INTRODUCTION

Asphalt is a viscoelastic material, thus it dissipates energy under mechanical work (loading and relaxation). Usually, in an elastic material the energy is stored in the system when the load is applied, all the energy is recovered when the load is removed; in this case the unloading and the loading curves coincide. Viscoelastic materials are characterised by a hysteresis loop because the unloaded material traces a different path to that when loaded (phase lag is recorded between the applied stress and the measured strain); in this case the energy is dissipated in the form of mechanical work, heat generation, or damage [14, 15].

The area of the hysteresis loop represents the dissipated energy in a load cycle and the following equation can be used to calculate its value in a linear viscoelastic material:

$$W_i = \pi \sigma_i \varepsilon_i sin\varphi_i \qquad (1)$$

Where:

- W_i = Dissipated energy in cycle i,
- σ_i = stress level in cycle i,
- ε_i = strain level in cycle i, and
- φ_i = phase angle in cycle i.

During a fatigue test, the stiffness reduces, the fatigue process starts and microcracks are induced in the material; therefore the dissipated energy, W, varies per loading cycle and it, usually, increases for controlled stress tests and decreases for controlled strain tests.

The aim of this study was to compare different dissipated energy methods to evaluate flexural fatigue of bituminous mixtures by 2 Point Bending (2PB) tests undertaken at IFSTTAR in Nantes (France).

2 TESTING PROCEDURE AND MATERIAL

2.1 2 Point Bending test (2PB)

The 2 Point Bending test is widely used for measuring fatigue resistance and stiffness for asphaltic paving materials. For this laboratory activity, fatigue tests were carried out performed at IFSTTAR in Nantes (France). The methodology consists of applying a continuous sinusoidal waveform at the top of a trapezoidal specimen. The specimen is glued between to plates (at the top and at the bottom) and the fracture usually occurs at 1/3 of the height, where the bending moment is a maximum (see Figure 3). Trapezoidal specimens are shown schematically in Figure 1. Usually four specimens were tested at each strain level. Figure 2 shows the 2PB equipment.

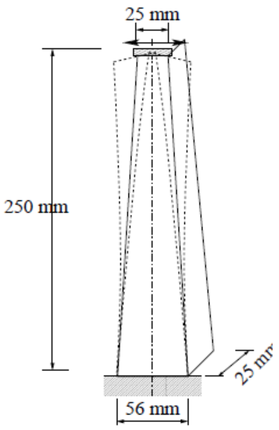

*Figure **1*** Trapezoidal specimen for 2PB

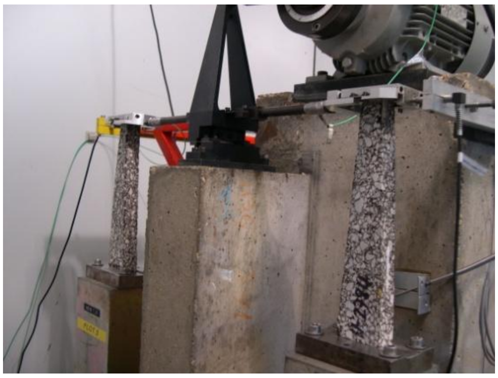

*Figure **2*** 2 Point Bending equipment

The trapezoidal specimen is mounted as vertical cantilever as you can see in the Figure 2. Sinusoidal constant displacement is applied at the top of the specimen, while the bottom base is fixed.

As mentioned before, fracture usually happens at 1/3 high from the bottom because that area is the most stressed in the specimen as shown in the Figure 3.

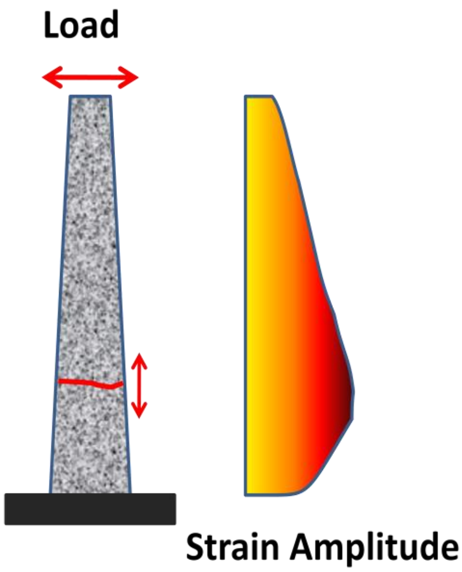

*Figure **3*** Fracture in trapezoidal specimen

The initial stiffness is usually chosen between the 50^{th} and the 100^{th} load application. Traditionally, a fatigue test ends when the stiffness has decreased to half of its initial value [14, 17].

2.2 Materials

A 10 mm Dense Bitumen Macadam (DBM) or asphalt concrete was chosen for the experimental work. A 100 Pen Binder was chosen for the mixture. The aggregates type selected was a crushed limestone. The aggregate gradation curve is shown in Figure 4; four lines are presented: the upper, the lower limits and the mid-point curve from the British Standards and the aggregate gradation.

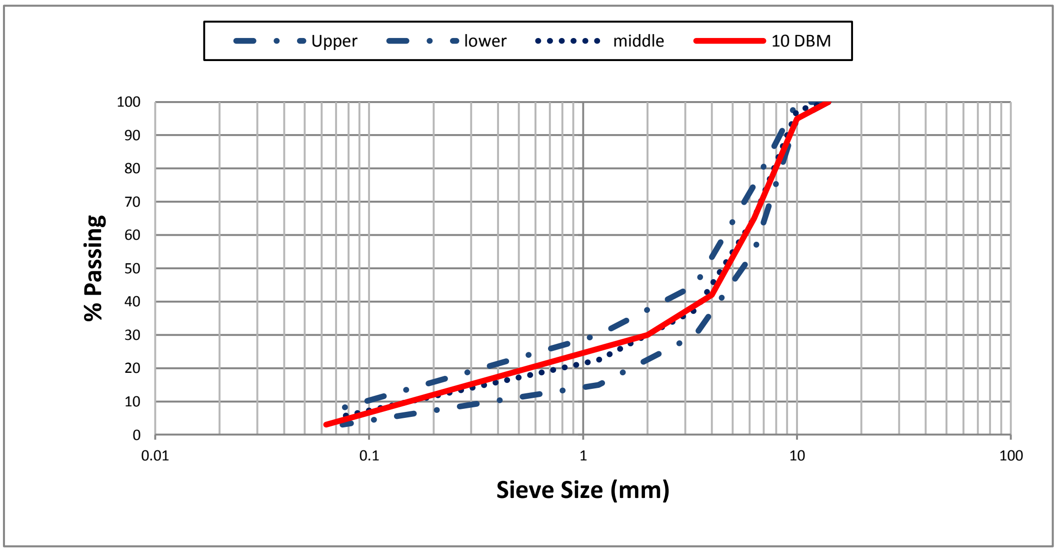

Figure **4.** Aggregate Gradation Curve

3 EXPERIMENTAL RESULTS

Fatigue tests were undertaken in controlled strain mode. Testing conditions were as follows: temperature 20°C degrees; frequency 15 and 25 Hz; sinusoidal loading; strain levels between 120 and 190με [4, 5]. For each test stiffness modulus, phase angle and dissipated energy were calculated.

Figure 5 shows the typical trend of the stiffness modulus. It is calculated considering the recorded stress divided by the applied strain. As it can be possible to see, a three stage evolution process is recorded during a fatigue test. After a rapid reduction of stiffness (phase I), due to the internal heating phenomenon, the stiffness decrease seems more regular (phase II). Fracture occurs in the final stage (phase III) and it is characterised by an acceleration of stiffness drop [1, 2, 9, 11].

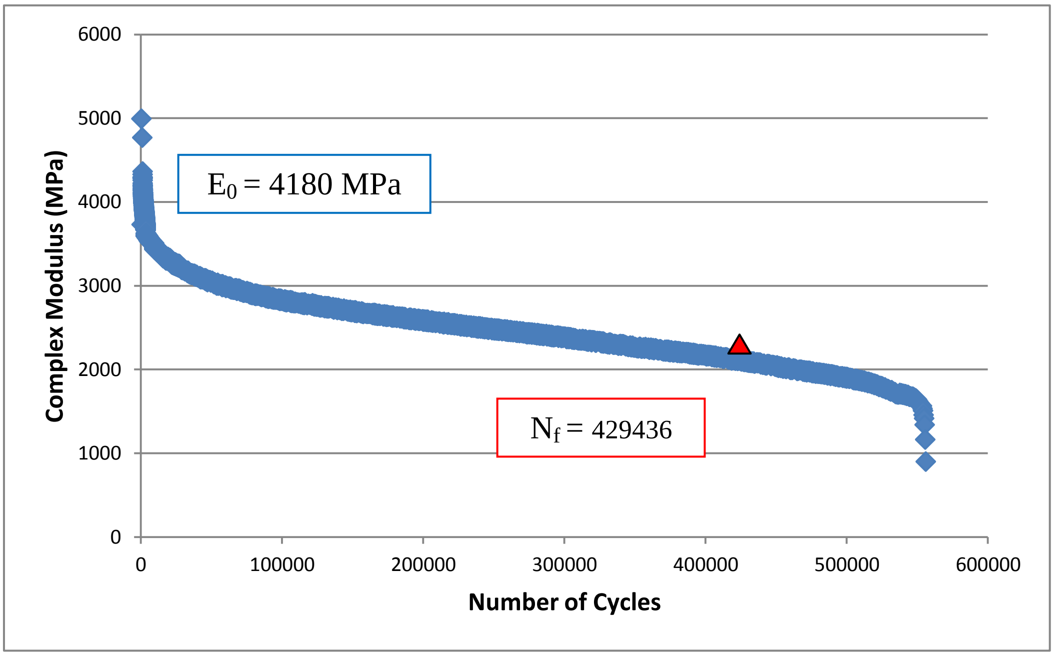

Figure 5. Stiffness evolution during a fatigue test (160με)

The phase angle, after a rapid increase, tends to have a constant behaviour during the test. For most of the tests shown in Figure 6, its value is about 47 degrees (see Figure 6).

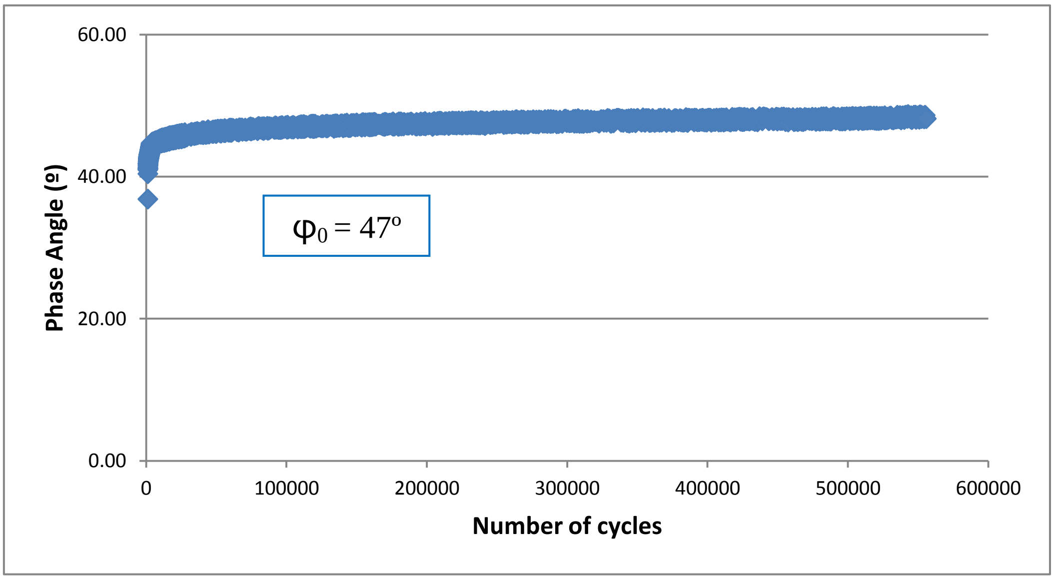

Figure 6 Phase angle evolution during a fatigue test (160με)

Figure 7 shows the decrease of the dissipated energy for the controlled displacement mode undertaken with the 2PB. Dissipated energy changes during a fatigue test, due to the beginning of microcracking during the fatigue process; the evolution of the hysteresis loop (dissipated energy) during a fatigue test is shown in Figure 8.

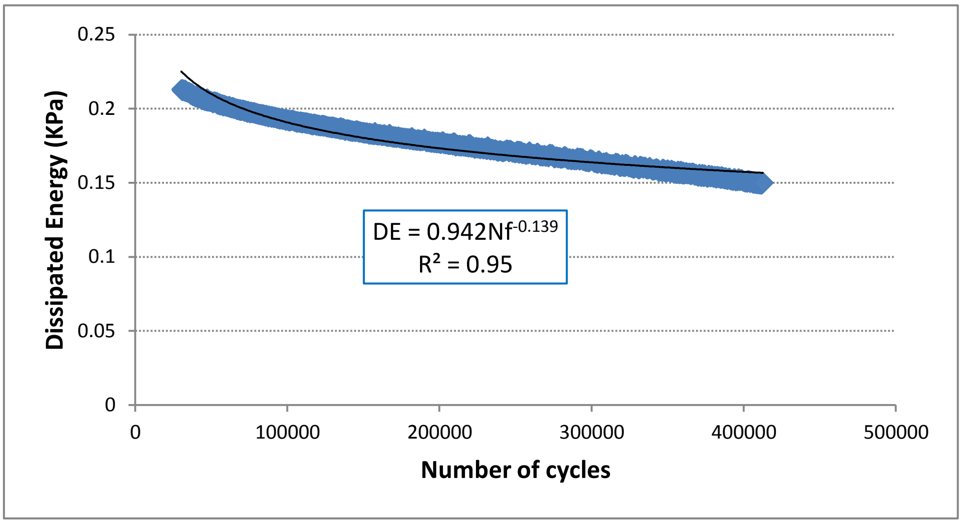

Figure 7 Dissipated energy versus number of cycles during a fatigue test (160με) fitted with power law (Ax^k).

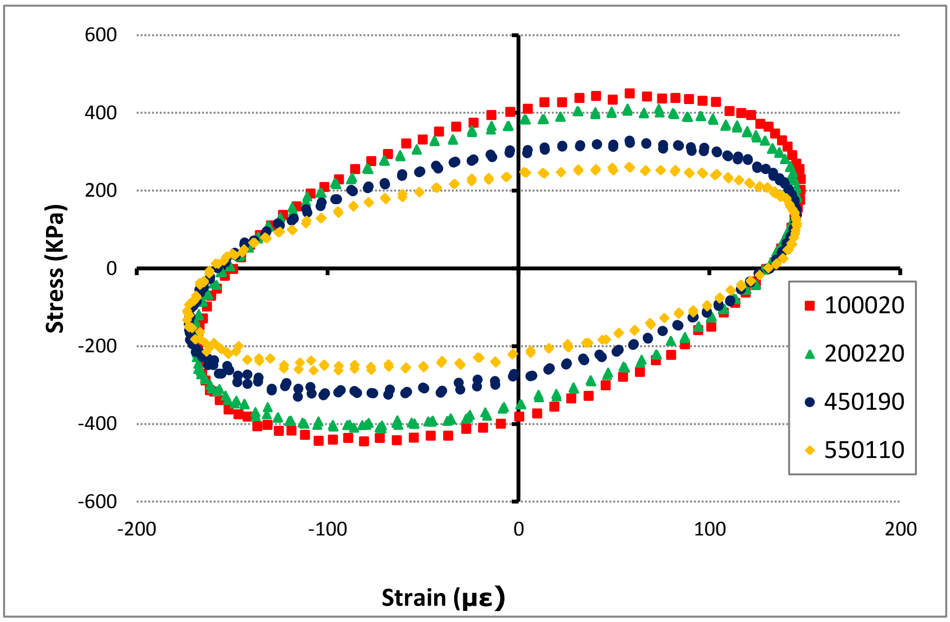

Figure 8 Evolution of hysteresis loop during a fatigue test

According to the classical analysis, fatigue life is conventionally defined as a number of cycles at which the stiffness modulus has decreased to the half of the initial value (see Figure 5). However, dissipated energy methods were also considered in order to determine the number of cycles to failure. Thus, a comparison between different fatigue failure criteria, based on dissipated energy concepts, and the conventional analysis was made.

The Energy Ratio (Rε) method was the first considered. It was introduced by Hopman et al. in 1989 [9]. The Energy ratio is the cycle number where cracks are considerend to initiate (N_1). N_1 is defined as the point at which the slope of the energy ratio versus the number of cycles deviates from a straight line. In a controlled strain test, energy ratio is defined as follows:

$$R_\varepsilon = \frac{nW_0}{W_i} = \frac{n(\pi\sigma_0\varepsilon_0\sin\varphi_0)}{\pi\sigma_i\varepsilon_i\sin\varphi_i} \quad (2)$$

Where W_0 is the energy dissipated in the first cycle, W_i is the energy dissipated at i^{th} cycle. If the stress is replaced by the product of strain and modulus, and considering that the strain level remains constant for a strain controlled test, then the eq. (2) can be simplified and written as follow [14]:

$$R_\varepsilon = \frac{n}{E_i^*} \quad (3)$$

Figure 9 shows the energy ratio and complex modulus plotted as function of load cycles. It can be seen that the number of cycles obtained by means of the classical analysis is generally greater than the energy ratio method.

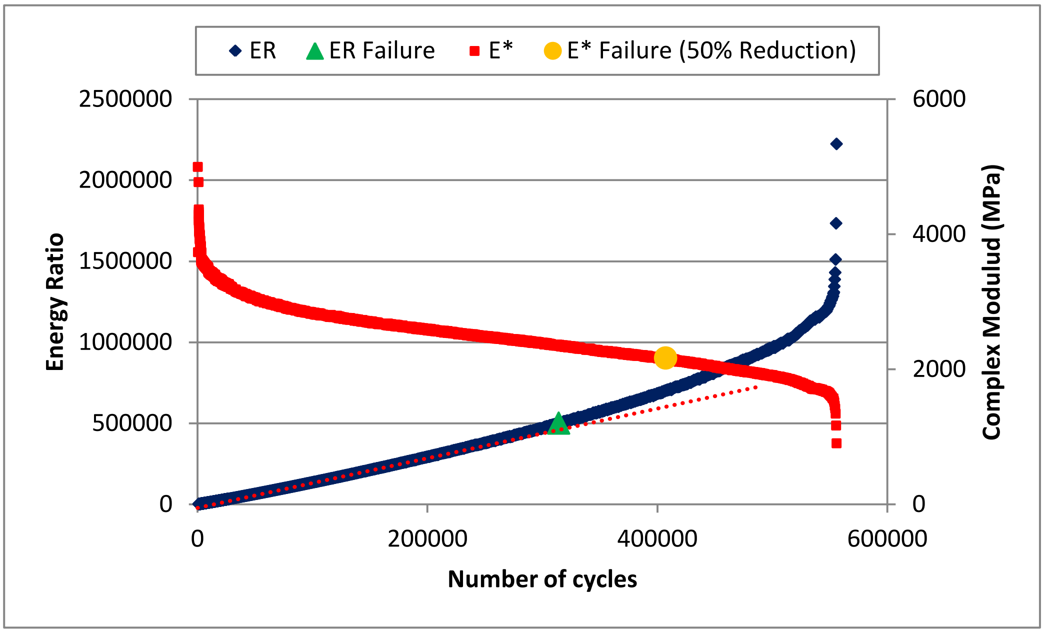

Figure 9 Energy ratio vs number of load cycles at 20 degrees and at 15 Hz

Figure 10 shows the classical Whöler curves that represents the life duration versus applied strain amplitude. In the conventional approach, the relationship between applied strain ε_0 and load cycle to failure N_f is [3]:

$$N_f = K_1(\varepsilon_0)^{-k_2} \qquad (4)$$

Where K_1 and K_2 are the intercept and the slope, respectively. These are determined experimentally and they seem to be highly correlated. Researchers [6, 10, 12] believe that mode of loading, testing temperature, frequency and asphalt content has a more significant effect on the K1-K2 relation than asphalt type, air voids levels and aggregate gradation.

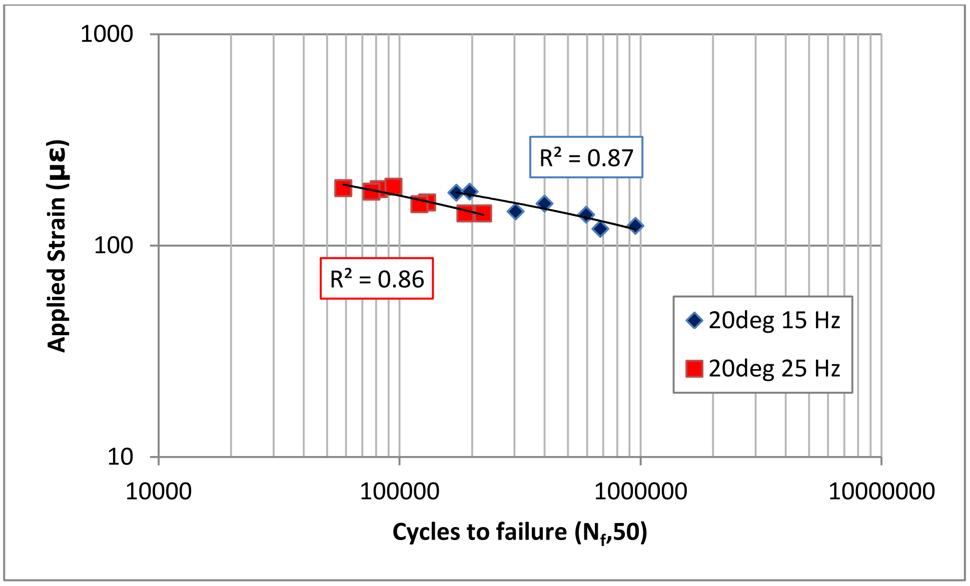

Figure 10 Classical fatigue life curves obtained at 20 degrees, at 15 Hz and 25 Hz.

Van Dijk and Visser [18] performed some of the first research to consider dissipated energy as a fatigue parameter. This work determined an equation that relates the cumulative dissipated energy (CDE) to the number of cycles to failure as shown in equation 5:

$$W_f = A(N_f)^z \qquad (5)$$

Where W_f is the cumulative dissipated energy to failure, i.e. the total energy dissipated by the material during the fatigue test (sum of all areas within the stress-strain hysteresis loop for every cycle until failure); N_f is the number of load cycle to failure, and A, z are the mixture dependent constants (determined experimentally).

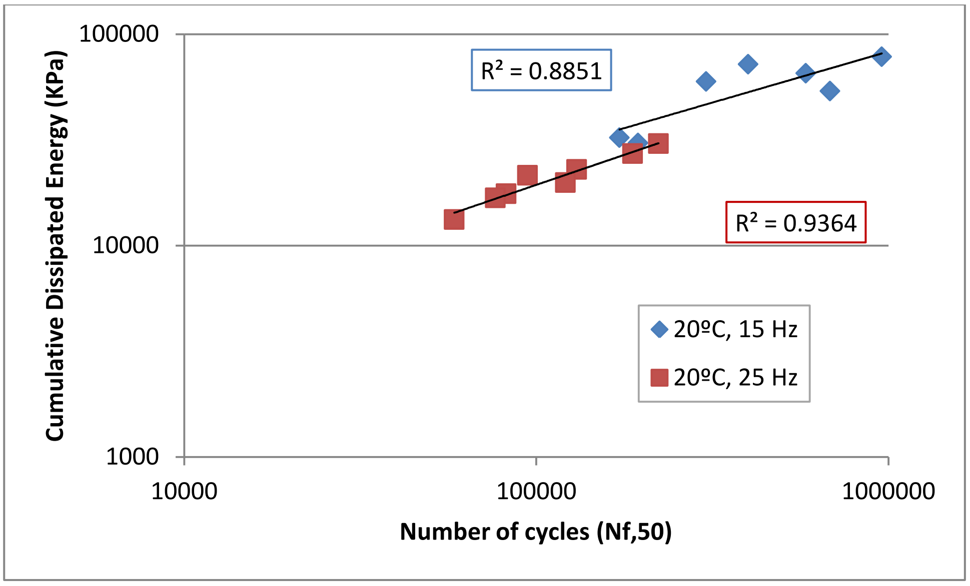

Figure 11 CDE vs Load cycle curve obtained at 20 degrees at 15 and 25 Hz.

CDE is not a good parameter to describe the fatigue phenomenon in asphalt materials, it does not distinguish the amount of DE due to damage rather than viscoelasticity. Also, the eq. 5 is not unique it was found that it changes depending on the mode of loading frequency and temperature. The same result was found by SHRP-A-404 1994 for stress controlled tests [17].

Some researchers [7, 16] have suggested the Ratio of Dissipated Energy Change, RDEC as a parameter to describe fatigue in asphalt materials. The same researchers believe that the RDEC is a true indicator of damage because it is able to eliminate the other forms of dissipated energy due to mechanical work or heat generation. Therefore, it can be considered a good parameter to describe the fatigue process in asphalt, and is calculated with the following expression:

$$\mathrm{RDEC} = \frac{\mathrm{DE}_{n+1} - \mathrm{DE}_n}{\mathrm{DE}_n} \qquad (6)$$

Where RDEC is ratio of the dissipated energy change per load cycle, DE_n is dissipated energy produced in load cycle n, and DE_{n+1} is dissipated energy produced in load cycle n+1.

Figure 12 shows the variation of the RDEC and the complex modulus ratio E*/E0 plotted against the number of load cycles.

Three main phases during a fatigue test are suggested. The RDEC, after a rapid decrease (I stage), reaches a plateau stage in which a plateau value (PV) can be obtained, corresponding to the RDEC value when initial stiffness modulus has been reduced of half. This represents an energy plateau where an almost constant rate of energy input is being turned into damage. It is verified that the PV is uniquely related to fatigue life. After the RDEC increases rapidly until true fatigue failure (III stage).

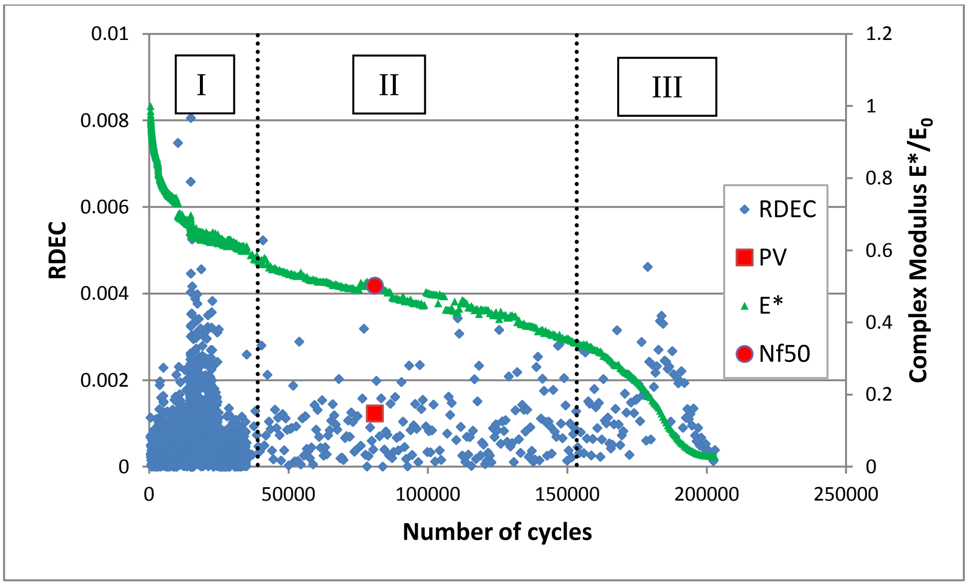

Figure 12 RDEC vs Load cycle curve obtained at 20 degrees at 15 Hz.

One issue of this method is to obtain PV. Often it is not easy to obtain the Plateau Value from experimental data and also they contain a high amount of dispersion. The same researchers made a hypothesis that if the dissipated energy curve follows a power law relationship ($DE=AN_f^k$), the RDEC can be simplified, considering the exponential slope of the power law k, as follows:

$$\mathrm{RDEC} = \frac{1-\left(1+\frac{100}{a}\right)^k}{100} \qquad (7)$$

Also in this case, it is not so easy to determine the PV depending on the evolution of the dissipated energy during the fatigue test. However, the plateau value is correlated with a number of fatigue cycles to failure by means of a statistical approach, using the following equation [7, 8]

$$\mathrm{PV} = cN_f^{\,d} \qquad (8)$$

The value of the constants c and d were determined experimentally. The coefficient d varies from -0.80 and -1.60 [8]. It can be seen from the experimental curve the fit the experimental data from both frequencies (15 and 25 Hz) is characterised by a coefficient d equal to -1.048 (see Figure13).

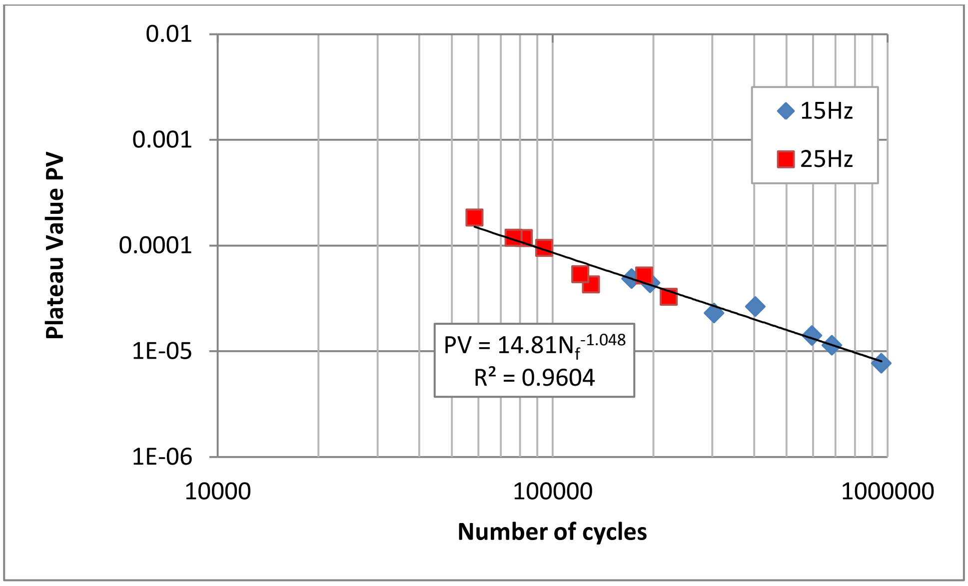

Figure 13 PV vs number of cycles obtained at 20 degrees at 15 Hz and 25Hz.

4 CONCLUSIONS

Different approaches are usually used to characterise fatigue resistance in asphalt mixtures including the phenomenological approach, the fracture mechanics approach and the dissipated energy approach. This paper presents a comparison of fatigue resistance calculated for different dissipated energy models using 2 Point Bending (2PB). Fatigue tests were undertaken in controlled strain mode. Testing conditions were as follows: temperature 20 ˚C degrees; frequency 15 and 25 Hz; sinusoidal loading; strain levels between 120 and 190με. For each test stiffness modulus, phase angle and dissipated energy are calculated. The following conclusions can be made:

- The Energy Ratio (Rε) method was the first considered and it was shown noticed that the number of cycles to failure obtained by means of the classical analysis is generally greater than the Energy Ratio method.
- The Cumulative Dissipated Energy method was also considered but it is not a good parameter to describe fatigue phenomenon because it does not distinguish the amount of DE due to damage rather than viscoelasticity and it depends on the mode of loading frequency and temperature.
- The RDEC method is interesting because it focuses the attention to the changing of DE during a fatigue test, but it is not so easy to obtain from the experimental data. However a good correlation was found between the plateau value and the number of cycles to failure.

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