Fatigue resistance: is it possible having a unique response?

C. Maggiore
University of Nottingham, UK

G. Airey[2], G. Di Mino[3] ,P. Marsac[4] , A. Collop & M. Di Liberto[3]
[2]*University of Nottingham, Nottinghamshire, UK*

[3]*University of Palermo, Palermo, Italy*

[4]*IFSTTAR, Nantes, France*

ABSTRACT: The mechanical characterisation of the asphalt concrete in terms of both the fatigue resistance and the stiffness modulus is necessary to use any design method of the flexible road pavements.

Different kinds of test are usually used in experimental work such as bending tests, uniaxial tests, etc., but sometimes they do not give the same answer.

In this paper mechanical characterization was carried out by means of fatigue tests undertaken with two most used testing machines for asphalt material: two point bending (2PB) test at IFSTTAR in Nantes (France) and four point bending (4PB) test at University of Palermo, in Palermo (Italy).

Different strain controlled tests were undertaken for the same material under the same loading conditions, frequency and temperature (15 Hz and 20°C), according to the European standard 12697 part 24 and 26.

The first results of this interlaboratory activity are showed in this paper.

1 INTRODUCTION

Flexural fatigue is one of the main failure modes in asphalt mixtures and flexible pavement structures. This means good prediction of a pavement's fatigue life will help to develop and improve pavement design procedures.

Fatigue resistance and stiffness are two required parameters for pavement design necessary to dimension the pavement structure (layer thickness).

European standards (EN 12697 part 24 and 26) specifies the methods for characterizing stiffness and fatigue of bituminous mixtures by different kind of tests, including bending tests (2PB and 4PB) and direct and indirect tensile tests. Usually tests are performed applying a sinusoidal loading (stress or strain) to a different kind of specimen (trapezoidal or prismatic), depending on the mode of loading.

1.1 *Fatigue*

Flexural fatigue due to repeated traffic loading is a process of cumulative damage.

From a mechanical point of view, the mechanism of fatigue can be divided into two parts: the first one is the occurrence of tensile stress/strain in the base layer; the second one is the repetitive occurrence of such tensile stress/strain under traffic repetitions. The repetition of the tensile stress/strain causes the accumulation of micro damage in the bottom of the base layer that, over time, results in the break between the aggregate and the binder, thus generating more or less deep cracks. In other words if a beam is subjected to load, the beam would tend to assume a convex downward shape, with tensile stress/strain in the bottom part and compressive stress/strain in the top one. Since the asphalt pavement has viscoelastic behaviour, it recovers when the load is removed. At the end of this first cycle there is part of the strain that is recovered and a small part that is permanent. Under the next load the pavement undergoes the same cycle. Ultimately the pavement will fail due to damage accumulation (Rajib B. et al. 2009).

Physically speaking, micro crackings originate at the bottom of an asphalt concrete layer caused by horizontal tensile strain; this compromises the contact between the aggregate skeleton and the binder (particle-to-particle contacts). Furthermore the water trapped in the cracks and the repeated loading leads to a decrease in the strength of the mixtures and micro crackings starting to propagate towards the layers above and leading to pavement collapse. This phenomenon is called Bottom-Up Cracking (Thom N., 2008).

According to European standards, fatigue can be evaluated by means of bending tests or direct and indirect tests. This paper focuses on bending tests, in particular on 2 Point Bending (2PB) and 4 Point Bending (4PB) tests. The two type of tests are widely used for measuring fatigue resistance and stiffness for asphaltic paving material. Usually a sinusoidal loading is applied to the specimen, but geometry of the specimen and loading mode are different in the two tests. In the 2PB, trapezoidal specimen is glued between to plates (at the top and at the bottom) and the fracture usually happens at 1/3 of height, where bending moment is maximum. In the 4PB, instead, the specimen is not glued and the fracture happens in the middle part of the beam characterized by a constant maximum value of bending moment. (see Figure 1).

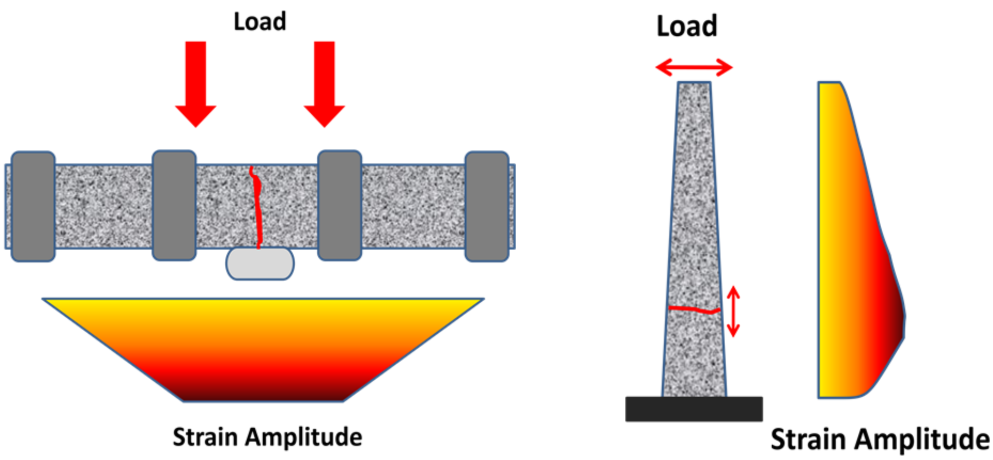

Figure 1 Load and strain amplitude for 2PB and 4PB

1.2 *4 Point Bending test (4PB)*

The 4 Point Bending test is the most used fatigue test in the United States.

The tests were performed for the experimental work with servo-hydraulic testing system at University of Palermo (see Figure 3). Prismatic beams were manufactured with dimensions of 380 mm in length, 50 mm in height and 63 mm in width.

The specimen is restrained at four points by means of four clamps: the two outside remains static (they can only shift horizontally), the centrals deflect according to the strain applied. The deformation of the specimen is measured at the bottom between the two central clumps.

This test simulates very well a pavement fatigue failure under traffic loading because repeated loading causes tension in the bottom zone of the specimen, cracking will initiate and propagates to the top zone until failure; failure usually occurs in the area of uniform bending moment between the two inner clamps. (see Figure 2).

In this type of test free lateral translation are permitted in order to prevent internal stresses developing in the specimen.

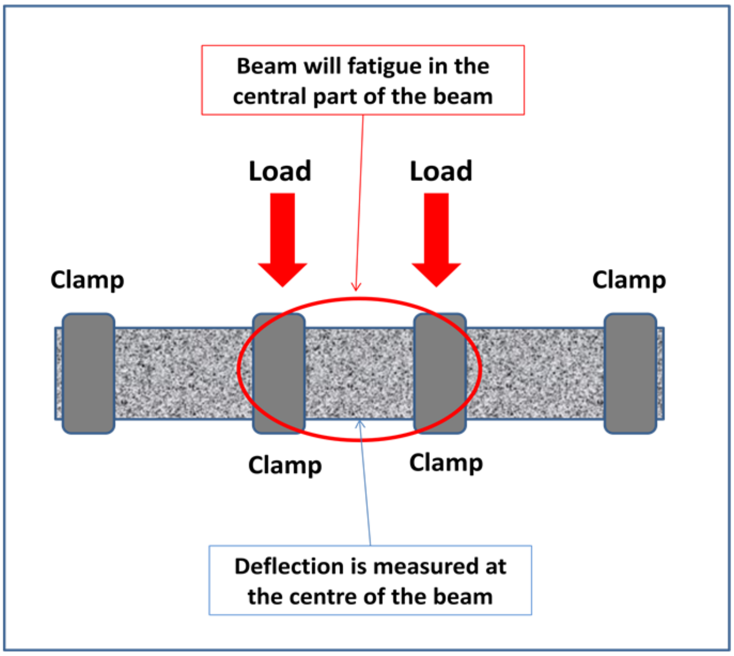

Figure 2. Configuration of 4PB test

In the 4 point bending test, initial stiffness is usually chosen between the 50th and the 100th load application. Conventionally, fatigue failure is the moment when the stiffness has decreased to half of its initial value (SHRPA-404, 1994, Di Benedetto et al,2004, Shen et al, 2007)

Figure 3 Beam Fatigue testing machine at University of Palermo

1.3 *2 Point Bending test (2PB)*

The 2 Point Bending test is more used and widely spread in Europe.

The tests were performed for the experimental work at IFSTTAR in Nantes. The methodology consists of applying a sinusoidal continuous waveform at the top of a trapezoidal specimen. Schematic of trapezoidal specimen is represented in the Figure 4. Usually four specimen for each tests were used. (see Figure 5).

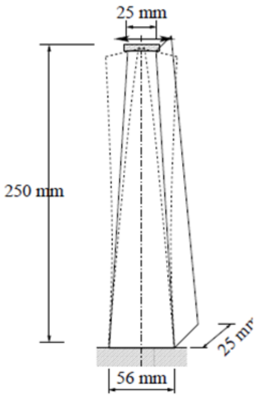

Figure 4 Trapezoidal specimen for 2PB

Figure 5 2 Point Bendng Test

The trapezoidal specimen is mounted as vertical cantilever as seen in Figure 5. Sinusoidal constant displacement is applied at the top of the specimen, while the bottom base is fixed.

As mentioned before, fracture usually occurs at 1/3 height from the bottom because that area is the most stressed in the specimen as shown in the Figure 6.

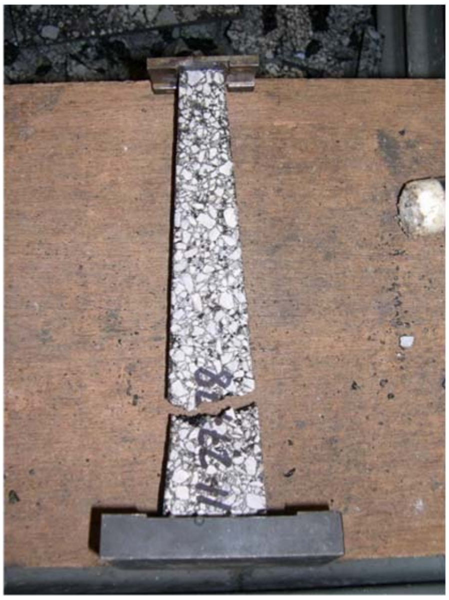

Figure 6 Fracture in trapezoidal specimen

As in the 4PB, in the 2PB, initial stiffness is usually chosen between the 50th and the 100th load application. Traditionally, fatigue test ends when stiffness has decreased to half of its initial value (Rowe, 1993, SHRPA-404, 1994).

2 LABORATORING TESTING

2.1 *Material*

A 10 mm Dense Bitumen Macadam (DBM) was chosen for the experimental work. 100 Pen Binder was chosen for the mixture. The aggregates type selected was a crushed limestone. The aggregate gradation curve is shown in Figure 7; four lines are presented: the upper, the lower and the middle point curve from the British Standards.

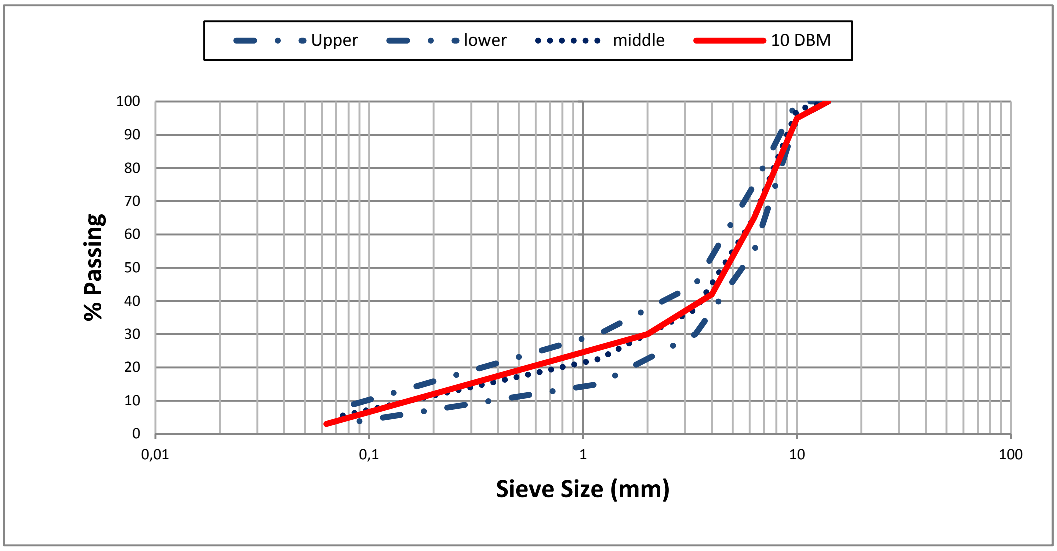

Figure 7. Aggregate Gradation Curve

3 TEST RESUTS

3.1 *4 Point bending test Procedure*

In this study, the fatigue tests were carried out applying a continuous sinusoidal cyclic waveform, in controlled displacement (strain) mode at constant temperature (20 °C degrees) and at constant frequency (15 Hz) (EN-12697-24-2007, EN-12697-26-2007).

Strain levels between 140-190 με were chosen for the testing

Typical strain waveform applied to the prismatic specimen and typical stress waveform recorded are presented in Figure 8 and 9.

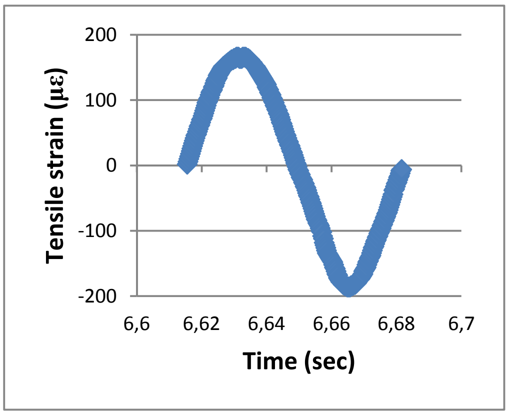

Figure 8 Strain waveform

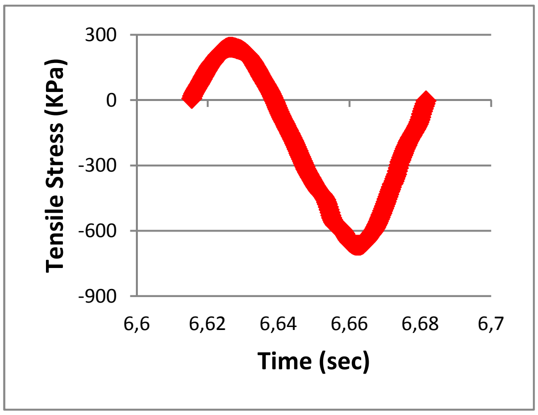

Figure 9 Stress waveform

For each test stiffness modulus, phase angle and dissipated energy are calculated.

Figures 10 shows the typical trend of the stiffness modulus. It is calculated from the measured force, displacement and phase lag between force and displacement, considering the mass of the beam and the clamps. As seen in the figure, a two stage evolution process is recorded during a fatigue test and it could be associated to two phenomenological aspects in flexible pavement: crack initiation and crack propagation (forming a network of micro and macro cracks), usually followed by the failure of the specimen (Pronk, 1999, Di Benedetto et al,2004).

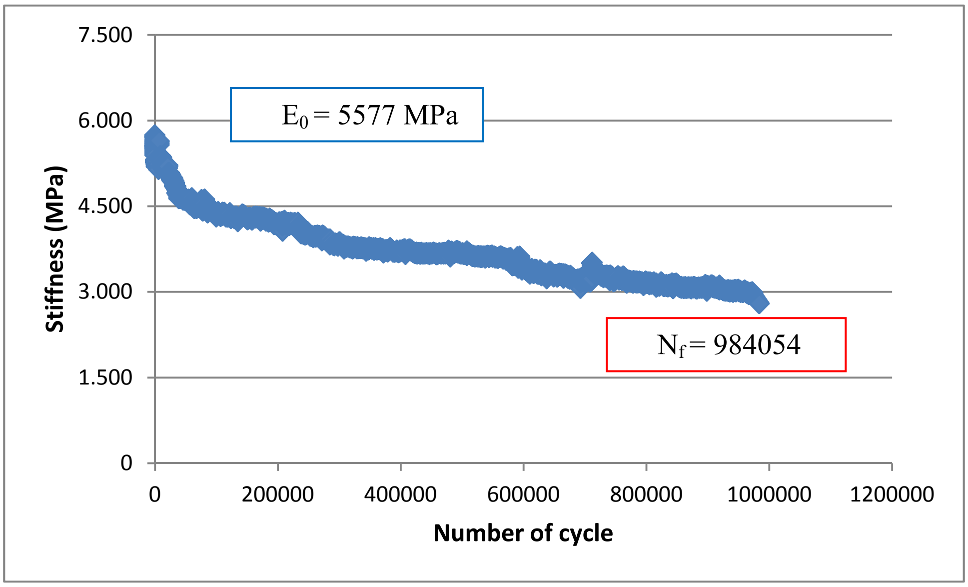

Figure 10 Stiffness evolution during a fatigue test (160µe)

Also for the phase angle, it is possible noticing the same behaviour as the stiffness modulus. After a rapid increasing, the phase angle shows a regular behaviour. (see Figure 11)

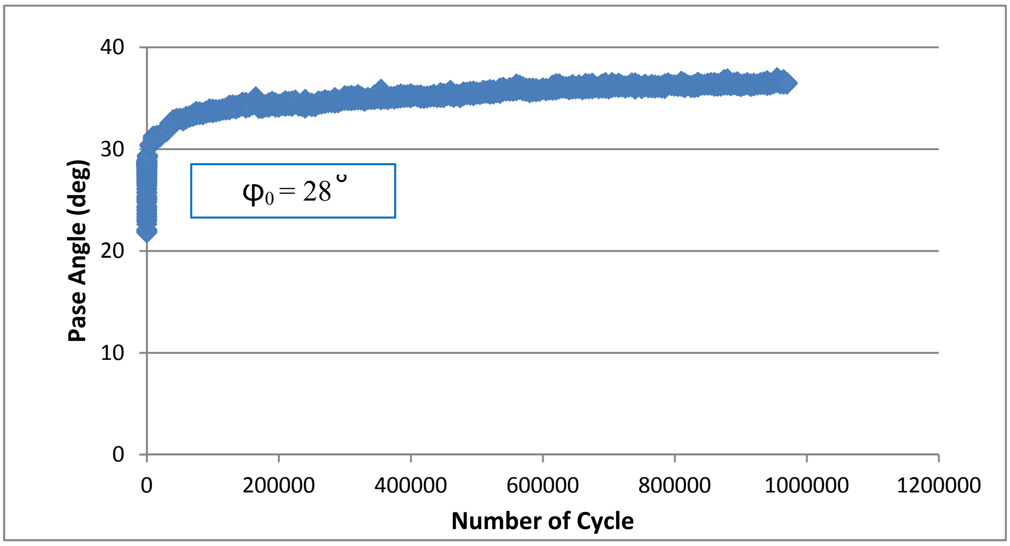

Figure 11 Phase Angle evolution during a fatigue test (160µe)

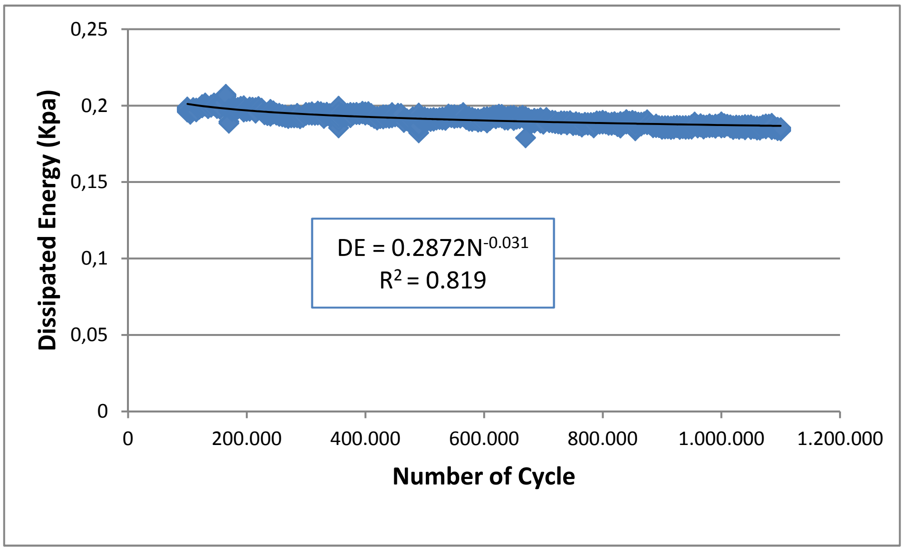

Figure 12 Dissipated Energy versus Number of cycle during a fatigue test (170µe) fitted with power law.

Dissipated energy usually changes during a fatigue test, due to the beginning of microcrack during the fatigue process; it usually decreases in strain controlled mode, it increase in stress controlled mode testing. (see Figure 12).

The evolution of dissipated energy is shown in Figure 13. In the first stage of the test, the hysteresis loop is well defined. After this the loop changes shape. It starts to rotate and the area becomes smaller (for strain controlled test mode). At the end of the tests, dissipated energy is usually characterised by an irregular hysteresis loop. Thus, variation in dissipated energy should be a good parameter to describe fatigue phenomenon in asphaltic material and it is considered the starting point for the development of the fatigue model.

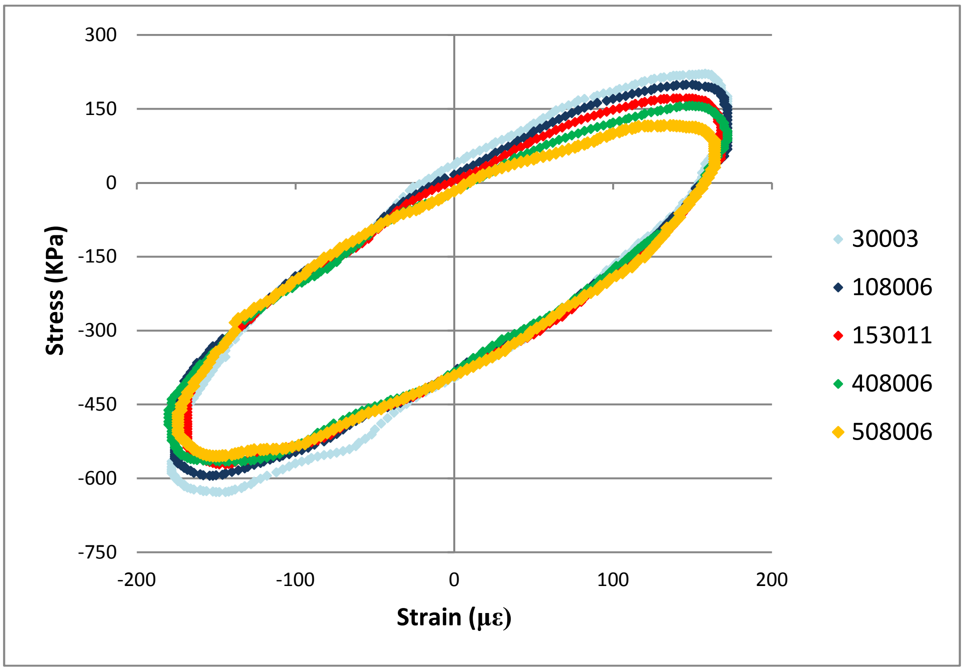

Figure 13 Evolution of hysteresis loop during a fatigue test

3.2 *2 Point bending test Procedure*

Same loading conditions were considered for 2 Point bending tests in Nantes. Fatigue tests were undertaken in controlled displacement mode at 15 Hz and 20 °C (EN-12697-24-2007, EN-

12697-26-2007).
Strain levels between 120-190 με were chosen for the 2PB tests.
Typical strain waveform applied to the trapezoidal specimen and typical stress waveform recorded are presented in Figure 14 and 15.

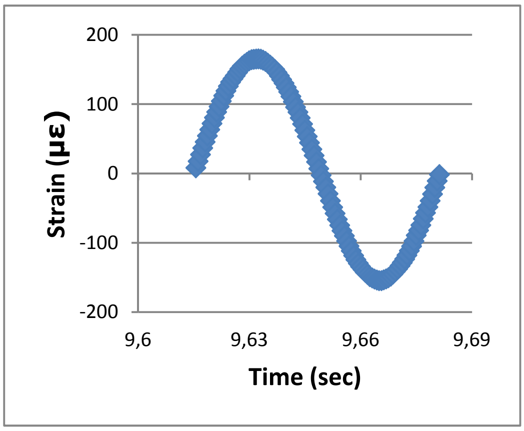

Figure 14 Strain waveform

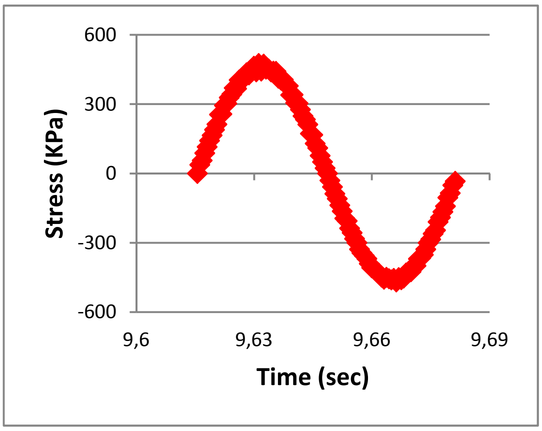

Figure 15 Stress waveform

The applied and the recorded waveform look symmetrical around the point zero.
As for the 4 PB tests, stiffness modulus, phase angle and dissipated energy are calculated.
Figures 16 shows the typical trend of the stiffness modulus. It is calculated considering the recorded stress divided by the applied strain. As it can be seen, a three stage evolution process is recorded during a fatigue test. After a rapid evolution of stiffness (phase I), due to the internal heating phenomenon, 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 (Pell, 1967, Hopman et al, 1989, Baburamani, 1999, Bankowskiet al., 2007).

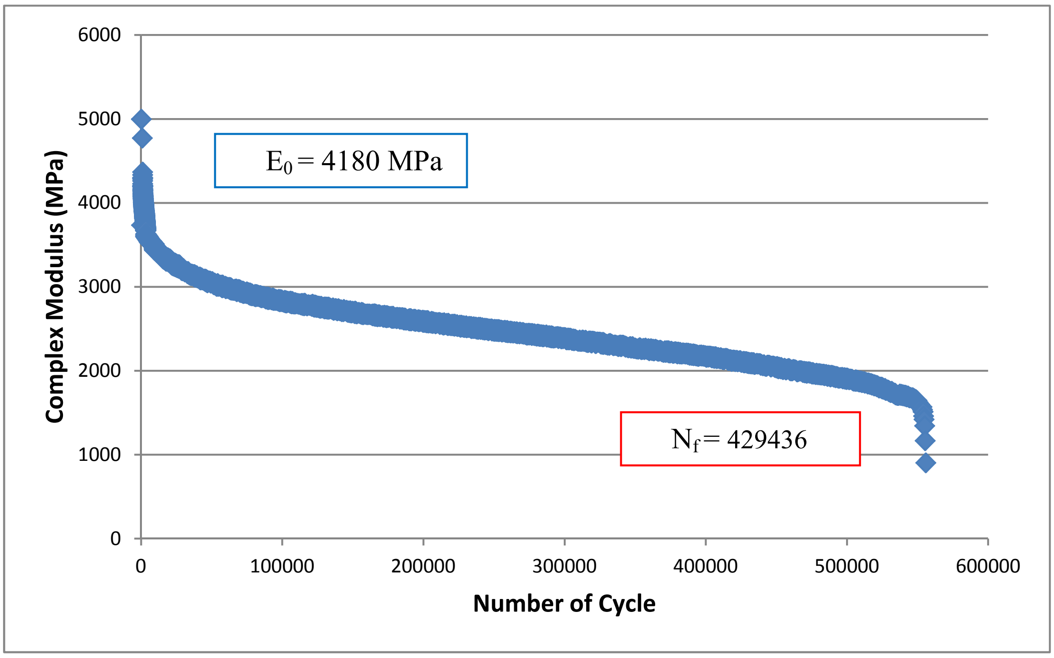

Figure 16. Stiffness evolution during a fatigue test (160με)

Phase angle, after a rapid increase, shows a constant behaviour during the test. As can be seen its value is 40 degrees during the fatigue test. (see Figure 17).

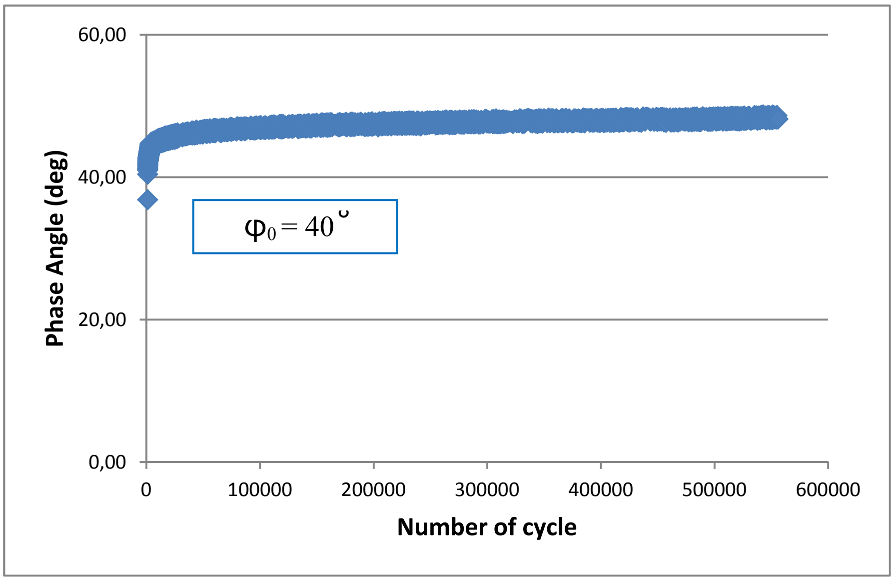

Figure 17 Phase Angle evolution during a fatigue test (160µe)

Figure 18 shows the decrease in dissipated energy for controlled displacement mode undertaken with the 2PB. Figure 19 shows the evolution of the hysteresis loop (dissipated energy) during a fatigue test.

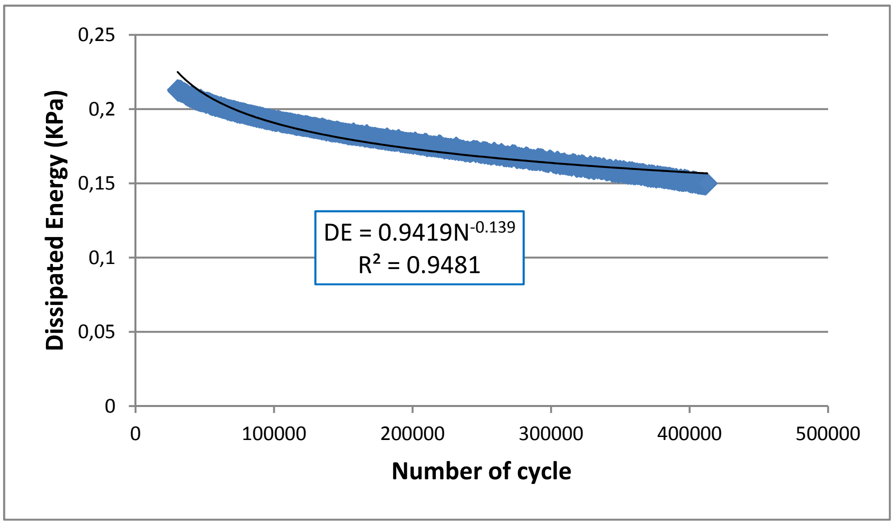

Figure 18 Dissipated Energy versus Number of cycle during a fatigue test (170µe) fitted with power law.

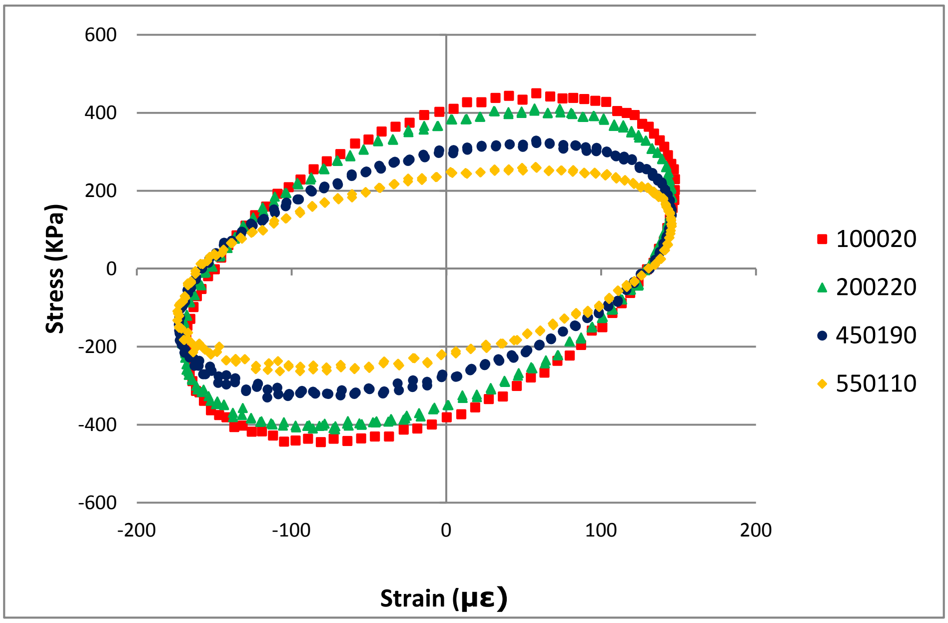

Figure 19 Evolution of hysteresis loop during a fatigue test

4 CONCLUSION

An interlaboratory study between IFSTTAR and University of Palermo have been developed to better understand the fatigue phenomenon by means of different testing machine.

Mechanical characterization was carried out by means of fatigue tests undertaken with two most used testing machines for asphalt material: two point bending (2PB) test and four point bending (4PB) test.

The first results of this interlaboratory activity seem to underline some difference between the two kinds of testing machines. Fatigue tests are undertaken on the same material, at the same loading conditions, same frequency (15 Hz) and same temperature (20°C); however differences are observed in the determination of stiffness, phase angle, number of cycle to failure and dissipated energy.

Several reasons may explain those behaviours:

- different loading conditions: constant bending moment in the middle section of the prismatic specimen and no shear stress in 4PB; only one point in the trapezoidal specimen is characterized by the highest bending in 2PB and shear stresses exist in the specimen.
- different boundary conditions (fixed trapezoidal specimen that is glued at the top and at the bottom between two plates in 2PB; free prismatic specimen, horizontal translation and rotation are allowed in 4PB);
- different size sample (Di Benedetto et al.2004);
- presence of shear forces in the 2PB bending test; no shear forces in 4PB (Pronk, 1999);
- other phenomena such as heating can influence the results differently in the two kind of tests (Di Benedetto et al.2004).

The most important point is understanding which testing machine simulates better the real fatigue phenomenon; which machine gives us the right response of the material. Those are not easy questions, thus further analysis within a wider spectrum of temperatures and frequencies, will be needed to answer to them.

Furthermore, dissipated energy (depending on strain, stress and phase angle) is a good parameter to describe fatigue behavior of bituminous materials and the key point to better understand the mechanical response of the same material from different kind of test.

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