FATIGUE LIFE OF BITUMEN AND MASTICS - ANALYSIS AND COMPARISON OF DIFFERENT CRITERIA

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ABSTRACT

A study on fatigue behavior of bitumen and mastics is currently led at University of Lyon, ENTPE/DGCB in collaboration with TOTAL Company. An innovative device, the Annular Shear Rheometer (ASR), is used to perform advanced experimental investigation. It allows practicing fatigue tests, which could be considered as homogenous, on large scale specimen contrary to other devices. Different types of materials, including pure bitumen and mastics (phase composed of bitumen and filler) are tested. In this paper, the ASR is presented, as well as the testing procedure and the tested materials. A fatigue life analysis of the results, based on the use of five different criteria, is proposed. The first criterion is classically used: it consists in defining the failure as a 50% loss of the initial stiffness. The other criteria establish a link between the appearance of non-homogeneities in the sample and the occurring of macro-crack, both due to repeated loadings. Two approaches are developed. The first one is based on the evolution of global parameters. The second one takes into account local measurements at different locations in the tested specimen. These two approaches give compatible results, whereas the classical criterion may give very different results, for some loadings conditions. The proposed analysis reveals the limits of traditional approach, mainly due to biased phenomena occurring during fatigue tests such as heating and thixotropy. The analysis provides an objective method to compare fatigue performance of tested materials.

Keywords: Fatigue, Bitumen, Mastic, Annular shear rheometer

1. INTRODUCTION

Bituminous materials are used in multiple areas especially in road pavements. Repeated loadings in pavement layers cause damage. Durability of road pavement materials is a recurring problem which is an important research topic. Different studies on bituminous mixtures and binders fatigue ([6]; [30]; [31]; [5]; [7]; [35]; [36]) were performed in order to characterize the occurrence of macro-cracks and evaluate the life duration of these materials. This paper presents the experimental device, the Annular Shear Rheometer. The testing procedure and specific results are developed. Moreover, fatigue criteria, for life duration, are introduced. Two of them are frequently used (classical criterion and Pronk criterion (Pronk, 1995)), and the other criteria are introduced, which provide a global and a local approach of the appearance of macro-crack. Then information about the fatigue characteristic of bitumen and mastics are discussed.

2. EXPERIMENTAL CAMPAIGN

2.1 Presentation of the annular shear rheometer [11; 13; 10; 12; 35]

The principle of the annular shear rheometer (ASR) consists in applying sinusoidal shear stress or sinusoidal shear strain (distortion) on a hollow cylinder of bitumen or mastic, at different temperatures and frequencies. The sample has a rather large size: 5 mm thickness, 95 mm inner diameter and 40 mm height. With such dimensions, the test is homogenous as a first approximation even with aggregate sizes up to 1 millimetre. A schematic view of the apparatus is presented in Figure 1.

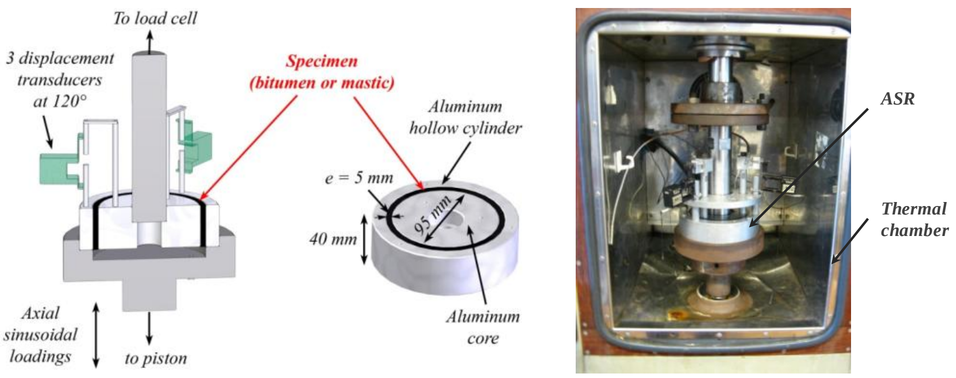

Figure 1 : Schematic view of the annular shear rheometer or ASR (left); picture of the apparatus placed in a thermal chamber (right)

The aluminum hollow cylinder is screwed on the piston of a 50 kN capacity hydraulic press. The core is linked to a fixed load cell. A sinusoidal cyclic loading is applied in stress or strain mode by means of the controlled hydraulic press movements. Three displacement transducers placed at 120° around the sample measure strain. The mean value of the three measured displacements is used to control the strain. The transducers measure the relative displacements between outer and inner lateral surfaces of the bituminous sample.
The ASR allows measuring the complex shear modulus (G*). For "small" strain amplitudes, the behavior is linear viscoelastic (LVE) and the modulus is called G^*_{LVE}. For higher strain levels applied during fatigue tests, the measured "equivalent complex modulus" is called G_e^* [36; 35].
Expression of the complex shear modulus is given by equation(1):

$$G^* = |G^*| e^{j\phi} = G_1 + jG_2 \quad (1)$$

$|G^*|$ is the norm of the complex shear modulus, ϕ is its phase angle, j is the complex number defined by $j^2=-1$, G_1 is the storage modulus and G_2 is the loss modulus. As the ASR is placed in a thermal chamber, G^* can be measured at different temperatures T (from -20°C to 80°C). It can also be measured on a large range of frequencies f (from 0.03 Hz to 10 Hz). $|G^*|$ is the ratio between the amplitudes of distortion γ_A and shear stress τ_A, where $\gamma(t)=\gamma_A \sin(\omega t-\phi)$ is the expression of the distortion signal, $\tau(t)=\tau_A \sin(\omega t)$ is the expression of the shear stress signal and $\omega=2\pi f$ is the pulsation.
A sensor is inserted in the aluminum mould and is in contact with the material. It allows measuring the heating of the sample during fatigue tests.

2.2 Testing procedure

The new proposed testing protocol was used in a study of the fatigue behavior of bituminous mastics led at the ENTPE/DGCB laboratory in collaboration with Total company. It is called “advanced fatigue test”. The general testing protocol is presented in Figure 2. Fatigue cyclic loadings are applied to a sample of bitumen or mastic at a 10 Hz frequency and at a constant regulated temperature (≈10°C). During fatigue test the strain level rather “high” and is not inside the linear range of the tested binder. The great originality and improvement of the test consists in the insertion of complex shear modulus measurements (in the linear domain) during fatigue test. The specimen is then punctually loaded at “low” strain levels. The measurements are made at 6 different frequencies (0.03, 0.1, 0.3, 1, 3 and 10 Hz) every 20000 fatigue cycles. Two additional measurements are performed, one before the beginning of the test, which is representative of the undamaged material, and one after the first 10000 fatigue cycles.

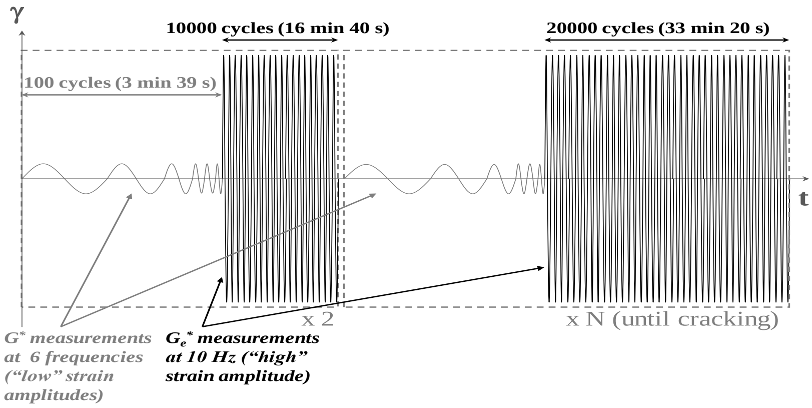

Figure 2 : Schematic representation of the advanced fatigue test protocol: G_{LVE}^* is measured at 6 frequencies from 0.03 to 10 Hz

2.3.Tested materials

2.3.1.Bitumen

The bitumen “Azalt® 50/70” used is a 50/70 grade pure bitumen commercialized by Total company. It is widely used for road applications. Its main characteristics are summed up in Table 1.

Table 1: Properties of Azalt® 50/70

Properties	Numeric values
Penetration at 25°C	56 dmm
Softening point (ring-and-ball method)	50°C
Pfeiffer penetration index	-0.84
Density at 25°C	1035.5 kg m^{-3}
Specific heat capacity C_m at 10°C	1.609 $kJ.kg^{-1}.°C^{-1}$
Volumetric heat capacity C_v at 10°C	1.666 $MJ.m^{-3}.°C^{-1}$

2.3.2. Fillers

Two kinds of fillers are considered. The first one is limestone filler, which particles bigger size is about 100µm. The second one is silica fume filler composed of ultrafine particles which sizes do not exceed 1µm. Hereafter, the two fillers are named “W100µ” and “S” respectively. The grading curves of both fillers are plotted in Figure 3. They can be characterized by the value of their uniformity coefficients C_U, defined in equation(2):

$$C_U = \frac{d_{60}}{d_{10}} \tag{2}$$

Where: d_{60} is the diameter of particle corresponding to a 60% passing,

d_{10} is the diameter of particle corresponding to a 10% passing.

A value of $C_U>3$ indicates that the filler is well graded, and a value of $C_U<3$ that the filler is uniformly graded. The values of C_U for W100µ and S are respectively 7.4 and 2.1.

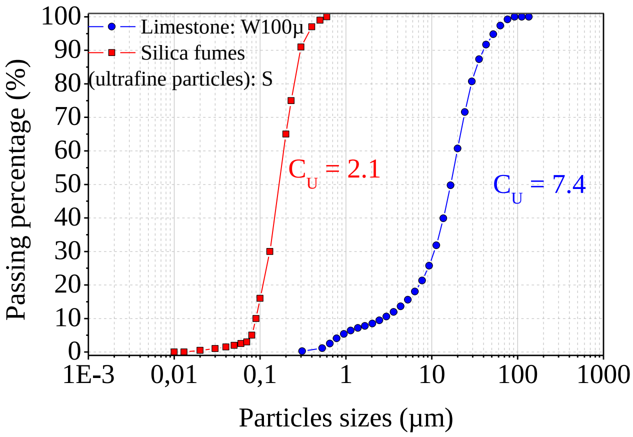

Figure 3 : Grading curves of the fillers

Advanced fatigue tests are performed on the bitumen without filler and on three bituminous mastics. The first one contains 30% of W100µ in volume, and the second one 50%. The third one is composed with 30% of S in volume. LVE mechanical characteristics of this mastic were studied in a previous work [10; 12]. In particular, the better stiffening effect of ultrafine particles at high temperature compared to classical fillers is underlined. In total, four materials are used, as summed up in Table 2.

Table 2: Materials used in the study

Material name	Composition
B5070	Azalt® 50/70
B5070W100µ30	Azalt® 50/70 + 30% in volume of limestone filler
B5070W100µ50	Azalt® 50/70 + 50% in volume of limestone filler
B5070S30	Azalt® 50/70 + 30% in volume of silicate fume filler

2.4. Performed tests

Five or six advanced fatigue tests are carried out on each material at different constant shear strain amplitude $\varepsilon_{rz}=\gamma/2$. It includes an extra test, which allows checking the repeatability of the test at given amplitude. Two repeatability tests are performed on the B5070W100µ30 mastic.
Test names are chosen as follow: "name of the material" +"D" (standing for "distortion", reference to constant strain mode) + "shear strain amplitude $\varepsilon_{rz}=\gamma/2$" (in µdef) + "R" (only for repeatability tests). Example: B5070W100µ50D2500 means "advanced fatigue test performed on B5070W100µ50 mastic (table 2) at a 0.25% shear strain amplitude".

3. TYPICAL RESULTS

In this section, B5070W100µ30D2500R test is used to show typical advanced fatigue test results.

3.1. Equivalent complex modulus |Ge*|

The norm $|G_e^*|$ and phase angle ϕ of the equivalent complex modulus G_e^*, measured during fatigue loadings (rather "high strain amplitude) are plotted in Figure 4 as a function of the number N of cycles. On both curves, discontinuities can be observed in the evolution. They correspond to the G_{LVE}^* punctual measurements in "small" strain domain. When fatigue loadings restart, measurements points reach a unique curve, so it can be assumed that applied small strain loading periods have no influence on the global result of the test.

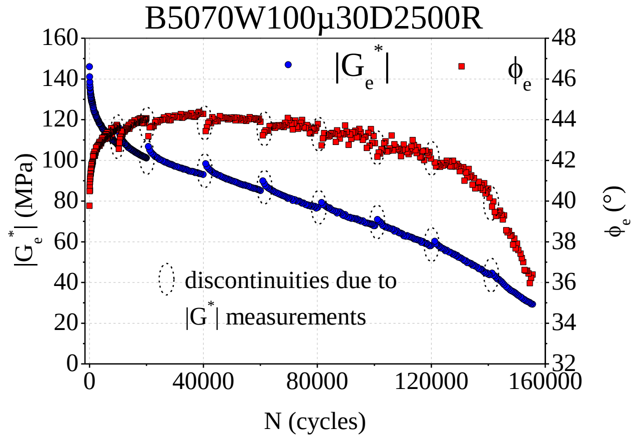

Figure 4 : Norm $|G_e^*|$ and phase angle ϕ_e of the equivalent modulus G_e^* plotted as a function of the number N of fatigue cycles during advanced fatigue test

As suggested in previous works [4; 15; 33], three phases appear successively during a fatigue test :

- Phase I (adaptation phase) characterized by a quick decrease of the norm and an increase of the phase angle of G_e^*. During this phase, fatigue damaging does not seem to be preponderant. Heating of the sample, as well as others phenomena such as thixotropy, may play an essential role, as underlined by some authors.
- Phase II (quasi-stationary phase) when the decrease of $|G_e^*|$ can be considered as quasi-linear, whereas the value of ϕ_e almost does not change.
- Phase III (failure phase) which corresponds to the macro-cracks propagation. The test cannot be considered as homogenous anymore

3.2. Energy ratio

Due to the viscoelastic behavior of bituminous material, a certain amount of energy is dissipated and generates heat, at each cycle. The formula of the dissipated energy W_N at cycle N is given in equation (3):

$$W_N = \pi(\gamma_A)_N (\tau_A)_N \sin((\phi_e)_N) \quad (3)$$

Where: $(\gamma_A)_N$ is the distortion amplitude at cycle N,

$(\tau_A)_N$ is the stress amplitude at cycle N,

$(\phi_e)_N$ is the phase angle of the equivalent complex modulus G_e^* at cycle N.

The dissipated energy W_N is plotted in Figure 5 as a function of the number N of cycles.

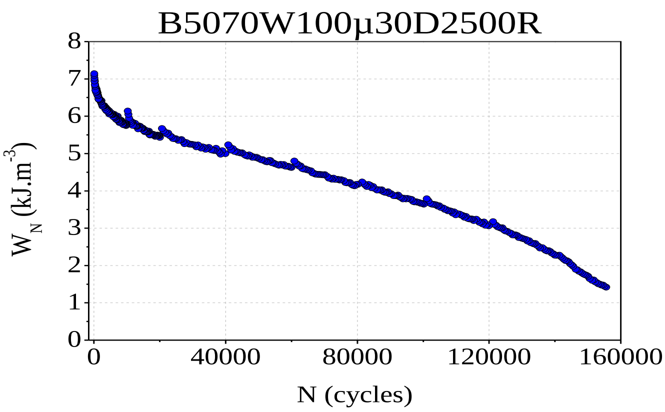

Figure 5 : Dissipated energy per cycle W_N plotted as a function of the number N of fatigue cycles during advanced fatigue test

3.3. Shear strain

The axial vertical displacement is measured by means of three transducers placed at 120° around the sample, as explained in section 2.1. A value of distortion amplitude γ_{Ai} and a phase angle ϕ_i can be associated to each transducer i. The comparison of γ_{Ai} and ϕ_i with the average values γ_A and ϕ_e, related to the mean signal, allows checking the appearance of non homogeneities in strain fields. Two parameters are considered for each transducers i: the relative amplitude deviation $\Delta\gamma_{Ai}$, expressed in percent, and the phase angle difference $\Delta\phi_i$, in degree, respectively defined in equation (4) and (5):

$$\Delta\gamma_{Ai} = (\gamma_{Ai} - \gamma_A) / \gamma_A \quad (4)$$

$$\Delta\phi_i = \phi_e - \phi_i \quad (5)$$

Parameters $\Delta\gamma_{Ai}$ and $\Delta\phi_i$ associated to transducers i=299, 300 or 301 are respectively plotted in Figure 6 as a function of the number N of cycles.

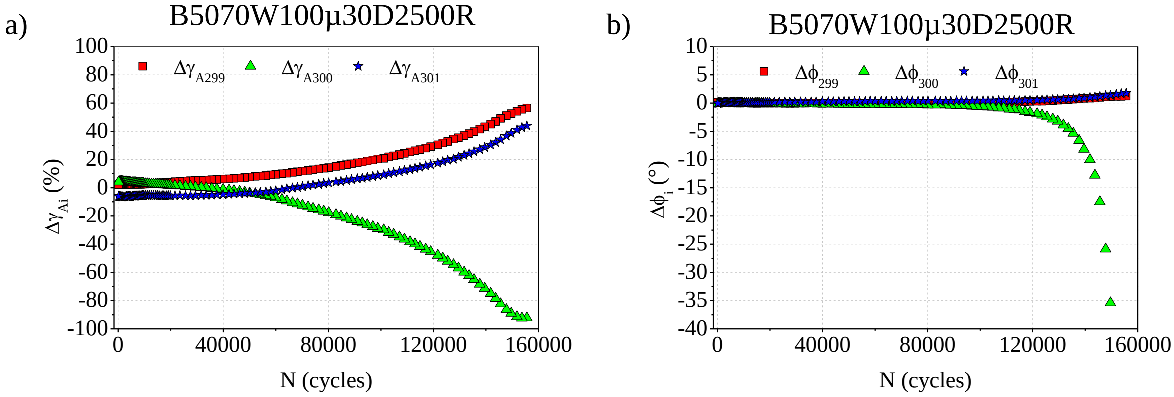

Figure 6 : a) Deviation $\Delta\gamma_{Ai}$ between distortion amplitude γ_{Ai} measured by each transducer i and the average distortion amplitude γ_A plotted as a function of the number N of fatigue cycles. b) Difference $\Delta\phi_i$ between the phase angle ϕ_i (from transducer i) and the phase angle ϕ_e plotted as a function of the number N of fatigue cycles during advanced fatigue test

4. LIFE DURATION

4.1.Considered life duration criteria

Fatigue behaviour is classically characterised by a correlation between applied amplitudes and number of cycles at failure (Wöhler curve). “Life duration” is the number of cycles that the sample can resist before rupture. It is a key point to find a correct criterion for life duration. Five criteria (i.e. five definition of rupture) are considered in this study, named hereafter Nf_1 to Nf_5

Classical criterion (Nf_1)

This criterion is widely used. Nf_1 corresponds to a 50% decrease of the equivalent complex modulus. A representation of the classical criterion is given Figure 7.

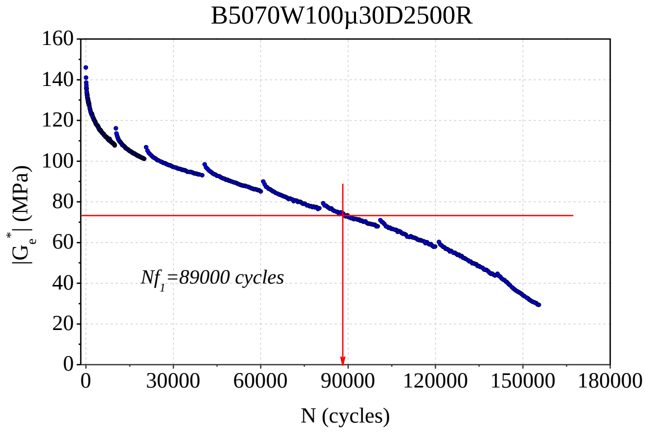

Figure 7 : Norm $|G_e^*|$ of the equivalent modulus G_e^* plotted as a function of the number N of fatigue cycles during advanced fatigue test and display of the so called “classical criterion” Nf_1

2nd Pronk criterion (dissipated energy ratio, Nf_2)

This criterion corresponds to change in the slope of the $\Sigma W_i/W_N$ versus N curve ([28]), as illustrated in Figure 8.

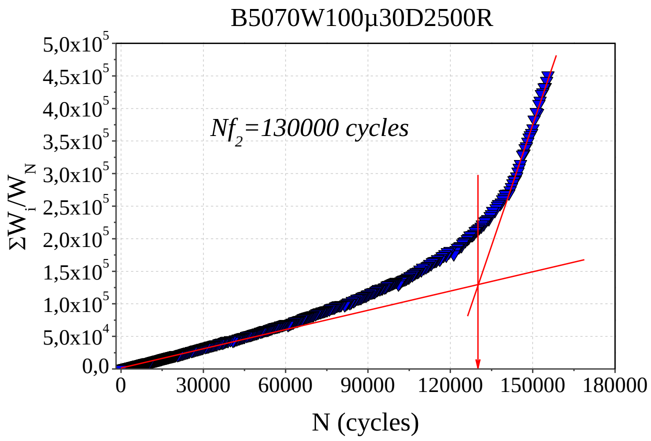

Figure 8 : Dissipated energy ratio SW_i/W_N plotted as a function of the number N of fatigue cycles and the 2nd Pronk criterionNf_2

Distortion criterion (Nf_3)

The difference in amplitude of the three transducers is used to define fatigue life criteria [5; 12]. It is considered that macro-cracking in the sample is effective when $\Delta\gamma_{Ai}$>25% (Figure 9).

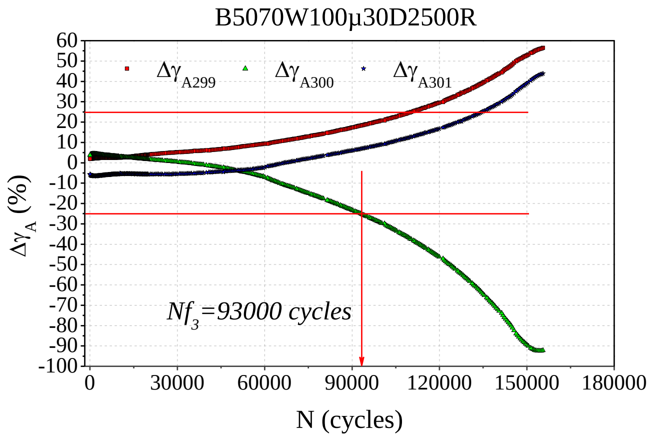

Figure 9 : Amplitude deviation of each transducer plotted as a function of the number N of fatigue cycles and distortion criterion Nf_3

Phase lag criterion (Nf_4)

Nf_3 considers the transducer amplitude, while Nf_4 considers the difference in phase angles given by the three transducers. It is considered [5; 12] that macro-cracking in the sample is effective when $\Delta\phi_i$>5° (Figure 10).

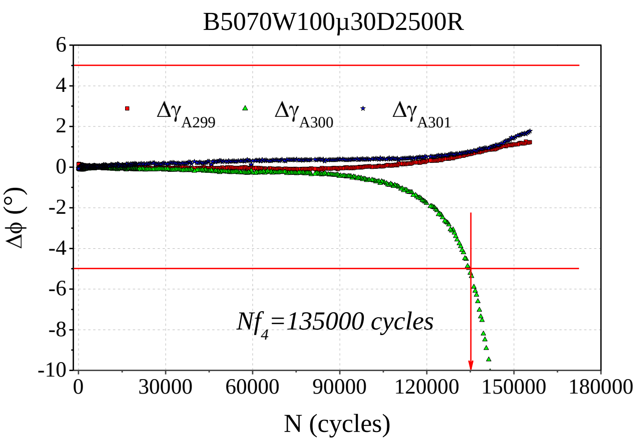

Figure 10: Phase angle of each transducer plotted as a function of the number N of fatigue cycles and the phase lag criterion Nf_4

<u>Inflexion criterion (Nf_5)</u>
Ge versus N curve is used. Failure is considered when a sharp change in the slope appears, as shown in Figure 11.

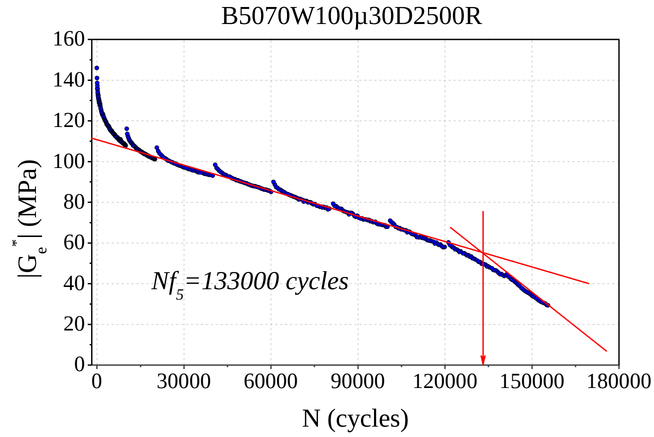

Figure 11: Equivalent modulus G_e^* plotted as a function of number of cycles N and the inflexion criterion Nf_5

4.2. Analysis

Wöhler curves for the 4 materials (table 2) and the 5 criteria are plotted in : *Wöhler curves, shear strain amplitude as a function of criteria (Nf) a) B5070, b) B5070W100µ30, c) B5070W100µ50, d) B5070S30*Figure 12, life duration is express in number of fatigue cycles.

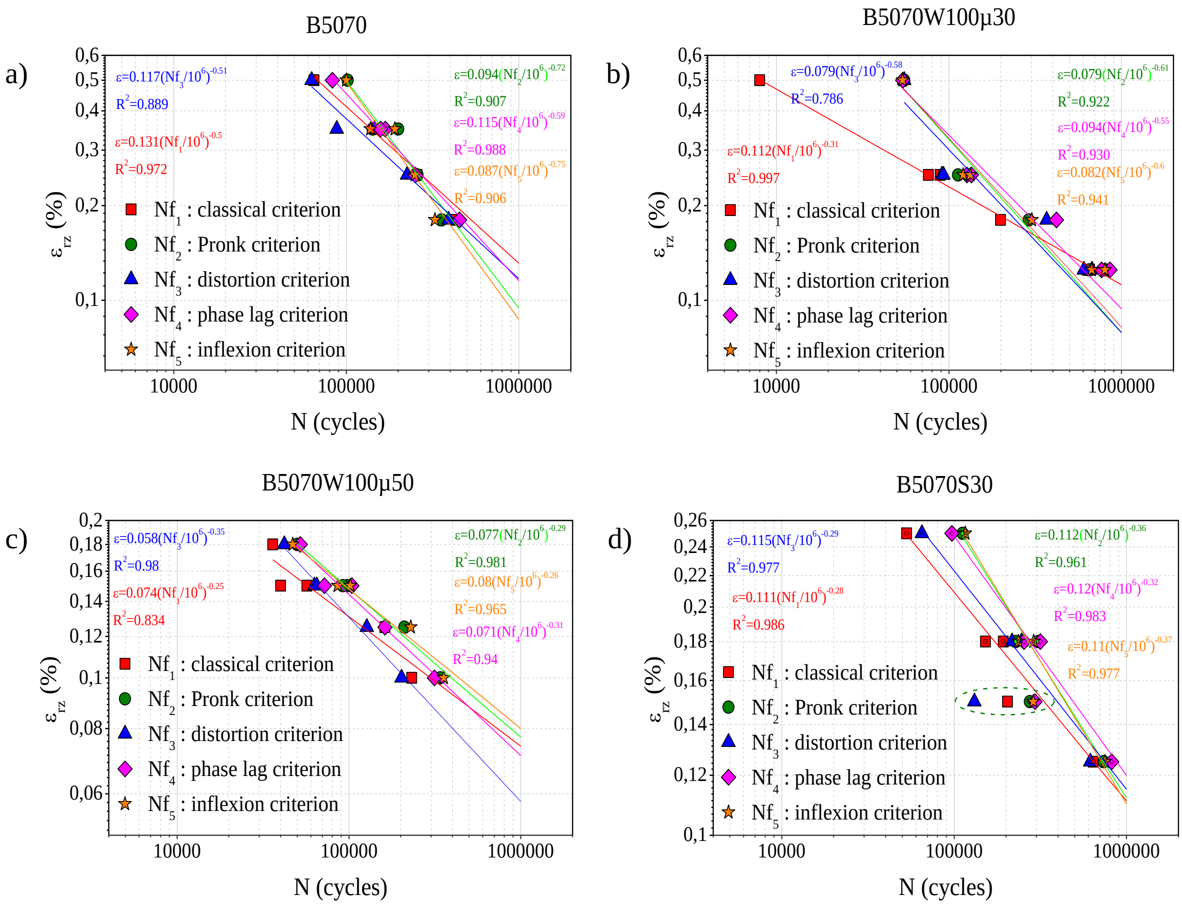

Figure 12 : Wöhler curves, shear strain amplitude as a function of criteria (Nf) a) B5070, b) B5070W100µ30, c) B5070W100µ50, d) B5070S30

Figure 12 shows that criterion Nf_1 underestimates the life duration specifically for high strain amplitude. Indeed the 50% decreased is arbitrary and failure could happen far after this limit. The criterion does not take into account

phenomena occurring in phase I such as heating and thixotropy [5,12] that can cause a significant modulus drop, especially at high strain amplitude.
Criteria Nf_2 and Nf_5 use global evolution. They illustrate a global ruin in the sample. Both criterion give similar life durations.
Criteria Nf_3 and Nf_4 are based on, local approach that is allowed thanks to the Annular Shear Rheometer prototype. Phase lag and amplitude difference between the three transducers highlight, in the sample, a local loss of homogeneity becoming macro-crack(s).
Criteria Nf_2, Nf_3, Nf_4 and Nf_5 aim at characterizing the appearance of a macro-crack. Their similar life duration indicates coherence between local and global approach. In the next section (Nf_4) is used to characterise fatigue life.

4.3. Life durations of tested materials

4.3.1. Influence of filler content

Life duration of mastics is smaller than the one of bitumen (Figure 13). Addition of filler increases the stiffness [10] but decreases the fatigue performance as can be in Figure 13. This observation is valid for both fillers, W100µ and S.

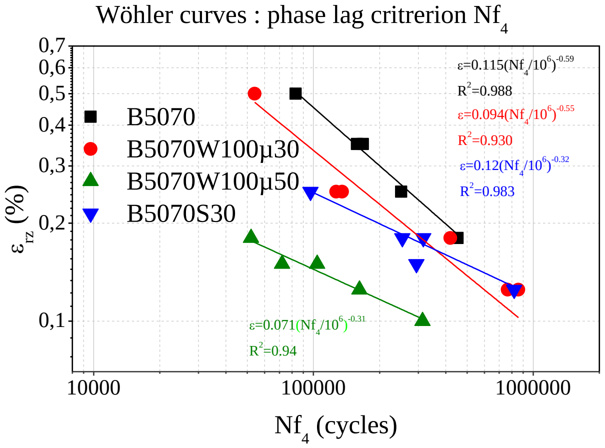

Figure 13 : Wöhler curves for the 4 materials (phase lag criterion (Nf_4)

4.3.2. Influence of the concentration of filler

As shown in Figure 13 fatigue performances B5070W100µ30 and B570W100µ50 differ a lot. At a given shear strain amplitude life duration is much smaller for the 50% concentration mastic.

4.3.3. Influence of the type of filler

Wöhler curves of B5070W100µ30 and B5070S30 shows similar life duration. The substitution of limestone (W100µ) by the same volume of silica fume (S) does not change fatigue properties. However mastics with ultra-fine particles are stiffer than W100µ [10], especially at high-temperature.

5. CONCLUSION

The ASR prototype, developed at the ENTPE/DGCB laboratory, is used to investigate fatigue behaviour of bitumen and mastics, and therefore obtain a better knowledge of bituminous materials fatigue in order to improve the durability of pavement. Five criteria characterizing the appearance of macro-crack were studied, using ASR specific instrumentation. These criteria offer two approaches. The first is a global approach with Nf_2 and Nf_5. The second is a local approach with Nf_3 and Nf_4. Overall life duration of the different criteria are similar indicates coherence between the two approaches.
The last criterion Nf_1, classical criterion, shows limited. The biasing phenomena occurring during the test are not taken into account.
The study of B5070 and its mastics shows the need to control filler addition to keep the fatigue quality of the material:

- addition of filler decreases the fatigue performance
- the fatigue performances decrease when the filler concentration increases

Moreover, for a same concentration, mastics with silica and limestone have same life duration but mastic with silica is stiffer than mastic with W100µ.
These results show the importance of filler in the bituminous materials design.

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