
EXPERIMENTAL STUDY OF BITUMINOUS MIXES, FATIGUE PHENOMENON UNDER TANDEM SOLICITATION AT LARGE STRAIN

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ABSTRACT

Asphalt mixture in pavement is exposed to a fatigue phenomenon which often causes its failure after a certain period of operation. Conventionally this is simulated in the laboratory by a mechanical stress in the form of continuous sine under the effect of a single axle. In recent years the designs of aircraft and large vehicles have changed a lot, given the needs in volume and transport capacity requested. We often see the tandem axles, tridem axel etc. Damage of asphalt mixture is related to vehicle characteristics (number and loads per axle, suspension type, speed, tyre type and configuration...); rest period, temperature and pavement material properties. Modern conceptions of jumbo aircraft type (e.g. Airbus A380, B777 etc…) and new designs of heavy trucks have imposed other forms of solicitation. This type of loading is dual axles with higher strain amplitude. Currently the road pavement and airport asphalt are subject to high levels of strain (or stress) of short duration at each passage of axles. The choice of the structure and the sizing of a roadway require consideration of several technical criteria, economic and geographic, such as heavy traffic and its developments. In this context, fatigue tests were carried out under load at large deformation (high strain amplitude) and can have multipeak shapes (tandem low valleys between two successive peaks). These tests were used to assess and compare the effect and aggressivity of large amplitudes of strain in terms of life, according to two types of signals (single axle and tandem).

KEYWORDS

Asphalt mixture; Pavement; Fatigue; Large strain; Sine; Single axle; Tandem

INTRODUCTION

Pavement layers are subjected to bending forces that do not cause immediate failure, but the repetition of which can eventually lead to a fatigue crack. The effects of multi-axle loads are taken into account in the form of coefficients of aggressivity, dependent on the geometry of the axles and the type of structure, often roughly, resulting from simplified assumptions of superposition of elastic fields [1], [2], [3]. The classical fatigue model, calculated from the fatigue of the laboratory tests with a sinusoidal signal applied at various levels of deformation, is only a function of the level of longitudinal deformation [4]. Future development of pavement operating conditions, appearance of trucks or heavy traffic loadings and jumbo aircraft like Airbus A380 and B777 in real-life conditions, requires a more detailed analysis of the behaviour of materials under this type of stress [5]. The specificity of the load with high level of deformation and the particular shape of the signal-time deformation of tandem axles must be at the heart of such an analysis. On pavements, the aggressiveness of these loads is even more dangerous in intersections [6].

Changes in traffic and recent architecture have imposed new conditions of stress, such as multipeak loading and large strain. Thus, the standard fatigue test is questionable. One of the main criticisms related to these conditions is that the test is not representative with the signal shape nor the magnitude of stresses applied during the successive passage of axles "heavy weights" on a pavement structure. Thermo-viscoelastic behaviour of the asphalt pavement materials induces a dependency on the pavement's response, in terms of strain, on several factors such as the speed of vehicle and the temperature of asphalt layers [7], [8], strain level, binder composition, healing and rest periods, frequencies, strain level [9], loading form [10], air voids content and compaction, aggregate characteristics [11], and even the configuration of the tire [12]. The natural frequency of an HMA layer depends on the delayed response associated with the viscous properties of the material, during the unloading phase [13]. There is a strong need to improve the design criteria, so that they integrate the different configurations of charges corresponding to the different vehicle types, with specific signals simulating complex loadings. On the floor, the frequency and temperature are not constant, and the solicitation is not continuous. In practice, signals are intermittent and there are often multipeak forms in tandem or tridem at high amplitudes. Aggression increases with increasing number of axis [14]. The objective in this work is to adapt the classic test of fatigue on trapezoidal specimen, to make a comparison and to analyze the differences between the sine and tandem signals, thus to quantify their aggressiveness and to take into account the particular context and improve knowledge of mix asphalt and design rules.

EFFECT OF TEST CONDITIONS ON ASPHALT MIXTURE FATIGUE – A REVIEW

Fatigue of asphalt pavement depends mainly on load conditions; different variables interact differently. Generally, the controlled strain mode of testing displays better fatigue life than the controlled stress mode of loading [16], but at higher levels of strain the difference with the imposed stress mode is reduced [17]. Application of very high deformation (600-1000 µstrain) under sinusoidal loading at 20°C, the lifetimes obtained are in the order of 10^4 - 10^5 cycles, with flexural stiffness in order of 1400 - 1600 MPa [18]. Fatigue life of asphalt mixtures and binders decrease with increase in frequency, the fatigue life of the blends and binders decrease with increasing stress level. The correlation is good between the durations of the mixture and the binder [19]. By increasing temperature, fatigue life of HMA decreases. By Indirect Tensile Fatigue (ITF) test when the temperature changes from 5; 25 to 40 ° C, the life of HMA falls in the order of 2100; 1800 to 1700 cycles at a stress level of 250 kPa. At a stress level of 400 kPa, it drops by (1300; 1150; 1000 cycles) for the same temperatures [20]. The "3D-MOVE" model treats the tire-pavement interaction as a moving loaded area. The model incorporates pavement response parameters such as the dynamic tire-pavement load variations and corresponding complex contact stress distributions (normal and shear), vehicle speed, and viscoelastic material characterization. The response from a conventional tandem axle, contact shear stresses did not significantly influence the tensile strain at the bottom of the asphalt concrete layer [21]. An example with VISCOROUTE, the response curves obtained, for a twin-wheel single axle, give very similar results to a sine signal in the longitudinal direction (for ε_{xx}) and to a tandem signal in the transverse direction (for ε_{yy}). The amplitude of these responses is relative to the solicitation rates [22]. HMA resistance is governed by two fundamental mechanisms: the number of repetitive load cycles for microcracks to coalesce into macrocracks in a crack initiation process (N_i) and the number of repetitive load cycles for macrocrack propagation through the HMA layer thickness in a crack propagation process (N_p), based on continuum fracture-mechanics and work theory to exhibit discriminate and rank HMA mixes [23]. When vehicle speed increases, the dynamic deflection of pavement surface is higher than the situation in static, due to the overlapping effect. A discontinuous zone of shear stress was observed on the base surface between the location under moving load and the location moving load just passed [24]. For HMA, fatigue test was conducted at

10 and 20 °C, and at loading frequency of 10 Hz, using the energy approach, either in the stress controlled mode or in controlled displacement mode. The rate of change of the dissipated energy indicates a value of the plateau which is dependent on the loading mode. And, the cumulative energy is independent on the loading mode; there is a relation between the two modes of loading. Stress controlled mode tests are more practical in the laboratory, but their lifetimes are shorter [25]. The increase in fatigue life with frequencies gives an exponential relation at 20 and 30 °C; and it is higher when the stress levels are lower. At higher load frequencies, the difference in fatigue time between the different levels of stress was much higher [26].

EXPERIMENTAL APPROACH

Material

The material used for this campaign has been widely studied for fatigue behaviour in the past IFSTTAR (LCPC) and international RILEM research committee projects [15]. This is an asphalt mixture (0-6mm). It is a 0/6 mm continuously graded dense asphalt concrete normally used for surface layers. The binder is a pure 50/70 and the binder content is 6.85%. The theoretical compaction ratio of the mix is 95%. The specimens were cut from slabs (400x600x120 mm) manufactured with a rolling compactor according the standard (EN 12697-33). Trapezoidal specimens were cut to perform mechanical tests as complex modulus (EN 12697-26) and fatigue. The complex modulus of the mix is around 8000 MPa at (20°C and 25Hz) and 14000 MPa at (10°C and 10 Hz).

Tab.1 – Composition and grading curve of considered material

Granulometry [% passing]							
Sieve [mm]	0,08	0,31	1,0	2,0	4,0	6,3	8,0
Mix Asphalt	11,8	22,6	39,0	59,5	70,2	97,0	100

Test Conditions and Applications

Load Signal and Forms

Fatigue tests of the following campaign are performed at 20 °C, and at different strain levels. Their range has been fixed to reach fatigue life between 10^4 and 10^5 loading cycles. This range of fatigue life is more representative for airfield pavements. They are higher than classical ones compared to levels to reach one million of cycles usually aimed to define the ε_6 value leading to a fatigue life of 10^6 cycles (EN 12697-24). Multi peak signal is compared to classical sinusoidal approaches. The experimental investigations are focused on the influence of the decrease between the two peaks. This is numerically controlled by the λ parameter. We take both cases: λ = 0.25 and 1, $\lambda = (\varepsilon_{max} - \varepsilon_{min})/2\varepsilon_{max})$, where ε_{min} is the minimum strain level between the two peaks and ε_{max} is the maximum strain level. We define the signals applied based on a single parameter λ, which sets the shape of the signal. Figure 1 shows the shape of the sine and obtained tandem. The factor λ may vary from: 0.0 to 1.0. From the tandem signal at 25/3 Hz, we find the sine signal for the maximum value of λ = 1.0, but at 25 Hz. Given the capabilities of the machine fatigue of LRPC-Bordeaux (F_{max}= 12daN), these bending tests at high amplitudes must be made on standard trapezoidal specimens, attached to the base and free at the top, at a temperature of 20 °C and frequency of 25Hz (sine) and 25/3= 8.33 Hz (tandem). Representing vehicle speeds about 100 and 35 km/h. Four pieces can move independently of each other. During the test, the system regulates on the corresponding channel and the vibratory pot for each specimen. The origin of the fatigue test is in the comparison of tensile deformation by bending, calculated at the base layers of asphalt pavement, with the values of maximum strain supported by a coated specimen in the laboratory [27].

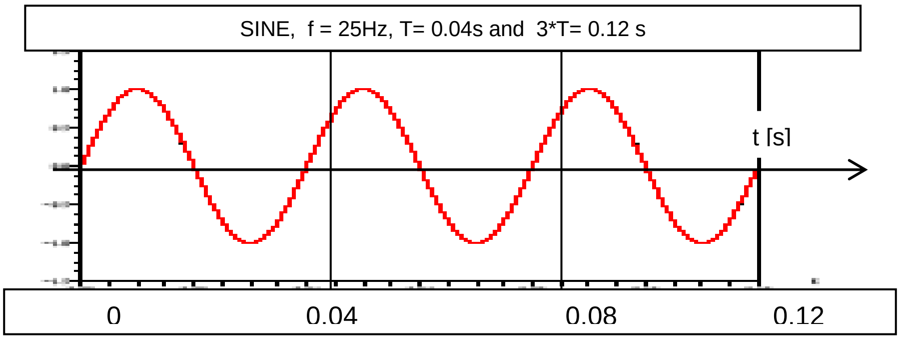

Fig. 1a - Illustration of Sine (Tandem_1,0) signal

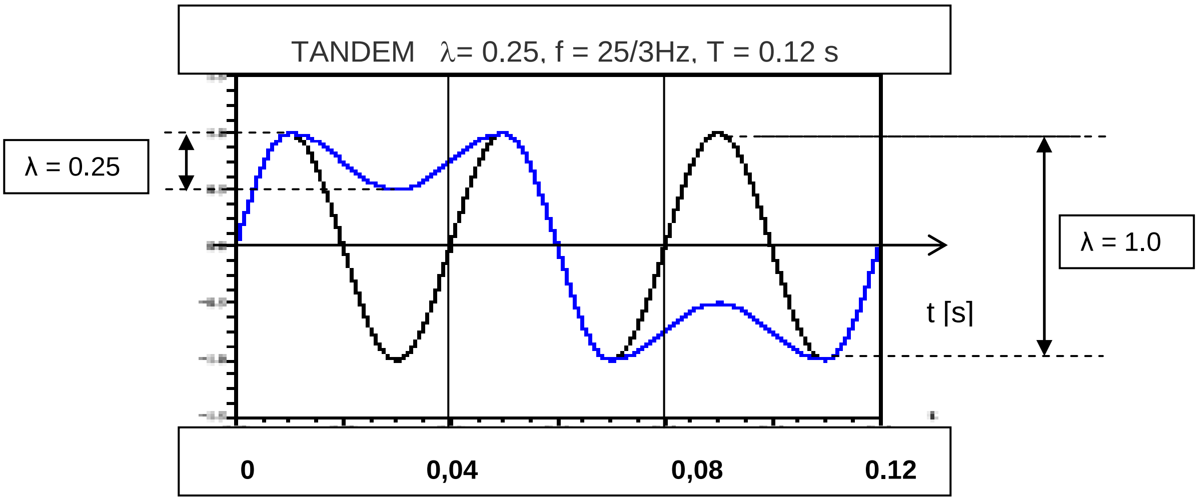

Fig. 1b - Illustration of Tandem_0,25 signal

Fatigue testing at high strain

Machine Test has four vibratory pots (Figure 2) to test four specimens simultaneously under the same test conditions. The four specimens can evolve independently of each other. During the test, the system regulates, on the corresponding channel, the vibratory pot for each specimen. Fatigue tests are performed in imposed constraint mode. We tried to reproduce in the laboratory the real conditions of large strain, using the protocol loading "software DataPhysique." The test program is to scan the spectrum amplitudes solicitations on pavement. If we translate the magnitude of stress in terms of life, we tried to reproduce life spans ranging from 10^4 to 10^5 cycles. The strain ε_f (ε_{moy}) and the temperature (20 °C) are constant for the entire program. We must quantify the tandem_0.5 effect to equivalent number of peaks, with respect to the sinusoidal loading reference: for the same period the sinusoidal signal has three peaks (positives), while the signal tandem has two peaks Figure 4.

Tests are performed continuously with alternating sequences of fatigue with a duration T_f (T_f= 11s) and sequences of rest period T_r (T_r= 1.5s), to facilitate storage of measurements [15].

Fig. 2a - Machine test of fatigue

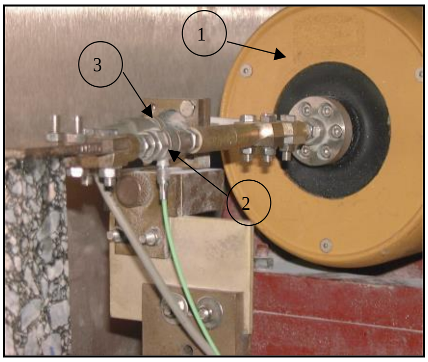

Fig. 2a - Specimen biasing device
(1) Vibrator, (2) Force sensor
(3) Displacement sensor

The maximum values of stress and strain were measured at regular intervals. The magnitude of ε_f corresponding to the third level of strain is the maximum allowed by the system. The three levels are well above ε_6 applied to conventional fatigue testing of this material and do not exceed about 200µstrain, but correspond to compare strains to those that can be measured in pavement.

The experimental simulation takes into account the phenomenon of viscoelasticity, which leads to more realistic stress field; it explains the presence of a higher strain in the second axle [28], especially in the passage of a rolling load. It allows rigorously take into account the speed of vehicles. It also helps to highlight phenomena that traditional elastic numerical modelling does not allow it, as the strain rate.

Fig. 3a - Tandem (Truck)

Fig. 3b - Tandem (A380) (Long. and Transv)

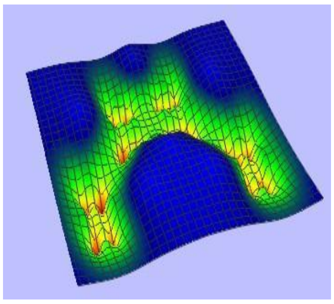

Fig. 3c - 3D graphical Visualization of deformations generated by a B747 aircraft (CESAR-LCPC) [29]

We define the parameter λ establishing the position of the descent (trough) between two successive peaks of a tandem. In this context it is proposed fatigue tests at high strain amplitudes, as both types of signals, sine or tandem_ λ = 1.0 (where the hollow between two successive peaks of the tandem is maximum) and tandem_ λ = 0.25 (where descent between two peaks is 1/4 of its maximum), in which we impose sequences fatigue and whose objectives are:

- Determine the laws of fatigue when imposed strain is much higher than those applied in the usual test fatigue.

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- Quantify the effect of large amplitudes of strain, which exceed those applied by an axle of 130 kN in road pavements, on the one hand and the effect of multi-peak signals on the other hand (tandem_ λ = 0,25).

The inclusion of these two parameters can provide answers on this subject, namely:

- The effect of large amplitudes, in order to scan the range of high stress, with cumulative shipments.
- The effect of tandem_0,25 and back to zero between two peaks of loading giving multi-peak loads, compared to the reference sinusoidal loading Figure 5.

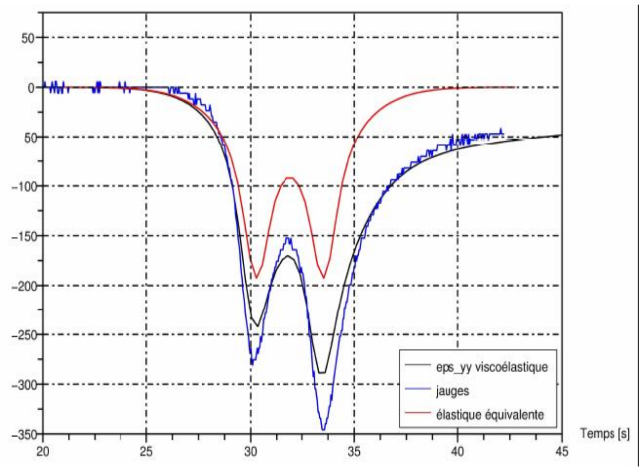

Fig. 4a- Elastic and viscoelastic simulations (Viscoroute) and transversal strain measurements at the bottom of bituminous layers [30]

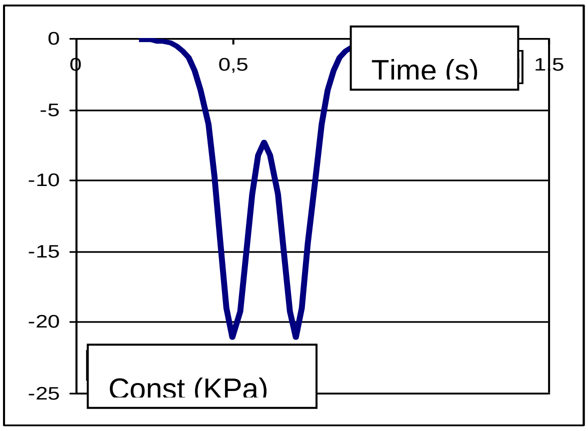

Fig.4b - Simulation of constraints evolution, according to Boussinesq

The imposed stress is measured in the order of 5 – 8 daN. This has been applied in the technical capacity margins of the testing machine, which must not exceed 10 daN.

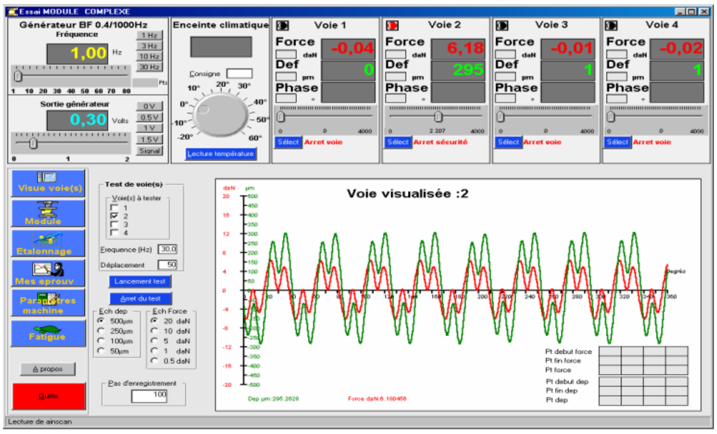

Fig.5 - Exp. Visualisation of the fatigue test

RESULTS

Treatment of raw results

In the literature several approaches are used to determine the fatigue criterion. Results are collected in log file, giving each moment, the imposed strain (ε_{moy}), the stress and time. These results are processed in MS Excel to calculate the number of cycles depending on the chosen frequency and the corresponding stiffness. The dispersions are minimal for sine signals by cons in tandem we recorded some dispersion translated by some outliers (in Figure 6), due to the complexity of the signal, the viscoelastic properties and the heterogeneous nature of the material itself.

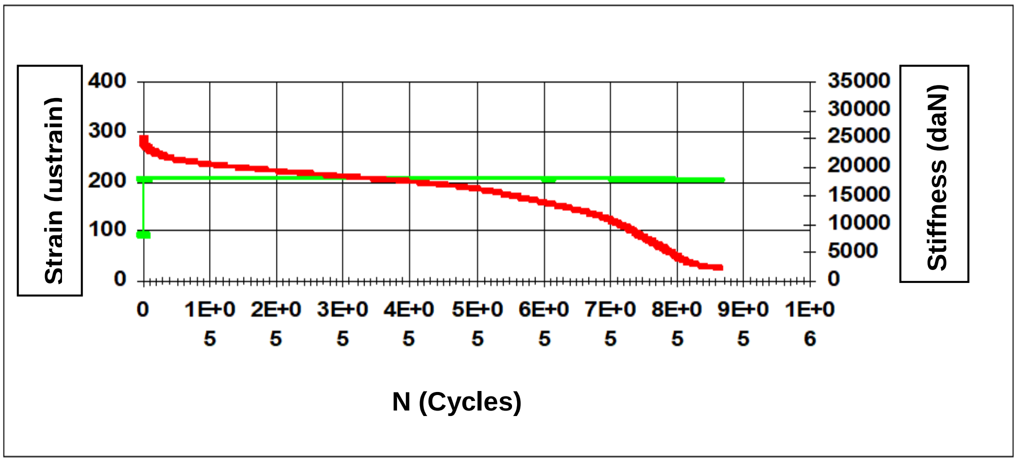

Fig. 6.a - Strain and fatigue curves of SINE Signal

To determine K_0 value, which corresponds to the initial stiffness, we can use a linear regression on the part of the fatigue curve called phase II [31]. In this phase the behaviour is approximately linear, which corresponds to the evolution of stiffness by increase of diffuse damage [32]. K_0 is the intersection of the regression line with Y axis of stiffness.

The phenomenon of fatigue damage (progressive) of bituminous mixes can be evaluated by the damage method on the linear part of the curve, called phase II (in Figure 6b). Along the plateau obtained for the ratio of dissipated energy changes (for the energy approach method).
This phase is often reached after phase I of rapid reduction of the initial stiffness, when the material is well heated [14], and before the crack propagation phase III at the micro and macro scales (sudden drop in stiffness which explains the ruin of the material).

The initial stiffness K_0 is a parameter characterizing the material and its response [33], according to the mode and magnitude of the stress.
There are linear relations between the rate of dissipated energy change and the number of load applications to failure without the rest period, showing approximately constant relations even if loading wave pattern is different and there are linear relations between the rate of stiffness change and the number of load applications to failure [34].

According to Molenaar [35], the idea behind the endurance limit principle for asphalt concrete is that there is an applied stress corresponding to "K_0 / 2", a non-unique, in which it is stated that fatigue does not occur. Fatigue failure results from an accumulation of plastic deformation, which is the case of controlled load. The latter depends on the temperature and the loading rate.

A comparison has been established between the traditional fatigue criteria, where the number of cycles corresponding to 50% of the initial rigidity and that based on energy are sought, where the number of cycles at the maximum energy ratio or the maximum stiffness of Rowe defined by the stiffness multiplied by the corresponding number of cycles, and the criterion based on the viscoelastic continuum damage (VECD) approach. The latter criterion is defined by the number of loading cycles at the point of inflection of the pseudo-stiffness standardized with respect to the curve of the damage variable. They showed that there is a correlation between the traditional criteria (especially those based on the energy ratio) and the VECD criteria, as well as the relative lifetime of the energy ratio or the maximum stiffness of Rowe is higher than that of fatigue at (N_f50%). This indicates that the traditional approach is conservative [36].

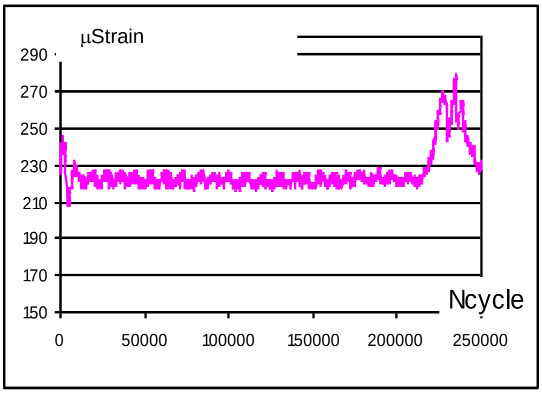

Fig. 6.b1- Strain curve, Tandem_λ= 0, 25

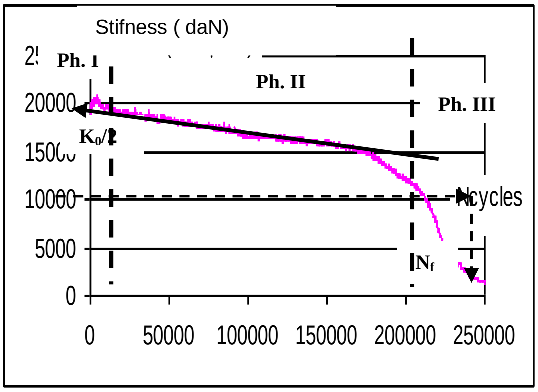

Fig. 6.b2- Fatigue curve, Tandem_λ= 0.25

In another approach based on the Crack Meander Technique, Muniandy et al. [37] observed that the Crack Meander method can be used as another way to study fatigue performance by mapping cracks, especially when fatigue resistance is desired. The analysis of the cracks has the tendency of progress of the stresses of traction, with the number of cycles. The sequence corresponding to the maximum value of the tensile strain and the maximum crack (length, area and density) were comparable for the different mixtures tested. The comparison of fatigue performance can be determined by this laboratory approach. The (reinforced) sample that had the longest life obviously showed the macro-crack aspect rather than the micro-crack. However, the control sample (less durable than the previous one) had balanced micro and macro cracks. The sample with the shortest life had more micro-cracks than the other two types of mixtures.

The application of the fuzzy estimation algorithm was developed by Tigdemir et al. [38]. It does not provide an equation but can fit linear or nonlinear shapes with fuzzy subsets of life and strain variables. Taking into account the specific variables of the bituminous mix, by increasing the conditional statements in the fuzzy implications, could increase the accuracy of the estimation of the fatigue life. The fuzzy logic model resembles the results better than the regression model, and has flexible ranges; it may be according to the tests results but this is not the case for the regression model.

Comparison of aggressivity

We calculate the average slopes on all the fatigue curves and the average strain using two different methods (mean of the values obtained directly by recording and the mean by integral). The slope of phase II increases with increasing levels of deformation. However, the third level of strain is the most damaging, under the effect of the signal tandem_0.25 (average gradient on phase II in the order of 0.22).

Knowing that the laws of fatigue have always obtained an exponent of about 0.2, this means that the increase of the deformation can be estimated by 2^5 aggressions. It is therefore possible to compare with the values of ε^5 and $d\varepsilon^5/dt$ for both types of loading in question. Three average levels of deformation have been applied for both types of signals:

- Sine at 25Hz : 192 ; 277 ; 386 μstrain
- Tandem_ λ = 0.25 at 25/3Hz : 235 ; 288 ; 358 μstrain

The average slopes obtained, corresponding to the fatigue curves of each level, are as follows:

- Sine at 25Hz: -0.0143; -0.0330; -0.1118
- Tandem_ λ = 0.25 at 25/3Hz: -0.0134; -0.0305; -0.1092

By observing the deformation levels close to the two signals as well as the slopes obtained, we can say that the recorded aggressivities are quite close.

Laws of behaviour

The pairs of values (ε_{moy}, N_f) are determined for each waveform, the laws of fatigue can be traced, according to the standard NF 98-261-1. Figure 7 summarizes the results obtained for the two tests.

Fatigue lines of two signals are combined and slopes obtained are close. Given the complexity of signal and the viscoelastic nature of mix, the dispersion is larger for tandem loads especially when the amplitude of deformation is higher. Direct characterization of the behaviour of mix on fatigue depends on the intrinsic behaviour of the tested material [39].

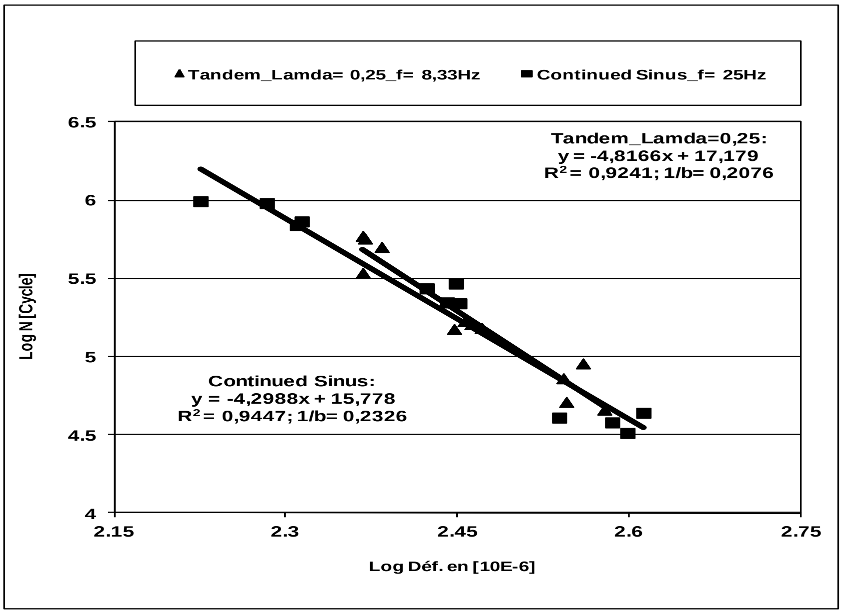

Fig. 7 - Fatigue laws for tandem_0.25 and sine (tandem_1.0)

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At high levels of strain, the effect of frequency is significant for conventional mixtures [40]. The low frequencies limit the power dissipation [41]. The magnitude of the stress increases this dissipation, and the phenomenon of heat is related to frequency. The latter plays a more important role in point of view of changes in the stiffness and performance of the mix in terms of life, than evolution of the shape of tandem (from $\lambda = 0.25$ to $\lambda = 1.0$).

From the results mentioned above, one can deduce that the shape of load in tandem has a negligible effect on fatigue response, irrespective of the factor form λ (from $\lambda = 0.25$ to $\lambda = 1.0$). At f= 25/3 Hz, the lifetime in tandem is the same as for the sinusoidal loading at f = 25 Hz. This means that the increase in λ value (depth of the peak through) has no remarkable effect, since it gives a life very similar or even identical to a sinusoidal with f = 25 Hz.
The effect of frequency is minimal on the evolution of complex modulus; linear viscoelastic limit is influenced more by temperature than by frequency [42]. These findings indicate the validity of the approach using the change in frequency for the transition from three sine signals 25Hz to a single tandem 25/3 Hz. When the load time decreases, the fatigue life will increase. This increase is much larger for lower stress (or strain) levels than the higher levels [43]. This is explained in the same sense of the decrease effect in frequency.

However, the combined effects of change in frequency (25 Hz to 25/3 Hz) and change in signal shape (sine for tandem) are fully compensated. It is found that damage caused by the dual-axles is much higher than single axles, for the same strain levels [44]. Fatigues laws confirm previous findings by similar slopes, where the difference only appears from the second decimal place to the order of 3 %. Indeed, testing sinus and tandem_0.25 lead to nearly identical values of ε_5 and ε_6, which correspond respectively to 10^5 and 10^6cycles (Table 2). The material behaviour within the range of large strain (300 to 400 μstrain), under the effect of two types of signals, is very close.

Tab. 1 - Summary table

Signal	Frequency [Hz]	Strain at 10^5 cycles ε [μstrain]	Strain at 10^6 cycles ε [μstrain]	Slope law of fatigue 1/b
Sine or Tandem_ λ = 1	25 or 25/3= 8,33	321	187	0,2328
Tandem_ λ = 0,25	25/3= 8,333	324	200	0,2078

Given the complexity of tandem_0.25 signal and the experimental difficulties (capacity of the testing machine, and the nature of the material) for larger strain, allowing more precision on the laws of fatigue under strain exceeding 350 μstrain, an extrapolation of the fatigue line of this signal in terms of life can easily be obtained by using the sine of fatigue signal. The lowest levels of strain lead to aggression less intense signals.

According to the overall reading of the results obtained, generally the service life is the same in both cases of loading, independently of the form factor λ. One could expect a lifetime that could be similar to that obtained in the case of a sinusoidal signal at a frequency f = 8.33 Hz. For the two signals used in the experiments, the fatigue laws have slopes close to 0.2.

The signal in tandem_0.25 is least aggressive. The variation between the peaks is lower and the damage is less different. For tow signals used in the experiments, with regard to the average amplitude (tensile strain) of the loading tandem $\lambda = 0.25$, this last loading is the most aggressive (large tensile period), but we cannot ignore that the frequencies are different between tandem and sine.

It is to highlight that: At the same level of strain the differences are notable, from the point of view of aggressiveness, between the effect of a high frequency (25Hz) and that of a low frequency (25/3 Hz).

CONCLUSION

- For tandem signal, the change in stiffness is also described in three phases as in the case of ordinary fatigue test (sine). Indeed, the loss of stiffness in phase I is greater in tandem stresses than in sine. However, the tandem_0.25 signal appears more aggressive than the sine signal.
- Large strains in the margin of "300-350μstrain" for tandem and sine signals, under 5 - 8 daN for stress, give lifetimes in the order of 10^5 cycles.
- According to the obtained results, generally the lifetimes are the same for both loading cases, regardless of the form factor λ. This means that a decrease in the value of λ (depth of the intermediate peak) has no remarkable effect (Tandem λ = 1.0 vs. Tandem λ = 0.25). The lifetime for Tandem_ λ = 0.25 signal at f = 8.33 Hz could be similar to that obtained in the case of a sinusoidal signal at f = 25 Hz. For tow signals used in the experiments, the fatigue laws have slopes (1/b) in the order of 0.2.
- The frequencies are different between tandem and sine. Since, we find the aggressive role of the highest frequencies. The signal of tandem_0.25 is more aggressive than the signal of sine. It is to highlight that: At the same level of strain the differences are notable, from the point of view of aggressiveness, between the effect of a relatively high frequency of sine (at 25Hz) and that of a low frequency of tandem (at 25/3 Hz).
- A signal tandem (λ = 0.25) at 25/3 Hz is almost equivalent to three signals sine at 25Hz. It can be noted that at the strain levels tested the passage of one tandem axle is equivalent to the passage of three single axles.
- For tow signals used, with regard to the average amplitude of the loading tandem λ = 0.25 (in the meantime of tensile strain), this last loading is the most aggressive (large tensile period).
- These tests presented a different view compared to traditional fatigue tests. Further improvements can be considered, to establish more extended tandem fatigue models, taking into account the effect of temperature, higher strain: levels, frequency variation, the combination of loading.

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