Influence of moisture on thermomechanical behaviour of bituminous mixtures used for railway trackbeds

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ABSTRACT

The influence of moisture on the thermomechanical properties of bituminous mixtures used for railway trackbeds is addressed in this paper. The use of asphalt base course materials has been identified as a suitable structural solution for the further development of both high-speed and conventional railways, notably in terms of circulation speed and axle load increases. Moreover, field experiences attest a reduction of the maintenance needs by using asphalt concrete in the railway platform. Nevertheless, the available in-situ feedback is not sufficient for observing the long-term degradation of the bituminous layers in railway trackbeds. The evolution of the thermomechanical properties of bituminous mixtures needs then to be characterized for the specific railway working conditions (loading, frequency and environmental exposure). For this, improved 3D tension-compression tests were performed on mixtures used in railway trackbed. The tests are performed on laboratory-compacted cylindrical asphalt specimens submitted to sinusoidal loading. A moisture conditioning procedure was defined and used to simulate the exposure of the materials to weather conditions. The thermomechanical performances of the materials are compared for the conditioned and non-conditioned states. A multi-parameter analysis allowed determining the effect of moisture exposure on the materials behaviour. The results allowed establishing selection criteria, based on moisture susceptibility and long-term degradation, for bituminous mixtures to be used in railway trackbeds.

Keywords: Ageing, Asphalt, Complex Modulus, Freeze-Thaw, Stiffness

1. INTRODUCTION

The use of bituminous sub-ballast layers has become a suitable solution for the construction of railway trackbeds as an alternative to compacted soil and concrete slabs. Bituminous sub-ballast layers were observed to reduce subgrade vertical deformation and to provide vibration control, improving the track structure's stability. Furthermore, they can be used as an access way to the rail track construction site [1-4]. Consequently, the French National Railway Company (SNCF in French) has great interest in bituminous materials for HSL and classic line permanent ways. In service since 2007, the French East-European High-Speed Line (EE HSL), from Paris to Strasburg, was built with a 3km long experimental track section with bituminous sub-ballast layer. The test section has presented, until now, a significant maintenance needs reduction compared to the surrounding sections made only with conventional granular materials. The positive feedback on the EE HSL encouraged the French railway company to build new HSLs with asphalt concrete sub-ballast layers. The bituminous mixtures used in these projects correspond to French GB3 and GB4 [5] commonly used road base-course mixtures. Nevertheless, the available feedback does not allow identifying the long term performance of the bituminous layers in the rail track. Unlike in road pavement, as sub-ballast layer the base-course mixtures are exposed to weather conditions, especially to moisture. Moisture susceptibility of the bituminous mixture is then determinant for the long term performance of the track.

Characterizing the thermo-viscoelastic behaviour of the bituminous materials is a first approach for identifying the materials properties and their performance in railway trackbeds. To this end, tension-compression 3-dimensional complex modulus tests were carried out on cylindrical core samples at the Laboratory of Civil Engineering and Building (LGCB) of the Ecole Nationale des Travaux Publics de l'Etat (ENTPE). A linear viscoelastic model developed at the ENTPE was used to simulate the linear viscoelastic (LVE) behaviour of the tested material. The tests were carried out on non-conditioned and moisture conditioned samples.

In the first part of this paper a brief explanation of the linear viscoelasticity of bituminous mixtures is presented. Secondly, the tested materials, the mechanical tests and the moisture conditioning procedure are described. In third, the used rheological model is presented. The experimental and modelling results are then exposed and compared. The analysis of the results is made in the light of typical loading conditions of high-speed and regular railway traffic in France. Finally, the conclusions and perspectives of the study are presented.

2. LINEAR VISCOELASTICITY

Bituminous mixtures are known to have a complex mechanical behaviour. Figure 1 presents the domains of behaviour for bituminous mixtures according to the applied strain level and number of loadings. Within the small strain domain (ε<100μm/m), and for a limited number of cycles, bituminous materials present LVE behaviour [6,7].

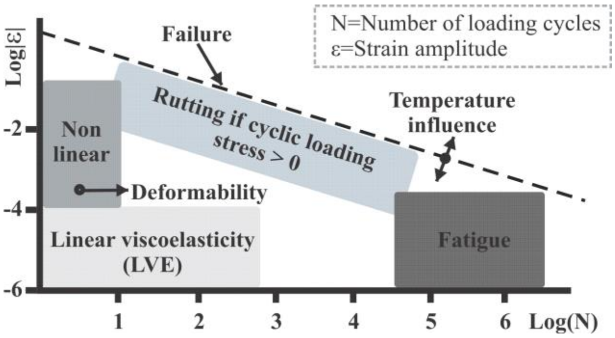

Figure 1: Behaviour domains of bituminous mixtures [8]

For a LVE case, when applying a sinusoidal strain ε in the axial direction 1 of a sample, as in Equation 1, the resulting sinusoidal stress is as expressed in Equation 2; with ε_{01} and σ_{01} the initial strain and stress amplitudes on the axial direction of the sample. An example is shown on Figure 2. Given the viscous properties of bituminous mixtures, there exists a time lag between the stress application and the material's deformation which is defined as the phase angle (φ_E) [9]. The phase angle φ_E is an important indicator of the bitumen structure and of its evolution with time and temperature changes [10].

$$\varepsilon_1(t) = \varepsilon_{01} \sin(\omega t) \tag{1}$$

$$\sigma_1(t) = \sigma_{01} \sin(\omega t + \varphi_E) \tag{2}$$

with ω the sinus pulsation.

Equations 1 and 2 can be rewritten in complex notation introducing the complex number j defined by $j^2=-1$. The complex modulus (E*) can then be defined as the ratio between stress and strain, as shown on Equation 3 [9].

$$\frac{\sigma_{01}}{\varepsilon_{01}} e^{j\varphi_E} = E^* = |E^*| e^{j\varphi_E} \tag{3}$$

The complex modulus is a crucial parameter for bituminous pavement dimensioning as it governs the response of the bituminous structure to traffic loading. Correlations between the complex modulus value and the resistance to rutting and fatigue can also been found in the literature. E* is dependent of the loading frequency and of the temperature [9]. When the Time-Temperature Superposition Principle (TTSP) is respected, the behaviour of the material can be described by a single variable generally chosen as equivalent frequency. Equation 4 expresses the shifting process to find the equivalent frequency f_{eq} of a certain tested temperature T:

$$f_{eq} = a_T(T, T_{ref}) f \tag{4}$$

Where a_T is the shift factor with respect to a chosen reference temperature T_{ref} and f is the real testing frequency. The evolution of the shift factor can be simulated by the Williams, Landel and Ferry (WLF) law [11]:

$$\log(a_T) = \frac{-C_1(T - T_{ref})}{C_2 + T - T_{ref}} \tag{5}$$

Where C1 and C2 are the constants of the WLF law. This shifting procedure allows the construction of a master curve which expresses |E*| in function of the frequency.

3. MATERIALS AND EXPERIMENTAL PROTOCOL

3.1. Tested Materials

The experimental campaign was carried out on French GB3 and GB4 mixtures [5]. The formulation characteristics of the tested mixtures are presented in Table 1 and Figure 2. French classification for bitumen is based on the needle penetration test at 25°C [12].

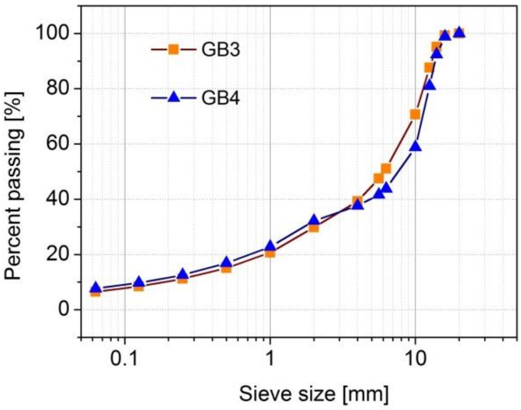

Figure 2: Aggregate grading curves

Table 1: Characteristics of the mixtures

	GB3	GB4
Bitumen penetrability at 25°C	35/50	35/50
Binder content [% of aggregate weight]	4.4	4.8
Mixture bulk specific gravity [g/cm^3]	2.49	2.48
Aggregate nature	Limestone	

The specimens were cored from 600x400x150mm slabs prepared at the Centre for Studies and Research of the French company EIFFAGE Travaux Publics using a wheel compactor [13]. The cylindrical samples dimensions are 75mm in diameter and 140mm in height. The coring direction was parallel to the compactor's wheel movement direction. Therefore, the axial direction of the sample corresponds to main loading direction when the structure reacts as a beam. The tested samples are presented in Table 2. The suffixes "w" and "d" stand for the moisture conditioned and non-conditioned state of the sample, respectively.

Table 2: Treated specimens

Specimen	Air void content [%]	Moisture conditioning
GB3-8.5%$_d$	8.5	No
GB3-8.4%$_W$	8.4	Yes
GB4-5.1%$_d$	5.1	No
GB4-5.4%$_W$	5.4	Yes

3.2. Moisture Conditioning

A moisture conditioning procedure was used on the tested samples as to accelerate moisture induced damage on the materials. The procedure was defined based on the European NF EN 12697-12 - 2008 and American AASHTO T283 – 2001 standards for moisture sensibility of bituminous mixtures [14, 15]. The cylindrical samples were submerged in a water bath at 60±1°C for 168±0.5h then surface dried and placed in a freezer at -18±1°C for 24±0.5h inside an hermetic plastic bag. Finally the samples were placed inside a temperature chamber at 40±1°C for 30±1h to conclude the freeze-thawing cycle. The samples reposed on a bed of sand during all three stages of the conditioning procedure.

3.3. Complex Modulus Test

Axial tension-compression sinusoidal loading is applied to the cylindrical samples by a hydraulic press which applies constant axial strain (ε_{01}) of amplitude 50µm/m. The considered axial strain value is the average of three strain measurements from three 100mm length extensometers disposed on the sample at 120° from one another, as shown in Figure 3. Figure 3 also shows four contactless transducers used to measure the radial strain of the sample which allows calculating the complex Poisson's ratio (ν^*). The measures from a load cell integrated to the press allow calculating the axial stress (σ_{01}). A temperature chamber is used to regulate the temperature conditions of the test.

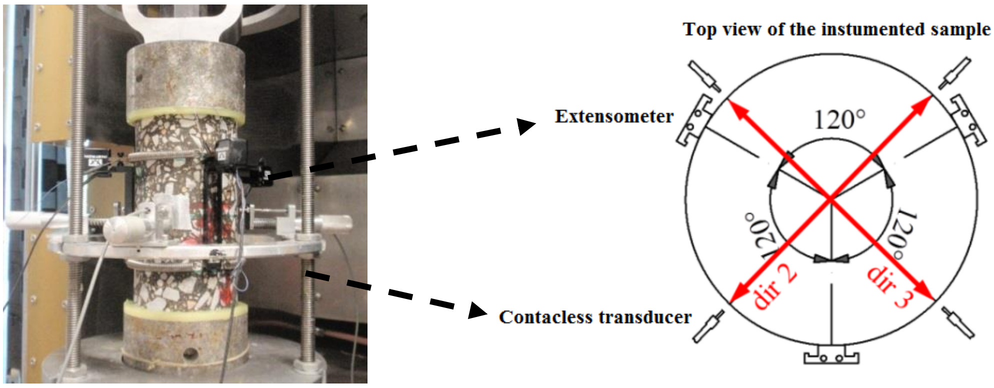

Figure 3: Instrumented sample for complex modulus test

3D-Complex modulus test consists in identifying the modulus a Poisson's ratio values at different temperatures and loading frequencies. The tested loading frequencies are shown in Figure 4. The samples were tested at each of those frequencies at ten different temperatures going from -25°C to 65°C (Figure 5). For this paper, each temperature change is considered a test stage. Previous studies demonstrate that applying less than 80 cycles per loading allows neglecting the heating problems due to viscous dissipation [16, 17].

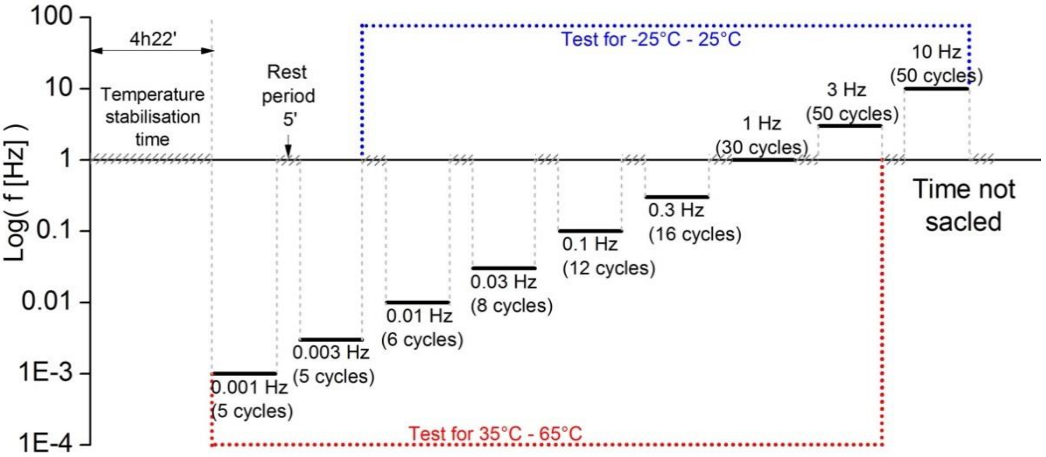

Figure 4: Tested frequencies per temperature of the complex modulus test

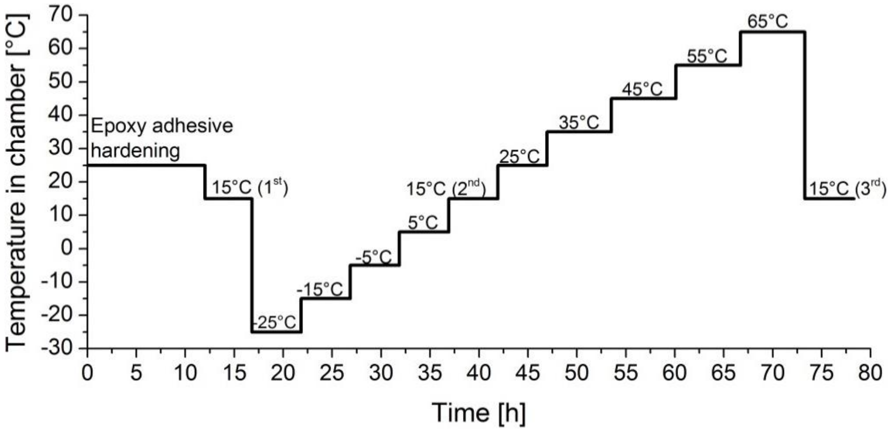

Figure 5: Temperatures used for the complex modulus test

4. LINEAR VISCOELASTIC BEHAVIOUR MODELLING

The experimental results presented in the next section of this paper where modelled with the 2S2P1D rheological model, developed in the Laboratory of Civil Engineering and Construction (LGCB) of the University of Lyon/ENTPE. The model is a generalization of the Huet-Sayegh model [18] and consists of 2 Springs, 2 Parabolic creep elements and 1 Dashpot [19, 20]. It was found to suitably describe the LVE behaviour of most bituminous materials over a wide range of frequencies and temperatures [21-23]. The model describes the complex modulus with 7 parameters (Equation 6) some of which are easily identified in a Cole-Cole diagram, as shown on Figure 6. Analogically, Equation 7 describes the model application for the complex Poisson’s ratio.

$$E^*(\omega) = E_{00} + \frac{E_0 - E_{00}}{1 + \delta(j\omega\tau_E)^{-k} + (j\omega\tau_E)^{-h} + (j\omega\beta\tau_E)^{-1}} \tag{6}$$

$$\nu^*(\omega) = \nu_{00} + \frac{\nu_0 - \nu_{00}}{1 + \delta(j\omega\tau_\nu)^{-k} + (j\omega\tau_\nu)^{-h} + (j\omega\beta\tau_\nu)^{-1}} \tag{7}$$

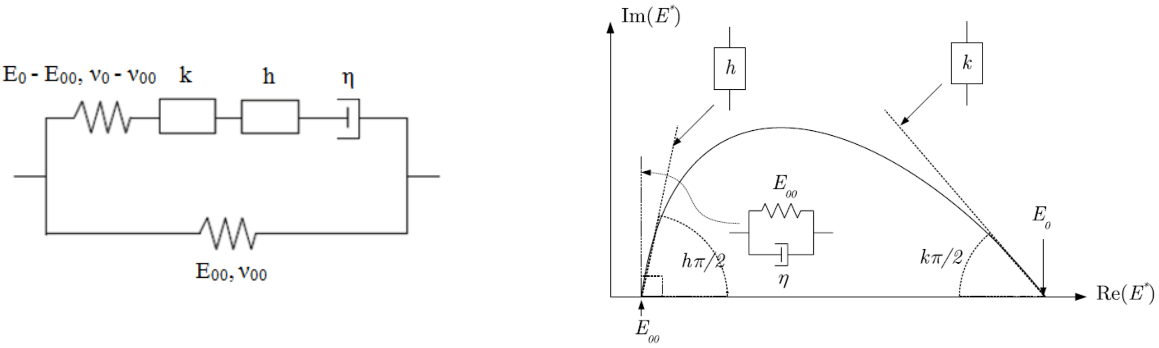

Figure 6: Analogical representation of the 2S2P1D Model (left) and representation of the model parameters on a Cole-Cole diagram (right) [17]

Where the pulsation $\omega=2\pi f$ with f the loading frequency. E_{00} is the static modulus ($\omega \to 0$) and E_0 is the glassy modulus ($\omega \to \infty$); analogically for the Poisson’s ratio. The complex number j is defined by $j^2=-1$, while δ is a calibration constant. The characteristic times τ_E and τ_ν depend on the reference temperature. The constants k and h are defined such that $0 < k < h < 1$. Finally, β is a constant that depends on the viscosity of the dashpot: $\eta = (E_0\text{-}E_{00})\beta\tau$. The WLF constants of Equation 5, calculated at the reference temperature, are also needed if the temperature effect is to be considered.

5. EXPERIMENTAL RESULTS

Isotherm curves of |E*| and φ_E were plotted for each tested temperature. An example is shown in Figure 7 for the sample GB3-8.5%d. Complex modulus norm considerably decreases as the temperature increases. However, |E*| increases with the frequency. The opposite effect is observed for the phase angle for temperatures between -23.8°C and 23.9°C. At high temperatures, the bitumen is soft and its behaviour becomes close to that of a Newtonian fluid. Therefore, the efforts on the sample are withstood only by the granular skeleton, which presents an elastic behaviour. This explains the change in sign of the phase angle slope for the temperatures between 33.2°C to 62.5°C.

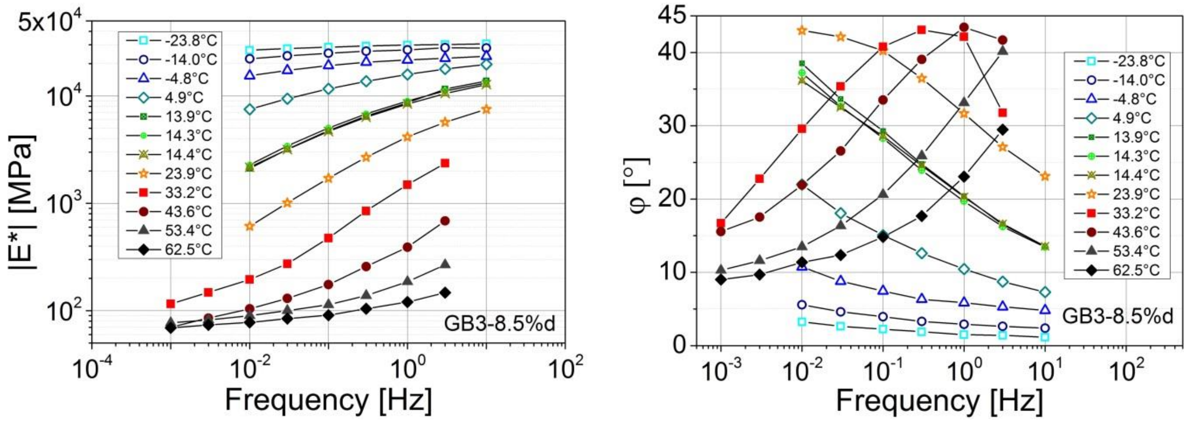

Figure 7: Complex modulus and phase angle isotherm curves – sample GB3.3-C1-8.5%$_d$

Figure 8 presents the complex modulus tests results for both materials in the Cole-Cole plan and in the Black space. The Cole-Cole plan relates the real (E1) and the imaginary (E2) components of the complex modulus. The Black's space expresses the modulus norm in function of its phase angle. The TTSP is verified for both materials as the experimental results describe a unique line in both diagrams. The principle is also validated for the moisture conditioned samples. The moisture conditioned materials can the also be assimilated as "thermo-rheologically simple", at least as a first fitting approximation.

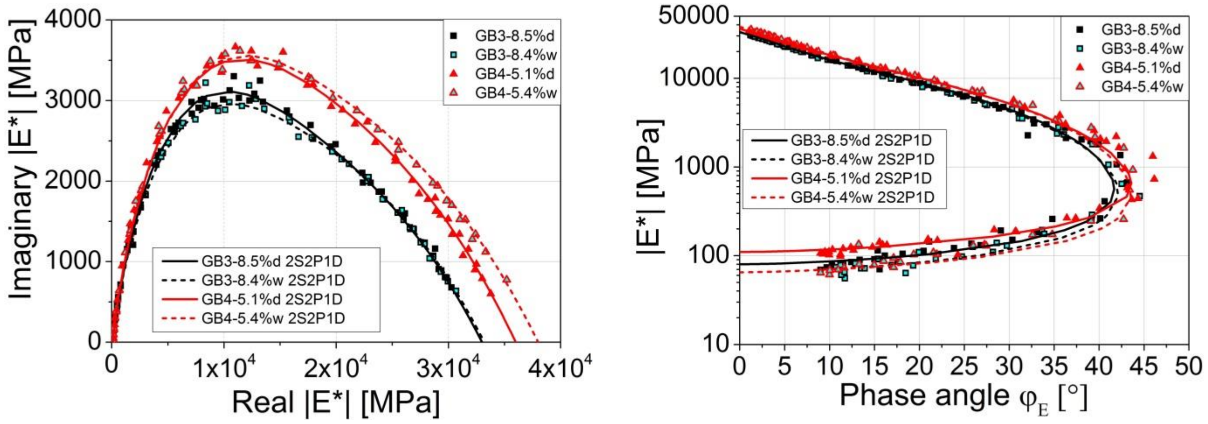

Figure 8: Complex modules test results in plan Cole-Cole (left) and Black space (right). GB3 and GB4 results for the moisture conditioned and non-conditioned states

Using the TTSP, complex modulus and Poisson's ratio master curves were built for each tested sample (Figures 9-12). Figure 9 shows how the high temperature stages (45°C – 65°C) allow observing the behaviour of the material at very low equivalent frequencies. Analogically, low temperature stages (5°C – -25°C) are related to high equivalent frequencies. The values of the 2S2P1D model parameters and of the WLF constants are indicated in Table 3 for a reference temperature of 15°C.

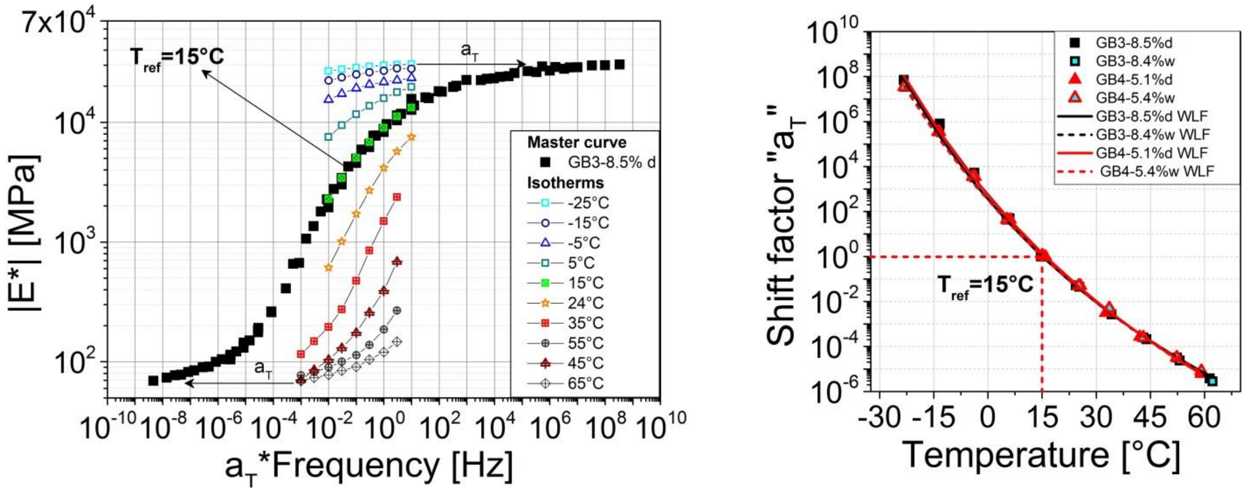

Figure 9: Illustration of the |E*| master curve construction procedure for GB3-8.5%d sample (left) and shift factor a_T for all the tested samples (right)

The shift factor a_T does not seem to be affected by the moisture conditioning as observed in Figure 9. This is in accordance with previous studies that found the a_T factor to be inherent to the bitumen nature [19, 20, 24].

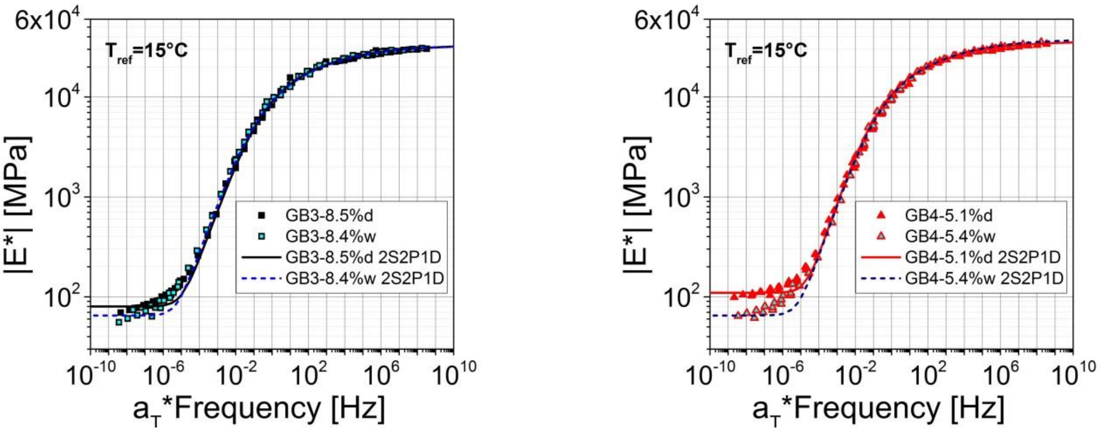

Figure10: GB3 (left) and GB4 (right) complex modulus master curves for the conditioned and non-conditioned states

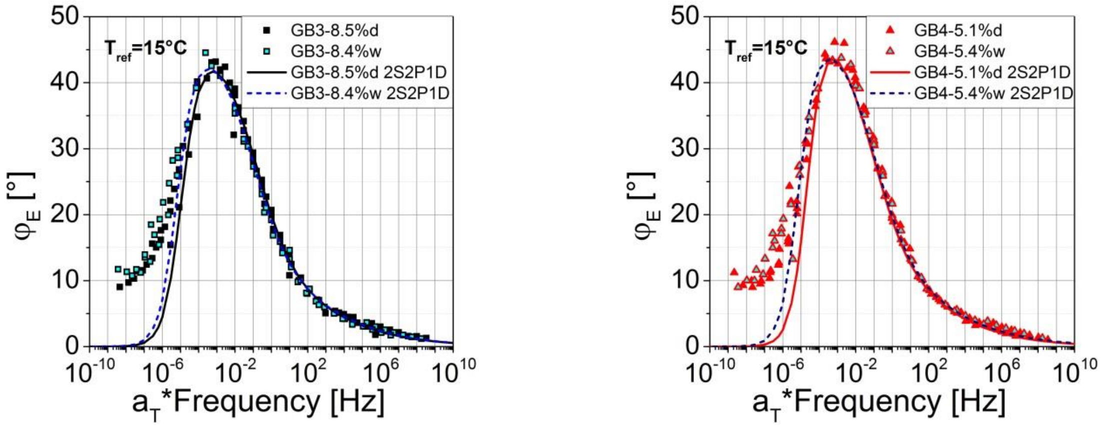

Figure 11: GB3 (left) and GB4 (right) phase angle master curves for the moisture conditioned and non-conditioned states

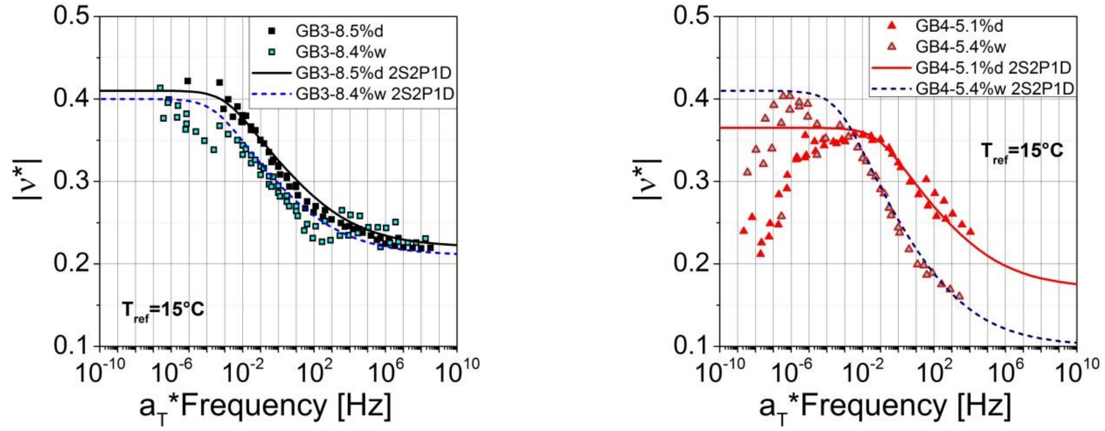

Figure 12: GB3 (left) and GB4 (right) Poisson's ratio master curves for the moisture conditioned and non-conditioned states

Table 3: 2S2P1D model calibration parameters for the tested materials

Sample	E_{00} [GPa]	E_0 [GPa]	k	h	δ	τ_0 [s]	β	ν_{00}	ν_0	C1	C2
GB3-8.5%$_d$	0.080	33.0	0.17	0.53	1.79	0.143	300	0.41	0.22	21.81	144.21
GB3-8.4%$_W$	0.065	33.2	0.17	0.52	1.94	0.174	350	0.40	0.21	24.63	162.74
GB4-5.1%$_d$	0.110	36.0	0.18	0.55	1.85	0.221	165	0.37	0.17	24.21	155.81
GB4-5.4%$_W$	0.065	38.0	0.18	0.54	1.90	0.163	300	0.41	0.10	23.41	156.69

The simulation using the 2S2P1D model show a good fitting for both E* and ν*. Nevertheless, the model hardly adjusts to the experimental values at high temperatures, especially for the phase angle of the complex modulus and for the Poisson's ratio. This can be evidence of the measuring limits of the used equipment or to other aspects such as the bitumen softening and possible flow at high temperatures/low frequencies, etc.

The GB4 mixture presents both higher glassy and static modulus values than the GB3 one. This can be attributed to the lower voids content of the GB4 due to its aggregate distribution. As for the phase angle, the GB4 mixture develops higher maximal phase angle values than the GB3, which can be related to its higher binder content. The GB4 mixture is also characterized by higher imaginary modulus (E_2) values. The GB4 is then expected to present a more viscous behaviour than the GB3, which can be related to higher energy dissipation in the form of heat. The GB4 mixture also presents a lower static Poisson's ratio which stands for a lower radial deformation at high temperatures. This can be related to the increased contact between aggregates of the GB4 by its granular distribution. For the GB4 mixture, experimental difficulties with the radial strain measurements at low temperatures don't allow the analysis of the glassy Poisson's ratio. Nevertheless, it is clear that the Poisson's ratio varies with temperature and frequency changes and should not be taken as a constant value.

The results presented in Figures 10 to 12 and Table 3 show some variations between the behaviours of the moisture conditioned samples with respect to the non-conditioned ones. The static modulus, which is associated to the material's response to very low-frequency loadings, shows a small reduction after moisture conditioning for both materials. This could be associated to stripping damage due to water. For the GB4, the higher E_{00} variation may be also due to the air voids content difference of 0.3% between the samples, as this parameter is highly influenced by aggregates distribution. As for the glassy modulus, it increases after moisture conditioning, which may be associated to mastic oxidation. These hypotheses are in concordance with the variation of the Poisson's ratio of the GB3 mixture after conditioning. Further tests on the GB4 will verify if the observed tendency is applicable for this material as well. As for the other parameters of the 2S2P1D model, moisture conditioning increases δ and β values. The observed variations of β, together with the small changes in E_0 and E_{00}, imply an increase in the viscosity η of the 2S2P1D model's dashpot after moisture conditioning. Nevertheless, given the observed variations, moisture conditioning does not seem to significantly affect the LVE behaviour of the studied base-course mixtures.

Table 4 shows the values of complex modulus at different excited frequencies which correspond to the passage of a TGV wagon and of a freight train locomotive at different speeds. The wavelengths considered for the calculation of the frequencies correspond to the distance between the axles of a bogie (3m) and to the wagon length (18.7m for the TGV wagon and 10.5m for the freight locomotive). Field experience from the EE HSL test zone [25], allowed identifying the bogie wavelength as the main exciting frequency at the bituminous sub-ballast layer. The wagon lengthwise was also studied as to observe the influence of a lower loading frequency. The |E*| values in table 4 were obtained from the 2S2P1D model simulation at the reference temperature of 15°C.

Table 4: Complex modulus values for at different excited loading frequencies (T_{ref}=15°C)

Frequency [Hz]	Source	|E*| GB3$_d$ [MPa]	|E*| GB3$_w$ [MPa]	|E*| GB4$_d$ [MPa]	|E*| GB4$_w$ [MPa]
10	European norm for road materials NF EN 13108-1*	13440	13274	15636	15430
31	Bogie 320km/h	15506	15274	17948	17810
7.4	Bogie 80km/h	12871	12727	14999	14778
5.3	TGV Wagon 320km/h	12233	12116	14284	14047
3.7	Bogie 40km/h	11538	11452	13504	13252
2.1	Freight locomotive 80km/h	10431	10400	12262	11989
1.2	TGV wagon 80km/h	9335	9359	11027	10738
1.0	Freight locomotive 40km/h	8979	9021	10624	10332
f→0	Quasi-static loading (infinitely long loading time)	80	65	110	65

[*] Thresholds imposed by the European normativity at 15°C and 10Hz are 9000MPa and 11000MPa for the GB3 and for the GB4 respectively.

Table 4 clearly shows that both materials present high modulus values for all loading frequencies associated to high-speed circulation. Additionally, they present |E*| values close to the European normativity threshold for the lowest loading frequencies. Measurements taken at the experimental site of the EE HSL show that the longitudinal stress levels at the bottom of the bituminous sub-ballast layer induced by a TGV passing at 320km/h are much lower than the modulus values shown in table 4. Furthermore, complex modulus does not seem to be significantly affected by moisture conditioning. The modulus losses for all of the treated frequencies are under 3%, except for E_{00}. Alike observations were made by other authors studying the use of dynamic modulus as indicator of moisture damage on bituminous mixtures [26-28]. Nevertheless moisture conditioning could affect the mixtures resistance to fatigue or to permanent deformations. Fatigue and permanent deformation (rutting) tests should be carried out in order to determinate the mixtures susceptibility to moisture conditioning.

5. CONCLUSIONS

The linear viscoelastic behavior of bituminous mixtures used in railway platform is treated on this paper. The influence of moisture conditioning on the LVE behavior of the mixtures is presented. Complex modulus tests were carried out on cylindrical samples of two base-course bituminous mixtures used in railway infrastructure in France. Moisture conditioned and non-conditioned samples were tested for both mixtures. For this, a moisture conditioning procedure was proposed and used. It includes submersion in water at high temperature and a freeze-thaw cycle. The 2S2P1D rheological model was used to simulate the experimental results. Results were analyzed in the light of typical railway loading conditions.

The 2S2P1D simulation results prove that the model is a powerful tool for the study of bituminous materials in the linear viscoelastic domain. It allowed identifying the complex modulus and Poisson’s ratio values at specific loading frequencies due to train traffic.

The studied mixtures where found to present satisfying complex modulus values for all of the studied loading and moisture conditions. The studied loading frequencies correspond to typical French railway traffic. The results are evidence of the low variation of the 3-dimensional linear viscoelastic behavior of the materials after moisture conditioning. Although the GB4 mixture was found to be stiffer than the GB3 one, both mixtures presented high complex modulus values for all the frequencies of interest. In terms of stiffness, the studied base-course bituminous mixtures were found suitable to be used in railway infrastructure. The GB4 mixture also presented a more viscous behavior than the GB3; hence, the GB4 is expected to dissipate more energy. The role of energy dissipation of the bituminous layer in the general track performance should be identified as it could be related to track vibration and to ballast degradation.

Regarding moisture damage, repeatability tests must be carried out in order to perform a statistical analysis. Given the non-destructive character of the performed complex modulus test, tests could be carried out on the same sample before and after moisture conditioning.

Other material properties such as fatigue and permanent deformation resistance need to be characterized for bituminous mixtures for railroad platforms. The influence of moisture conditioning on these properties needs to be identified as it will determine the long term behavior of the bituminous layer and of the track structure.

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