Anisotropic Behaviour of Bituminous Mixtures in Road Pavement Structures

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ABSTRACT

The compaction of bituminous mixture during the road pavement construction induces anisotropic properties. However, bituminous mixture is generally considered as isotropic. This paper presents the investigations on the anisotropic behaviour of bituminous mixture in road pavement structure. A pavement block (55×46×28cm) was sawn and extracted from a highway in France. Cylindrical specimens were cored and sawn from the middle layer of this block in three directions: longitudinal direction I, vertical direction II and transversal direction III. Complex tension/compression modulus tests were performed at ENTPE laboratory to investigate the anisotropic behaviour of bituminous mixture. These tests consist in measuring axial stress and radial strains when sinusoidal axial strain whose amplitude is lower than 10^{-4} m/m was applied on the sample. Tests were performed on the 3 types of specimens (cored in directions I, II, III) at 9 temperatures and 6 frequencies. For each specimen, the complex modulus E^* and the complex Poisson's ratios ν^* in two perpendicular diameter directions were measured. Thus, the three E^* (E^*_I, E^*_{II} and E^*_{III}) and the six ν^* (ν^*_{I-II}, ν^*_{I-II}, ν^*_{II-I}, ν^*_{II-III}, ν^*_{III-I}, ν^*_{III-II}) could be obtained and investigated. The Time Temperature Superposition Principle was verified for both norm and phase angle of E^* and ν^*. The anisotropic properties of material were studied by comparing the three E^* and six ν^*. The obtained results reveal an anisotropic behaviour of bituminous mixture and the difference in E^* and ν^* varied with the equivalent temperature-frequency. But rheological tensor was shown to be symmetric within the middle range of reduced frequency. The experimental results were then simulated using a 3D viscoelastic model. A unique normalised curve can be considered for E^* and ν^* regardless of some dispersion for ν^* values. Stability of the material behaviour was also investigated within the tested frequency–temperature range.

Keywords: anisotropy, bituminous mixtures, linear viscoelasticity, complex modulus, complex Poisson's ratio

1. INTRODUCTION

Bituminous mixture is generally considered as an isotropic material. In fact, the compaction during the road pavement construction can induce some anisotropic properties of this material. The anisotropic behaviour of bituminous mixture has been studied by very few authors [1-5]. This paper focuses on the anisotropic behaviour of field-compacted bituminous mixtures. The 3D tension-compression complex modulus tests were performed on cylindrical specimens that were cored and sawn from the bituminous mixture layer of a highway in France. The complex modulus E^* and the complex Poisson's ratios ν^* were measured at different temperatures, frequencies and at small applied strain amplitudes (< 100 µm/m). The anisotropic properties of material were studied by comparing the complex moduli E^* and the complex

Poisson's ratios ν^* in different material directions. In addition, the Time Temperature Superposition Principle (TTSP) [6-8] was verified for the tested bituminous mixture.

2. MATERIALS AND 3D COMPLEX MODULUS TESTS

A pavement block (55×46×28 cm) which comprises 3 bituminous mixture layers (28 cm in total depth) was sawn and extracted from a highway in France. Cylindrical specimens (75 cm in diameter and 140 cm high) were cored and sawn from the middle layer (11 cm in depth) of this block in three directions: longitudinal direction (direction I), vertical direction (direction II) and transversal direction (direction III).

Complex modulus tests were performed on three specimens BI, BII, BIII cored in three directions I, II, III, respectively. For each specimen, the complex modulus E^* and the complex Poisson's ratios ν^* in two perpendicular diameter directions (see Figure 1) were measured at nine temperatures (from -16°C to 40°C) and six frequencies (from 0.03 Hz to 10 Hz). Thus, the three E^* (E^*_I, E^*_{II} and E^*_{III}) and the six ν^* ($\nu^*_{I\text{-}II}$, $\nu^*_{I\text{-}II}$, $\nu^*_{II\text{-}I}$, $\nu^*_{II\text{-}III}$, $\nu^*_{III\text{-}I}$, $\nu^*_{III\text{-}II}$) of tested bituminous mixture could be obtained for a large range of temperature and frequency. The set up for accurate measurements of axial and radial strains (Figure 1) has been developed at ENTPE for many studies [9-11]. Due to the limit of the paper, details on the test equipment are not presented.

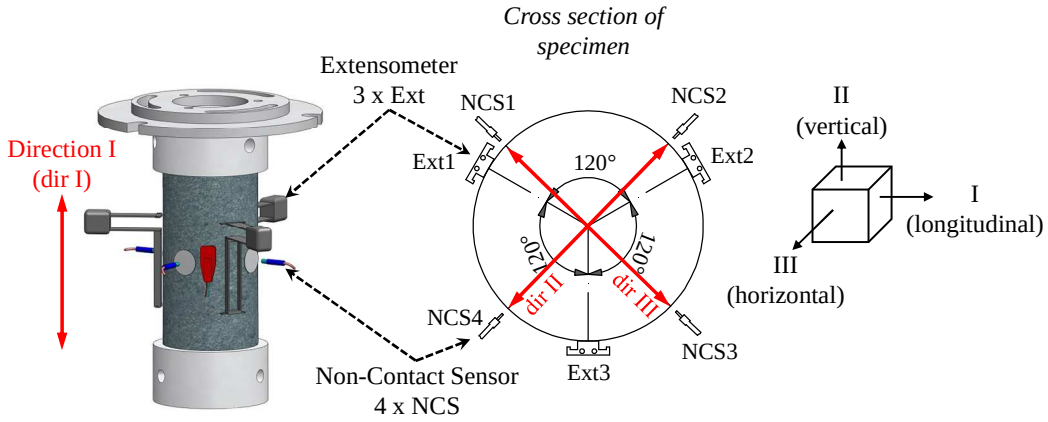

FIGURE 1 Measurement of axial strain, radial strains on specimen cored in direction I

When the sinusoidal axial strain is applied in direction I, the sinusoidal evolution with time of measured stress and strains is defined by Eqs.(1, 2, 3), where $\phi_{E\ I}$ is the phase angle between the strain in direction I (ε_I) and the stress in direction I (σ_I). $\phi_{\nu\ II\text{-}I}$, $\phi_{\nu\ III\text{-}I}$ are the phase angle between the strain in direction I (ε_I) and the strain in direction II, III (ε_{II}, ε_{III}), respectively.

$$\varepsilon_I(t) = \varepsilon_{0I}\sin(\omega t) \quad (1)$$

$$\sigma_I(t) = \sigma_{0I}\sin(\omega t+\phi_{E\ I}) \quad (2)$$

$$\varepsilon_i(t) = -\varepsilon_{0i}\sin(\omega t+\phi_{\nu\ i\text{-}I}) \quad (i = II, III) \quad (3)$$

From Eqs.(1, 2, 3), the complex modulus in direction I (E^*_I) and two complex Poisson's ratios in direction II and III ($\nu^*_{II\text{-}I}$, $\nu^*_{III\text{-}I}$) can be given by Eqs.(4, 5), where j is the complex number ($j^2 = -1$).

$$E_I^* = \frac{\sigma_{0I}}{\varepsilon_{0I}} e^{j\phi_{E\,I}} = \left|E_I^*\right| e^{j\phi_{E\,I}} \quad (4)$$

$$\nu_{i-I}^* = \frac{\varepsilon_{0i}}{\varepsilon_{0I}} e^{j\phi_{\nu\,i-I}} = \left|\nu_{i-I}^*\right| e^{j\phi_{\nu\,i-I}} \quad (i = II, III) \quad (5)$$

The relation between stress and strain, expressed in principal axes I, II, III, is defined by Eq.(6), where $\underline{\underline{M^*}}$ is the complex compliance tensor.

$$\underline{\varepsilon^*} = \underline{\underline{M^*}}\,\underline{\sigma^*} \quad with \quad \underline{\underline{M^*}} = \begin{pmatrix} \frac{1}{E_I^*} & -\frac{\nu_{I-II}^*}{E_{II}^*} & -\frac{\nu_{I-III}^*}{E_{III}^*} \\ -\frac{\nu_{II-I}^*}{E_I^*} & \frac{1}{E_{II}^*} & -\frac{\nu_{II-III}^*}{E_{III}^*} \\ -\frac{\nu_{III-I}^*}{E_I^*} & -\frac{\nu_{III-II}^*}{E_{II}^*} & \frac{1}{E_{III}^*} \end{pmatrix} \quad (6)$$

3. TEST RESULTS

Figures 2 and 3 present the measured complex modulus E^* of three tested specimens BI, BII and BIII. Figure 2 shows the complex modulus in Cole-Cole diagram and Black diagram. The master curves of norm and phase angle of complex modulus at the reference temperature T_R = 15°C were plotted in Figure 3. The results in Figures 2 and 3 indicated that complex modulus in all three directions respects the TTSP. At low temperature (high frequency), the modulus of BIII specimen is highest, followed by BI and BII specimens. At high temperature, the BI specimen has a higher norm of complex modulus $|E^*|$ than one of BII and BIII specimens. The behaviour of tested bituminous mixture can be considered anisotropic. The 2S2P1D model was used to simulate the linear viscoelastic behaviour of material in each direction. The readers can find more details of this model in [12]. The simulation of E^* with 2S2P1D model is also presented in Figures 2 and 3.

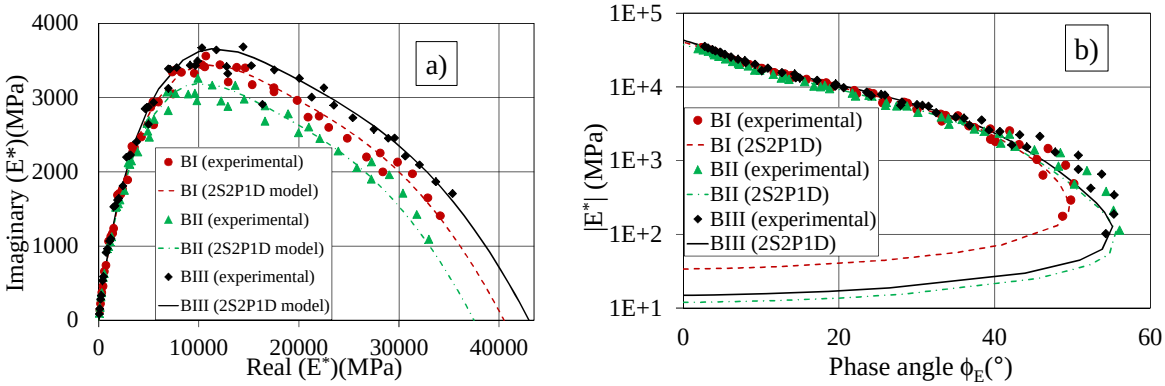

FIGURE 2 Complex modulus in Cole-Cole diagram (a) and Black diagram (b)

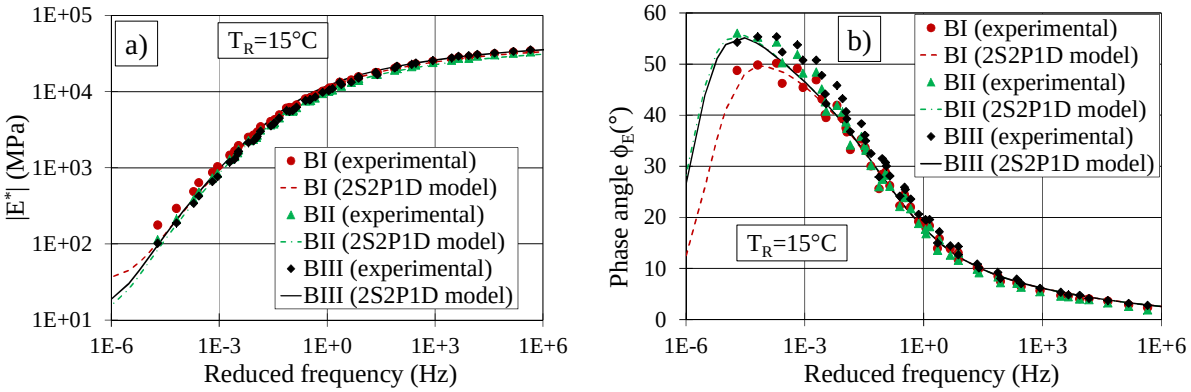

FIGURE 3 Master curves of $|E^*|$ (a) and ϕ_E (b) at T_R = 15°C

Figure 4 presents the master curves of all $|\nu^*|$ (norm of complex Poisson's ratio) plotted at the reference temperature TR = 15°C. This result shows that the TTSP is verified and applicable in the 3D case. It can be seen that the value of $|\nu^*_{III-II}|$ is highest on the whole tested range of reduced frequency. At low frequency, the value of $|\nu^*_{III-I}|$ is smallest. At high frequency, the values of $|\nu^*_{I-II}|$ and $|\nu^*_{I-III}|$ are smallest. The good fitting of data for both E^* and ν^* in Figures 2, 3, 4 confirms the good performance of 2S2P1D model. It should be underlined that the shift factors used to build the master curves of E^* and ν^* of all three specimens are identical. In addition, the simulation by 2S2P1D model used the same viscous and temperature constants for all three specimens. These remarks are important when modelling the anisotropic behaviour of tested bituminous mixtures.

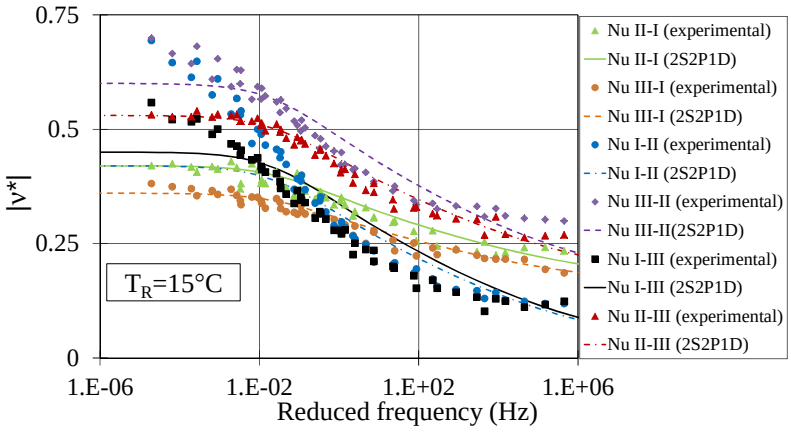

FIGURE 4 Master curves of $|\nu^*|$ at T_R = 15°C

The normalised complex modulus $(E^* - E_{00})/(E_0 - E_{00})$ and normalised complex Poisson's ratio $(\nu^* - \nu_{00})/(\nu_0 - \nu_{00})$ as a function of reduced frequency are presented in Figure 5. E_{00} and E_0 (ν_{00} and ν_0) are asymptotic values of the norm of complex modulus (the norm of complex Poisson's ratio) when the frequency tends towards 0 and infinity, respectively. E_{00}, E_0, ν_{00} and ν_0 are determined by the simulation using the 2S2D1P model. The results in Figure 5 indicated that the normalised E^* and ν^* curves of all three specimens are close regardless of some dispersion for normalised ν^* values at high temperature/low frequency.

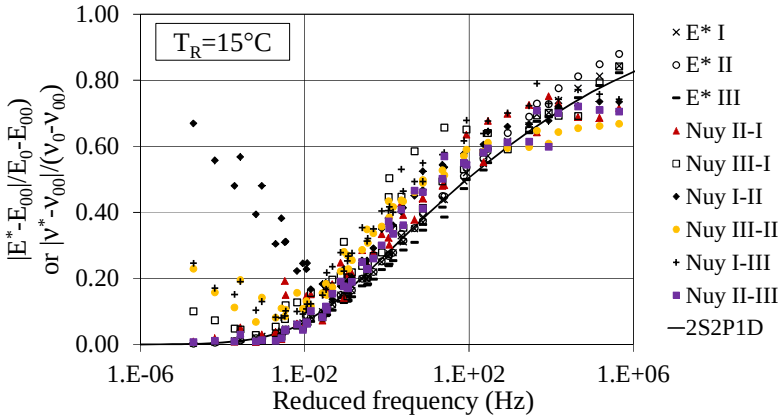

FIGURE 5 Normalised E^* and normalised ν^* as a function of reduced frequency

The symmetry of compliance tensor $\underline{\underline{M^*}}$ (Eq.(6)) was verified and presented in Figure 6. Each couple of $|\nu^*|/|E^*|$, which corresponds symmetric terms of tensor $\underline{\underline{M^*}}$, was compared together on the whole tested range of temperature and frequency. The results indicated that the compliance tensor can be considered as symmetric at middle values of reduced frequency (from 0.01 Hz to 10 Hz) at T_R = 15°C. At high and low reduced frequency, the tensor is not symmetric.

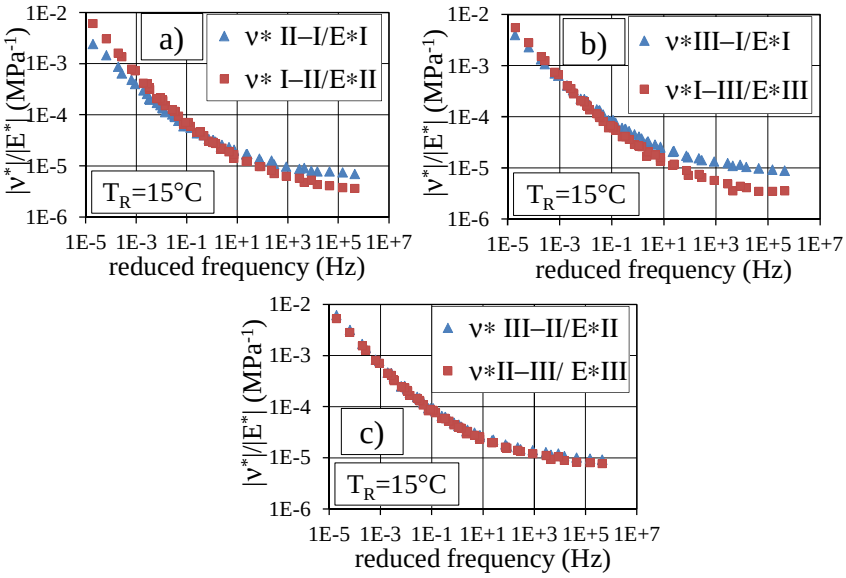

FIGURE 6 Verification of symmetry of compliance tensor $\underline{\underline{M^*}}$

In the linear elastic case, the necessary and sufficient condition giving the stability of behaviour from thermodynamics consideration is expressed by Eq.(7) [13].

$$\Delta = 1 - \nu_{I-II}\nu_{II-I} - \nu_{II-III}\nu_{III-II} - \nu_{III-I}\nu_{I-III} - 2\nu_{II-I}\nu_{III-II}\nu_{I-III} > 0 \qquad (7)$$

Making analogy with linear elastic case, validity of Eq. (7) was checked on the whole frequency temperature range, for norm of the complex Poisson's ratios. The values of Δ as a function of reduced frequency were plotted in Figure 7. The result shows that the condition given

by Eq. (7) is respected for the reduced frequency higher than 0.0033 Hz at T_R = 15°C. At lower reduced frequency, this condition is not respected. In fact, very high accuracy is needed to measure Poisson's ratio ν^* at high frequencies/low temperatures and low frequencies/high temperatures. This remark should be considered when analysing the difference between symmetric terms $|\nu^*|/|E^*|$ at high and low reduced frequency (Figure 6) and the negative values of Δ at very low reduced frequencies (Figure 7).

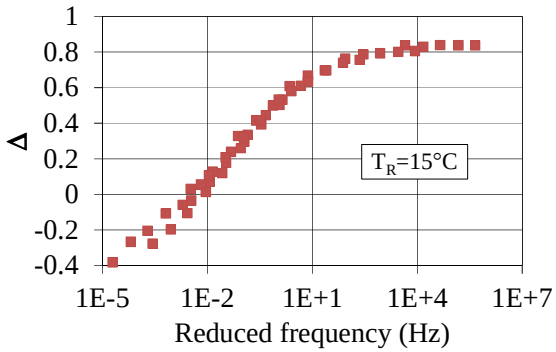

FIGURE 7 Values of Δ as a function of reduced frequency at T_R = 15°C

3. CONCLUSIONS

This paper focuses on the linear viscoelastic (LVE) behaviour and the anisotropic behaviour of bituminous mixture in road pavement structure. From the obtained results, the following conclusions can be drawn:

- The Time Temperature Superposition Principle (TTSP) was verified for both norm and phase angle of complex modulus E^* and complex Poisson's ratio ν^*. The master curves of E^* and ν^* of three specimens cored in three directions I, II, III were built using the same shift factors.
- The 2S2P1D model shows a good simulation of 3D LVE behaviour of tested bituminous mixture. The viscous constants of this model are identical for E^* and ν^* of all three tested specimens BI, BII, BIII (cored in direction I, II, III, respectively).
- From experimental results, the difference in E^* and ν^* of specimens cored in different directions was observed. This difference varied with the equivalent temperature-frequency. The behaviour of specimens extracted from a highway in France can be considered as anisotropic.
- The rheological tensor was shown to be symmetric within the middle range of reduced frequency. At high and low reduced frequency, the symmetry was not observed but this point needs to be further investigated.
- The normalised E^* and ν^* curves of three specimens are close and can be considered as identical if unavoidable dispersion for normalised ν^* values at high temperature/low frequency are considered.
- Stability of the material behaviour was verified within the tested frequency–temperature range. The necessary and sufficient condition giving the stability of material behaviour is respected for the middle and high reduced frequency (> 0.0033 Hz at T_R = 15°C).

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