

Viscoelastic Behaviour Characterization of a Gap-graded Asphalt Mixture with SBS Polymer Modified Bitumen

Diego Alejandro Ramirez Cardona^{a*}, Simon Pouget^b, Herve Di Benedetto^a, François Olard^b

^aLaboratoire Génie Civil et Bâtiment and Laboratory of Tribology and System Dynamics – LTDS (UMR CNRS 5513), Ecole Nationale des Travaux Publics de l'Etat – ENTPE, University of Lyon, (FR) 69518 Vaulx en Velin, Lyon, France

^bResearch and Development Division, EIFFAGE Travaux Publics, (FR) 69960 Corbas, France

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A characterization of the linear thermo-viscoelastic behaviour of a gap-graded bituminous mixture with SBS-polymer modified bitumen and RAP aggregates is presented in this paper. A comparison was made, in terms of their viscoelastic behaviour, between this innovative mixture and two commonly used well-graded base-course French mixtures made with pure bitumen. The materials were also compared in terms of viscous dissipated energy. Complex modulus tests on cylindrical samples were performed for each mixture. The viscoelastic behaviour of the materials was modelled using the 2S2P1D (2 springs, 2 parabolic elements, 1 dashpot) constitutive model which was developed in the Laboratory of Civil Engineering and Construction (LGCB) of the ENTPE, University of Lyon. The tests results allowed validating the time-temperature superposition principle for the studied mixtures. Experimental and modelled complex modulus ($|E^*|$) master curves were built for each material. The gap-graded mixture was found to present higher stiffness values at low frequency/high temperature conditions, lower viscous behaviour and lower values of viscous dissipated energy compared to the conventional mixtures. Complex modulus tests were also carried out on the polymer modified bitumen of the gap-graded mixture. A link between the viscoelastic behaviour of both binder and mixture could be established thanks to the SHStS transformation developed by the ENTPE team.

Keywords: bituminous mixture, viscoelastic behaviour, thermo-mechanical properties, gap-graded mixture, complex modulus test, viscoelastic constitutive model, linear viscoelasticity

1. Introduction

Road transportation is experiencing a constant increase in traffic intensities. The higher traffic loads and circulation speeds and the ever increasing number of vehicles imply the need for road building materials with better mechanical performances and longer life expectancy. Parallel to this, the actual environmental context calls for a reduction of raw construction materials use. An innovative base-course mixture was conceived as a solution to the challenge of improving the properties of bituminous mixtures while reducing the use of raw aggregates and new bitumen. The formulation of this mixture, called GB5[®], takes into account two important aspects: first; the optimization of the aggregate packing for higher stiffness^{1,2}; and second, the use of SBS-polymer modified bitumen for reducing fatigue cracking and ageing³⁻⁷. Coupling both techniques would allow creating a sufficiently stiff and fatigue resistant material. In addition, the formulation includes a moderate to high percentage of reclaimed asphalt pavement (RAP) in order to cope with the environmental requirements. This paper focuses on the characterisation of the linear viscoelastic (LVE) behaviour of such a bituminous mixture in order to verify its mechanical performances and its advantages compared to conventional base-course mixtures.

Bituminous materials are known to have a complex mechanical behaviour⁸⁻¹¹. As shown on Figure 1, bituminous materials present a linear viscoelastic (LVE) behaviour within the small strain domain ($\epsilon < 100 \mu\text{m/m}$) which can be fully defined by means of the complex modulus (E^*) and the complex Poisson's ratio (ν^*)¹². The characterisation of the complex modulus presented in this paper was made on a large frequency and temperature domain by means of a mechanical tension-compression test on cylindrical samples. The complex modulus has been identified as a main parameter for calculating the response of a bituminous structure to traffic loading as well as its resistance to rutting and fatigue¹³.

In addition, the link between the rheological behaviour of the GB5[®] mixture and its binder is studied. The SHStS transformation developed at the ENTPE¹⁴⁻¹⁷ was used and validated. It allows predicting the complex modulus of the mixture from the complex modulus of the binder (and vice versa).

2. Linear Viscoelasticity

Figure 1 presents the different types of behaviour observed for bituminous mixtures according to the amplitude of the applied strain and the quantity of loading cycles. Within the small strain domain ($\epsilon < 100 \mu\text{m/m}$) and for limited number of

*e-mail: diego.ramirezcardona@entpe.fr

cycles, bituminous materials present a LVE behaviour^{8,9}. This means that the material’s response to a number of elementary loadings is the addition of each of the elementary responses¹⁰.

The stress response of linear viscoelastic materials to any strain loading can be expressed using the relaxation function (R(t)) (Equation 1). Applying the Carson transformation (Equation 2), the R function can be transformed to an expression similar to an elastic law (Equation 3)¹⁰.

$$\sigma(t) = \int_0^t R(t-\tau) d\varepsilon(\tau) \tag{1}$$

$$\tilde{f}(p) = \int_0^\infty p e^{-pt} f(t) dt \tag{2}$$

$$\tilde{\sigma}(p) = \tilde{R}(p) \cdot \tilde{\varepsilon}(p) \tag{3}$$

Where p is a complex number. For a sinusoidal loading, given the viscous properties of bituminous mixtures, there exists a phase lag (φ) between stress and strain. Equations 4 and 5 express strain ε and stress σ for this type of loading, where ε₀₁ and σ₀₁ are the strain and stress amplitudes and ω the pulsation (ω = 2πf, where f is the frequency). The subscript 1 means axial direction for the performed test conditions, which are presented in the next section. Figure 2, presents an example of the obtained stress and strain signals from the complex modulus test on the gap-graded mixture.

$$\varepsilon_1(t) = \varepsilon_{01} \sin(\omega t) \tag{4}$$

$$\sigma_1(t) = \sigma_{01} \sin(\omega t + \varphi) \tag{5}$$

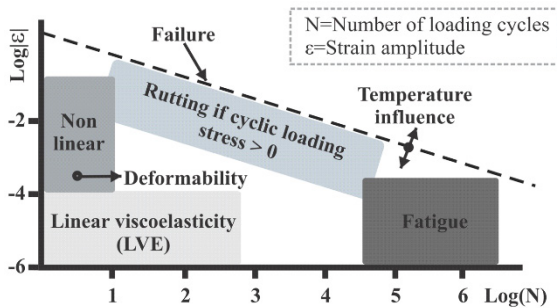


Figure 1. Domains of behaviour for bituminous mixtures¹⁰.

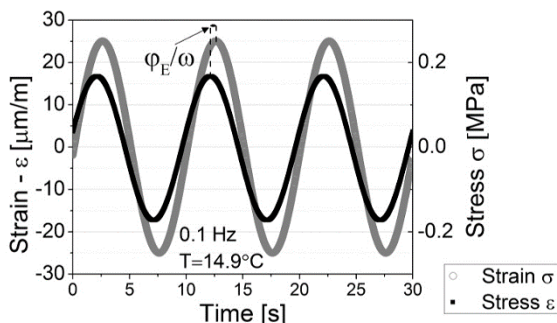


Figure 2. Example of stress and strain signals – Complex modulus test on the GB5[®] mixture (gap-graded) (f = 0.1Hz and T = 14.9 °C).

Introducing a complex number j defined by j²=-1, Equations 4 and 5 can be rewritten and placed in Equation 3 as presented in Equation 6. The complex modulus is classically described from the results of sinusoidal loading tests as it corresponds to the value of the Carson transform of the relaxation function () at a point “jω” (Equation 6)¹⁰. The evolution of the complex modulus with frequency and temperature gives the complete LVE characterisation of the material¹⁸.

$$E^* = \tilde{R}(j\omega) = \frac{\sigma_{01}}{\varepsilon_{01}} e^{j\varphi} = |E^*| e^{j\varphi} \tag{6}$$

E* depends on the loading frequency as well as the temperature¹⁰. The Time-Temperature Superposition Principle (TTSP) stands that a unique reduced variable, the equivalent frequency f_{eq}, can be introduced to describe the evolution of the complex modulus for every frequency/temperature loading condition (Equation 7). Hence, a same complex modulus norm (|E*|) value can be obtained at different combinations of loading frequency ω and temperature T, as long as ω₁f(T₁) = ω₂f(T₂). Considering a complex modulus test including various temperatures (T_i), this allows building a unique |E*| curve (log(|E*|), log(f)) by expressing the test results at an arbitrarily chosen reference temperature (T_{ref}). Applying the TTSP results in a shifting procedure of the |E*| isotherm points alongside the frequency axis to their equivalent frequency value:

$$f_{eq} = f_i \frac{f(T_i)}{f(T_{ref})} = f_i \times a_i(T_i, T_{ref}) \tag{7}$$

Equation 7 considers the shifting function as a shift factor a_i that depends on the test temperature and the chosen reference temperature. In this paper, the evolution of the shift factor is fitted by the Williams, Landel and Ferry (WLF) equation¹⁹:

$$\log(a_T) = \frac{-C_1(T - T_{ref})}{C_2 + T - T_{ref}} \tag{8}$$

Where C1 and C2 are the constants of the WLF equation. Validating the TTSP for bituminous materials requires the existence of a unique line of the complex modulus test results when plotted in the Cole-Cole and Black spaces. These are presented in section 6 of this paper.

3. Tested Materials

The gap-graded studied mixture, named GB5[®], was developed at the Centre for Studies and Research of the French road contractor *EIFFAGE Travaux Publics*. It is characterized by an optimized aggregate packing combined with the use of a SBS polymer modified binder (PMB). Two other French mixtures were tested: an “*enrobé à module élevé*” grade 2 (EME2) and a “*grave bitume*” grade 4 (GB4). These two materials are standardised French base-course mixtures (NF EN 13108-1)²⁰.

The granular structure of the mixtures is composed of virgin basaltic aggregates, limestone filler and reclaimed asphalt pavement (RAP) aggregates. The characteristics of the three mixtures are presented in Table 1 and the aggregates grading curves are given in Figure 3. The EME2 and GB4 mixtures

Table 1. Characteristics of the tested mixtures.

Mixture	Bitumen type (origin and grade)	Binder content [total mass %]	RAP content [total mass %]
"Enrobé à Module Elevé" grade 2	EME2	BP Lavéra Pen 20/30	19.1
"Grave Bitume" grade 4	GB4	BP Lavéra Pen 35/50	20
"Grave Bitume" grade 5	GB5®	Biprène® 41 R Pen 31	20

were made using pure bitumen. The GB5® contains modified bitumen called Biprène® 41R, which was developed by the company *EIFFAGE Travaux Publics*. Its base bitumen is the same as the one used for the EME2 mixture and it contains 2.5% in weight of reticulated SBS polymer.

The specimens were obtained from 600x400x140 mm slabs made in the laboratory using a wheel compactor according to the European standard EN 12697-33^[21]. They were cored and sawed to obtain cylindrical samples of 64.4 mm in diameter and 160 mm height. The coring direction was parallel to the compactor's wheel movement direction. The voids content of each sample was obtained by means of the gamma-ray method (NF EN 12 697-7)^[22]. Three samples were tested by material. Given the good repeatability of the tests, the results of only one test per material are presented of this paper. Table 2 presents the characterisation of the samples.

4. Performed Complex Modulus Tests

A hydraulic press is used to apply axial tension-compression sinusoidal loading to the cylindrical samples.

The axial strain amplitude (ϵ_x) was maintained constant at 25 μ m/m. The considered axial strain used for monitoring the test was the average of the measurements from three 100mm length extensometers disposed at 120° from one another, as shown in Figure 4. A load cell was used to measure the force applied to the sample; the axial stress (σ_1) was calculated. A temperature chamber was used to maintain the temperature conditions during the tests.

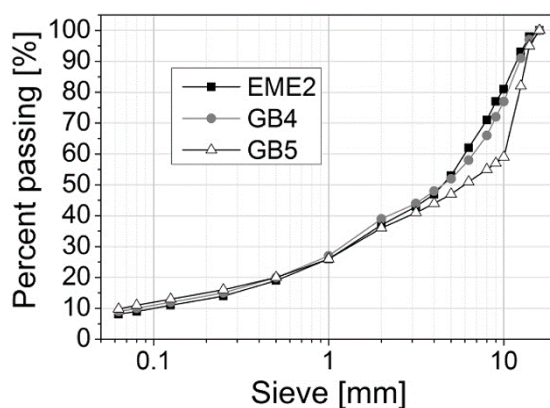
The used loading frequencies are shown in Figure 5. The samples were tested at each of those frequencies at seven different temperatures going from -25 °C to 45 °C. The used temperatures are presented on Figure 6. For this paper, each temperature change is considered a test stage. The lowest used frequency, 0.001Hz, was only applied during the stages at 35 °C and 45 °C whith the aim of observing the behaviour of the material at very low equivalent frequencies. For the stage at 45 °C, the 10Hz frequency was not tested. Less than 80 loading cycles were applied at each temperature-frequency couple. Previous studies demonstrate that this allows neglecting the heating problems due to viscous dissipation^{23,24}. In order to verify the integrity of the sample throughout the entire test, three stages at 15 °C were made at the beginning; middle and end of the test.

5. Modelling

The 2S2PID rheological model, developed in the Laboratory of Civil Engineering and Construction (LGCB) of the ENTPE/University of Lyon, was used for the presented simulation curves. It is a generalization of the Huet-Sayegh²⁵ model and consists of 2 springs, 2 parabolic creep elements and 1 dashpot^{13,14}. The authors have found

Table 2. Characteristics of the presented samples.

Sample	Mixture	Voids content [total mass %]	Max voids content allowed [total mass %]
ENL 7142-6	EME2	5.0	6.0
ENL 7144-3	GB4	6.5	8.0
ENL 7212-3	GB5®	4.7	6.0

**Figure 3.** Grading curve of the tested mixtures.**Figure 4.** Instrumented sample in temperature chamber.

the 2S2PID model to suitably describe the linear viscoelastic behaviour of most bituminous materials over a wide range of frequencies and temperatures^{13,14,26,27}. Equation 9 is the expression of E^* according to the 2S2PID model at a given temperature:

$$E^*(\omega) = E_{00} + \frac{E_0 - E_{00}}{1 + \delta(j\omega\tau)^{-k} + (j\omega\tau)^{-h} + (j\omega\beta\tau)^{-1}} \quad (9)$$

Where:

- ω is the pulsation, equal to $2\pi f$ with f the loading frequency.
- E_{00} is the static modulus ($\omega \rightarrow 0$). It is associated with the behaviour at low frequencies or high temperatures.
- E_0 is the glassy modulus ($\omega \rightarrow \infty$). It is associated with the behaviour high frequencies or low temperatures.
- δ is a calibration constant.
- j is the complex number ($j^2 = -1$).
- τ is the characteristic time which depends on the temperature. It can be expressed as a function of the shift factor a_T , $\tau(T) = a_T(T) \tau_0$, where τ_0 is determined at the reference temperature T_{ref} .
- k and h are constants defined such that $0 < k < h < 1$.
- β is a constant that depends on the viscosity of the dashpot: $\eta = (E_0 - E_{00})\beta\tau$.

Only 7 parameters (E_{00} , E_0 , δ , β , τ , k and h) are then required to completely characterise the LVE behaviour of

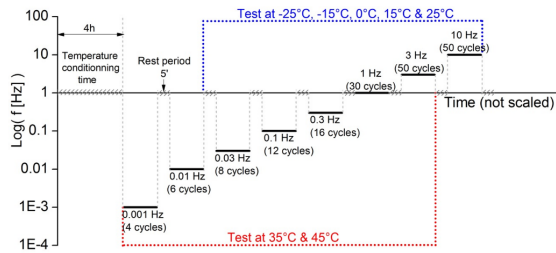


Figure 5. Tested frequencies for complex modulus test.

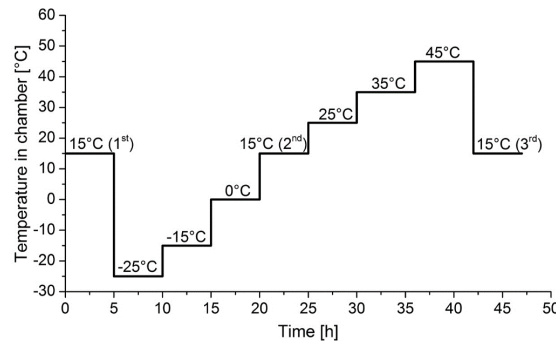


Figure 6. Applied temperatures for complex modulus test.

a bituminous material. The WLF constants of Equation 8, calculated at the reference temperature, are also needed if the temperature effect is to be considered. Figure 7 presents the analogical representation of the 2S2PID model and its parameters on a Cole-Cole diagram.

The values of the 2S2PID model and of the WLF equation are shown in Table 3 for each of the studied materials; including the binder in the GB5[®] mixture. These constants are used in all the simulation curves presented in the next sections.

6. Tests Results

6.1. Complex modulus

Figure 8 presents the isotherm $|E^*|$ and ϕ curves for a GB5[®] sample. These express the evolution of the complex modulus and its phase angle for each test temperature at the tested loading frequencies.

The dependence of $|E^*|$ and ϕ with temperature is observed. The complex modulus norm increases with the decrease of temperature, while the opposite is observed for the phase angle.

Figure 8 also shows the influence of the loading frequency. An increase in the loading frequency implies an increase of $|E^*|$. As for the phase angle, it decreases with the increase of the frequency for all temperatures from -25°C to 25°C . For higher temperatures, this tendency seems to be reversed. A maximum phase angle value is obtained near 0.03Hz at 34.4°C .

For the two highest temperatures, phase angles measured at 0.001Hz (dashed zone in Figure 8-right) do not fit with the other results. This is due to experimental limits of the test devices. For such a low frequency, the press is not able to impose a correct sinusoidal loading. The results at the lowest temperature tested (-25°C) seem to indicate an asymptotic behaviour of $|E^*|$ for very low temperatures.

Figure 9 presents the tests results for each of the studied mixtures in the Cole-Cole and Black diagrams. The Cole-Cole diagram expresses the relation between the real (E_1) and imaginary (E_2) components of the material modulus, while the Black's diagram expresses the relation between the material stiffness and its viscosity. Simulation curves, also plotted in Figure 9, are obtained with the 2S2PID model (cf. section 5). The used model constants are presented in Table 3. The existence of a unique line in both diagrams validates the application of the TTSP for all of the mixtures. The 3 materials can then be considered as "thermorheologically simple", at least as a first (and good) approximation.

The lower maximum values of E_2 and of the phase angle indicate a smaller viscous tendency of the GB5[®] mixture respect to the two regular French mixtures. The GB4 mixture reaches a maximal phase angle close to 45° , which is more

Table 3. Calibration parameters for the 2S2PID model for the tested materials at $T_{ref}=14.9^\circ\text{C}$.

Mixture	E_{00} [MPa]	E_0 [MPa]	k	h	δ	τ_0 [s]	β	C1	C2
EME2	180	38700	0.162	0.490	2.25	0.16	300	29.05	191.3
GB4	160	34800	0.163	0.530	1.95	0.3	100	24.85	161.5
GB5 [®]	200	37600	0.132	0.430	2.15	0.3	800	29.15	191.3
Biprène [®] 41 R	0	2700	0.132	0.430	2.15	$8 \cdot 10^{-7}$	$1.8 \cdot 10^6$	24.49	183.0

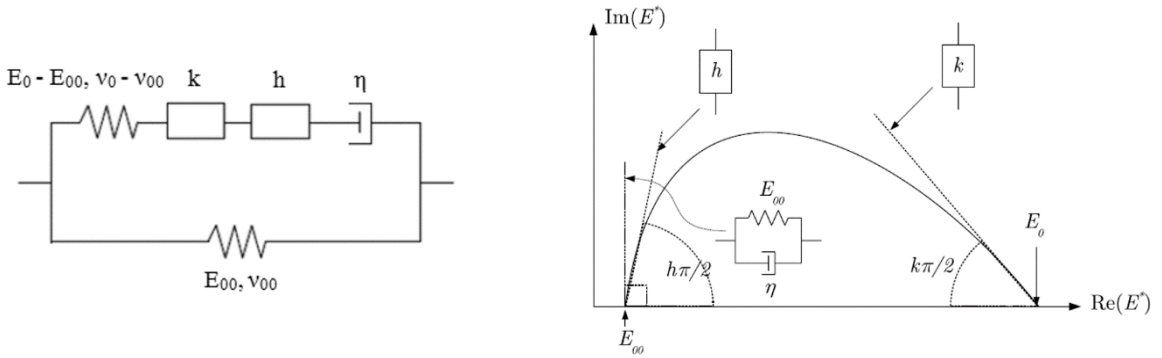


Figure 7. Analogical representation of the 2S2P1D Model (left)¹² and graphical representation of the model's parameters on a Cole-Cole diagram (right).

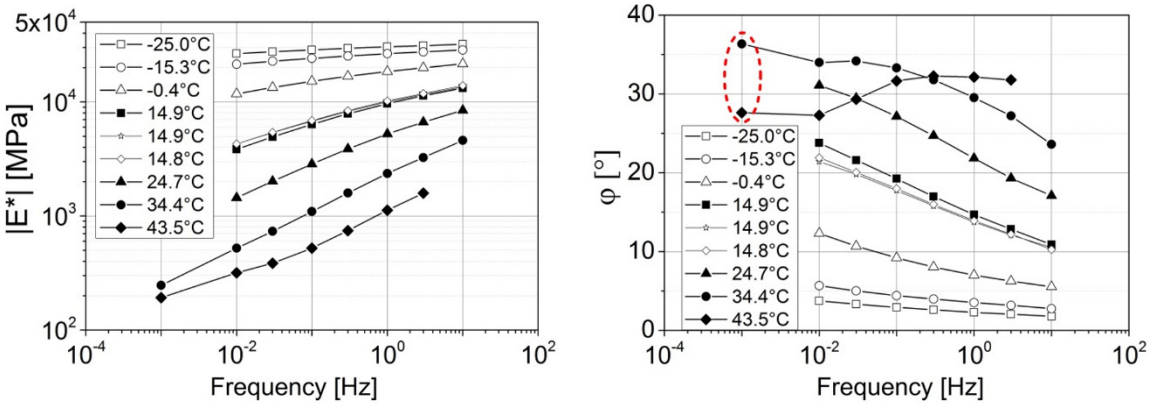


Figure 8. Experimental $|E^*|$ (left) and ϕ (right) isotherm curves - GB5[®] mixture – Dashed zone (right) corresponds to data at very low frequency and high temperature where system accuracy imply measurement error for phase angle.

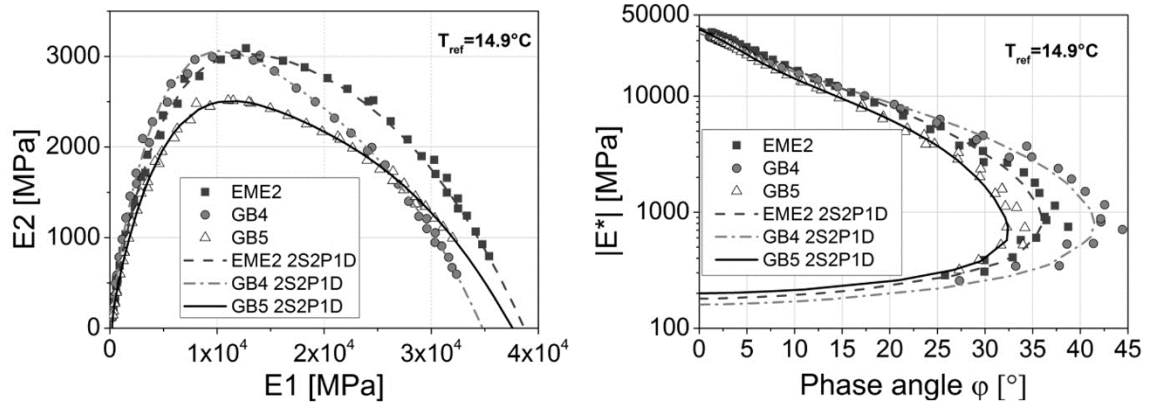


Figure 9. Cole-Cole (left) and Black (right) diagrams curves for each mixture.

than 10° higher than the GB5[®]s. As for the EME2 mixture, there is a difference of 5° between its maximal ϕ at that of the GB5[®]s. The GB5[®] glassy modulus E_0 (the maximal $|E^*|$ value) is higher than the GB4's and very close to the EME2's. It is important to note that the latter is a mixture specially designed to have high complex modulus values. These results show the positive effect of the optimized granular packing which increases inter-granular contacts and gives high mechanical properties to the GB5[®] mixture. Clear conclusions cannot be drawn for the static modulus

E_{00} due to the limitations of the experimental device at high temperatures and very low frequencies.

Master curves of $|E^*|$ and ϕ are plotted in Figure 10 for the GB5[®] mixture, and in Figure 11 for all three tested mixtures. Obtained shift factors (Equation 8), and their correspondent WLF fitting curves, are plotted in Figure 12. The chosen T_{ref} for this paper was 14.9°C ; then $a_1=1$ for the 14.9°C isotherms. The fitted shift factor a_1 associated to the GB5[®] mixture is very similar to the one of the EME2. It appears that SBS modification of the GB5[®] binder does

not affect the shift factor of the mixture. All fitting curves presented in Figures 10 and 11 are obtained from 2S2P1D model with constants given in Table 3.

The low phase angle values at high frequencies/low temperatures and low frequencies/high temperatures is an evidence of the more elastic behavior ($\varphi \rightarrow 0$) of bituminous mixtures at such extreme loading conditions. For high frequencies and low temperatures, the bitumen presents a very elastic behavior and it strongly influences the mixture behavior. For low frequencies/high temperatures the bitumen becomes very soft and the elastic aggregate structure dominates the mixture behavior. Bitumen polymer modification may, in part, explain the lower phase angle values developed at low frequencies by the GB5[®] mixture and its frequency offset of its maximum value respect to the other two mixtures. The optimized granular interlocking allows the GB5[®] mixture to maintain high modulus values at such extreme loading as the aggregates are in contact and able to undertake the efforts as the modified bitumen softens.

The simulation using the 2S2P1D model show a good fitting for both $|E^*|$ and φ . Nevertheless, the model hardly adjusts to the experimental values at very low frequencies, condition for which the experimental device also reaches its accuracy limit.

6.2. Dissipated viscous energy

During one loading cycle, dissipated energy due to viscous effects can be calculated for a unit volume using Equation 10:

$$W = \pi \cdot \sin(\varphi) \cdot \sigma_0 \cdot \varepsilon_0 \tag{10}$$

Experimental data presented in Figure 13 indicate the dissipated viscous energy obtained during the tests (at axial strain amplitude of 25 μ m/m) for the three tested materials. The curves represent the 2S2P1D model simulation results for two types of loading conditions: constant axial strain amplitude of $\pm 25\mu$ m/m and constant axial stress amplitude of 25kPa. The strain amplitude corresponds to that used for the presented complex modulus tests. The chosen stress amplitude value allows attaining a similar energy dissipation maximal value as the one found under constant strain of $\pm 25\mu$ m/m

In real working conditions, a pavement structure is loaded under a combination of both strain and stress modes^{28,29}. A clear difference on the energy dissipation curves is observed between the two piloting modes. It can be seen in Figure 13 that at constant stress amplitude, the maximum W value is reached at very low frequencies (circa 10⁻⁶Hz), while for a constant strain amplitude mode, the maximum W value is reached between 1Hz and 10Hz. On either case,

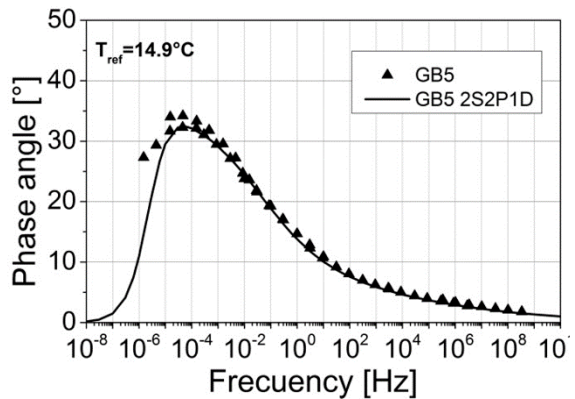
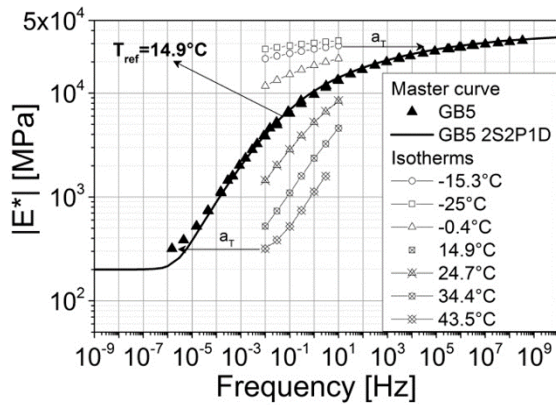


Figure 10. Master curves of the complex modulus (left) and phase angle (left) for GB5[®].

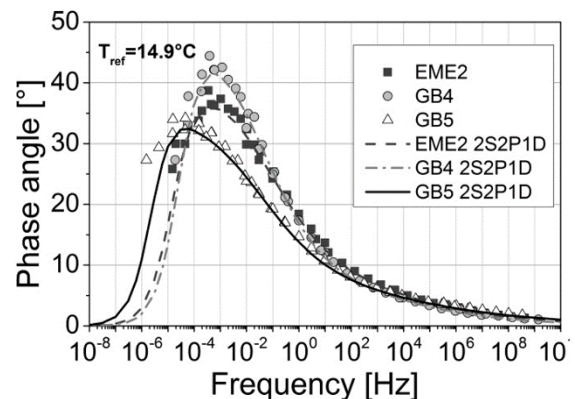
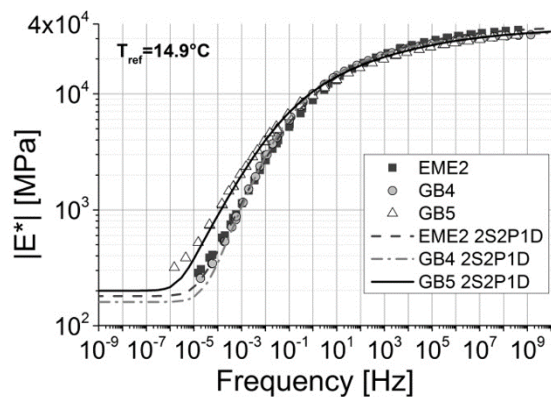


Figure 11. Master curves of the complex modulus (left) and phase angle (left).

the GB5® mixture presents lower maximal dissipated energy than the tested regular base-course mixtures. Given that the usual exiting frequencies in road structures are lower than 100Hz, the GB5® mixture is expected to dissipate less energy than the two other studied mixtures.

7. Mixture Complex Modulus Prediction from Binder Properties

The relation between bituminous mixture and binder complex moduli has been extensively studied^{13-16,26,27}. Equation 11 presents the SHStS transformation (for Shift, Homotety, Shift and time Shift) expression proposed by Di Benedetto and Olard¹³⁻¹⁶ that relates mixture and binder moduli:

$$E_{mix}^*(\omega, T) = E_{00\ mix} + \left[E_{binder}^*(10^\alpha \omega, T) - E_{00\ binder} \right] \frac{E_{0\ mix} - E_{00\ mix}}{E_{0\ binder} - E_{00\ binder}} \quad (11)$$

The proposed expression is independent of any rheological model. E_{00} and E_0 (glassy modulus) correspond to the minimum and maximum asymptotic values of $|E^*|$ either for the mixture (" $_{mix}$ ") or for the binder (" $_{binder}$ "), respectively. As mentioned on section 5, E_{00} is the static modulus, obtained at very low loading frequencies (and/or very high temperature), and E_0 is the glassy modulus, obtained at very high loading frequencies (and/or very low temperature). The exponent α is a constant that depends on the mixture.

The expression in Equation 11 corresponds to a transformation in the Cole-Cole diagram as explained on Figure 14. The points of the binder Cole-Cole curve are shifted of the $E_{00\ binder}$ value to the left along the E_1 axis. An intermediate Cole-Cole curve is then built with homothetic transformation of the shifted binder points. The points of this intermediate curve are then shifted of the $E_{00\ mix}$ value to the right along the E_1 axis in order to attain the Cole-Cole curve of the mixture. The points of the mixture Cole-Cole curve are associated to the same test temperature and to a frequency equal to $10^{-\alpha}$ times the frequency of the binder curve points.

Given the fact that binder E_{00} is either nil or much smaller than E_0 , Equation 11 can be simplified. Equation 12 takes into account this simplification as well as the hypothesis that the TTSP is verified for the binder.

$$E_{mix}^*(\omega, T) = E_{00\ mix} + \left[E_{binder}^*(10^\alpha \omega \alpha_T(T), T_{ref}) - E_{00\ binder} \right] \frac{E_{0\ mix}}{E_{0\ binder}} \quad (12)$$

Figure 15 shows the results of the predicting procedure for $|E^*|$ of the GB5® mixture. The binder tests results and 2S2P1D simulations are also presented. The comparison between the predicted and the experimental values shows that the transformation method gives good results. The complex modulus of the binder was obtained using a Dynamic Shear Rheometer - DSR (NF EN 14770)³⁰ at the Research Centre of *EIFFAGE Travaux Publics*. The tested binder was the virgin Biprène® 41R, so it does not take into account the RAP binder contribution. Figure 16 presents the experimental shift factor a_T and the fitting curves obtained with the WLF equation (cf. section 2). The results confirm that the shift factor values for both binder and mixture are close to each other. The results presented in this section confirm the findings on the subject found in the literature³¹⁻³⁹ as well as the powerful general approach developed at the ENTPE laboratory team in Lyon.

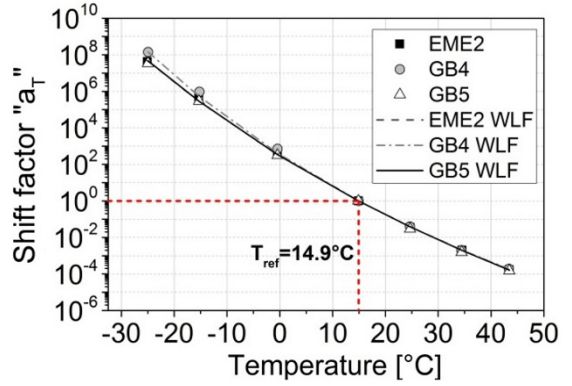


Figure 12. a_T coefficient for each mixture.

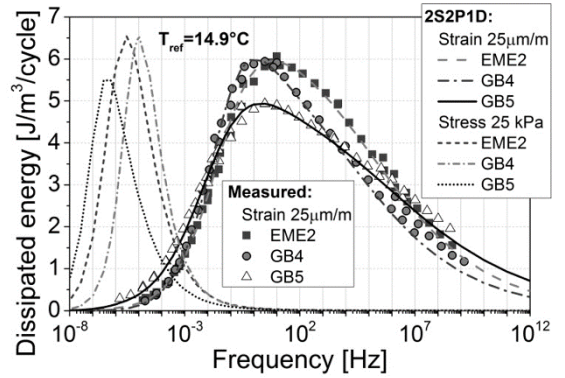


Figure 13. Viscous energy dissipation curves for each mixture – Strain and stress control modes.

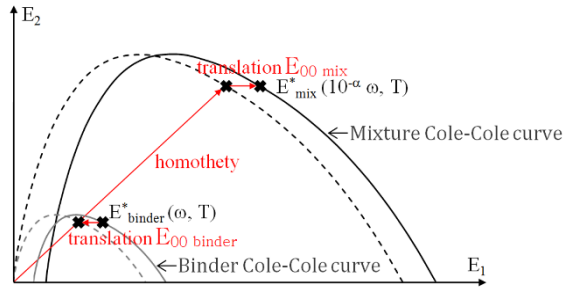


Figure 14. Geometrical transformation of the binder Cole-Cole diagram for prediction of the mixture modulus.

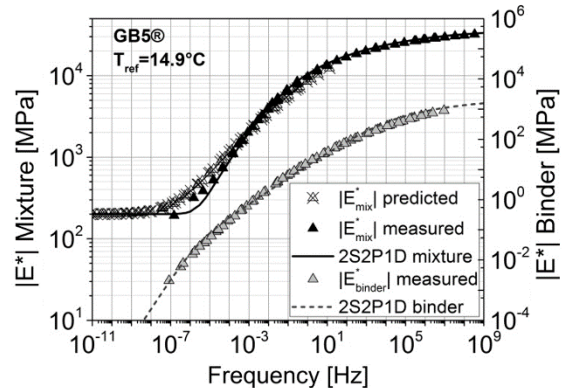


Figure 15. Measured master curves of $|E^*|$ of the GB5® mixture and its binder and predicted-from-binder $|E^*|$ master curve of the GB5® mixture.

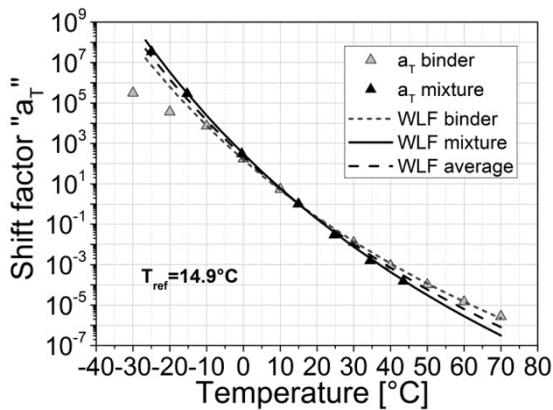


Figure 16. Shift factor a_T for the GB5[®] mixture and its binder and comparison with the WLF equation fit.

8. Conclusions

The linear thermo-viscoelastic behaviour of an innovative gap-graded base-course asphalt mixture, called GB5[®], with polymer-modified bitumen is presented in this paper.

This was made by means of the complex modulus test on cylindrical samples under tension-compression loading. The GB5[®] mixture was compared to two standardized and commonly used base-course French mixtures. It was found to have slightly different viscous behaviour than the other two tested mixtures. The GB5[®] mixture presents a better performance at high temperatures and/or low frequencies,

which may be of practical interest for road design. This was mainly attributed to the mixture's optimized gap gradation.

The studied GB5[®] mixture reaches the performances of a high-performance mixture, EME type, while using a low quantity of softer bitumen and by optimizing the aggregates packing. The GB5[®] mixture presents high modulus values associated with lower phase angle values compared to the EME mixture. This is most probably due to the optimized granular interlocking of the GB5[®] mixture. Moreover, its mechanical performances were not compromised by the inclusion of RAP. Given the actual economic and ecological context, this represents a noticeable advantage over regular base-course mixtures used in France. Nevertheless, other properties must also be studied, such as its fatigue resistance, in order to validate its use as a base-course mixture.

The 2S2P1D model was used to simulate the LVE behaviour of the tested mixtures. The presented results of the simulation prove that the 2S2P1D model represents a powerful tool for the study of bituminous materials in the linear viscoelastic domain.

The SHStS transformation expression¹³⁻¹⁶ was used to establish the relation between the GB5[®] mixture and its binder complex moduli. This expression was found to accurately predict the complex modulus master curve of the mixture. It was observed that the shift factors a_T of the polymer-modified binder and of the GB5[®] mixture are nearly identical. The polymer modification of the GB5[®] binder doesn't seem to alter the fact that the TTSP of the mixture directly depends on that of binder, which confirms results already found for other types of mixtures by the ENTPE team of Lyon¹³⁻¹⁶.

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