1 PREDICTION OF ISOTROPIC LINEAR VISCOELASTIC BEHAVIOR FOR BITUMINOUS MATERIALS – FORWARD AND INVERSE PROBLEMS

S. Pouget[1], C. Sauzeat[2], H. Di Benedetto[2], F. Olard[1]
[1] EIFFAGE Travaux Publics – R&D Department
8, rue du Dauphiné 69960 Corbas, FRANCE
simon.pouget@eiffage.com; francois.olard@eiffage.com
[2] University of Lyon – ENTPE/DGCB
3, rue Maurice Audin 69518 Vaulx-en-Velin, FRANCE
cedric.sauzeat@entpe.fr; herve.dibenedetto@entpe.fr

ABSTRACT

Due to economic and environmental benefits, the development of new road materials such as polymer modified materials, Reclaimed Asphalt Pavement (RAP), etc., has become a top priority. It is therefore essential to develop tools to determine mechanical properties of these materials while avoiding lengthy and costly laboratory studies. A number of models were developed and used to predict composite bituminous asphalt properties from properties of single components. This type of approach is generally known as forward problem. Recently, researchers started to investigate the possibility of predicting bitumen properties from asphalt properties (inverse problem).
In this paper both forward and inverse problems are investigated for materials obtained from two types of bitumen: pure bitumen and polymer modified bitumen. Experimental measurements of bitumen complex modulus are performed with a Dynamic Shear Rheometer (DSR), while bituminous asphalt complex modulus is measured using the three-dimensional complex modulus test developed at ENTPE ("Ecole Nationale des Travaux Publics de l'Etat"). First, the forward problem of predicting bituminous asphalt three-dimensional linear viscoelastic properties from bitumen one-dimensional linear viscoelastic properties is investigated using the proposed ENTPE SHStS transformation. This transformation in the complex plane allows asphalt behaviour to be predicted easily and efficiently from bitumen complex modulus on both large frequency and temperature ranges. Then, the same transformation is applied to obtain bitumen properties from asphalt properties (inverse problem). It is shown that the transformation can be successfully used for both forward and inverse problems. This prediction tool could be really helpful in laboratory for practical design of bituminous asphalts.

Key words: bituminous materials, linear viscoelastic behaviour, prediction tool, forward and inverse problems, ENTPE SHStS transformation

2 INTRODUCTION

2.1 Context

This study has been realized within the framework of a partnership between the “DGCB” (French acronym for “Building and Civil Engineering Department”) of the “ENTPE” (French acronym for “National School of Public Works”) and the company EIFFAGE Travaux Publics.

2.2 Objectives

Due to economic and environmental benefits, the development of new road materials such as polymer modified materials, Reclaimed Asphalt Pavement (RAP), etc., has become a top priority. It is therefore essential to develop tools to determine mechanical properties of these materials while avoiding lengthy and costly laboratory studies. A number of models were developed and used to predict composite bituminous asphalt properties from properties of single components. This type of approach is generally known as forward problem [1] [2] [3] [4] [5] [6] [7] [8] [9] [10] [11] [12] [13]. Recently, researchers started to investigate the possibility of predicting bitumen properties from asphalt properties (inverse problem) [14].

In this paper both forward and inverse problems (Figure 1) are investigated for materials obtained from two types of bitumen: pure bitumen and polymer modified bitumen. Experimental measurements of bitumen complex modulus are performed with a Dynamic Shear Rheometer (DSR), while bituminous asphalt complex modulus is measured using the three-dimensional complex modulus test developed at ENTPE. First, the forward problem of predicting bituminous asphalt three-dimensional linear viscoelastic properties from bitumen one-dimensional linear viscoelastic properties is investigated using the proposed ENTPE SHStS transformation. This transformation in the complex plane allows asphalt behaviour to be predicted easily and efficiently from bitumen complex modulus on large frequency and temperature ranges. Then, the same transformation is applied to obtain bitumen properties from asphalt properties (inverse problem). It is shown that the transformation can be successfully used for both forward and inverse problems. This prediction tool could be really helpful for practical design of bituminous asphalts.

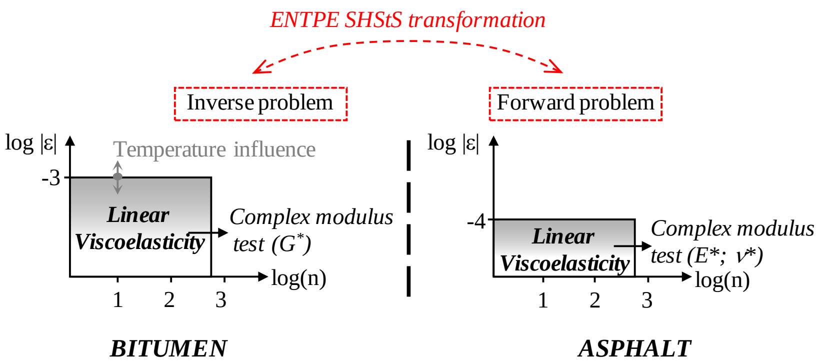

Figure 1: Linear viscoelastic domains for bitumen and asphalts in the axes log(strain amplitude)-log(number of cycles). The link between the two behaviours is presented section 3.2.

3 PREDICTION OF ISOTROPIC LINEAR VISCOELASTIC BEHAVIOR FOR BITUMINOUS MATERIALS

In this paper, only linear behaviour is considered (small strain domain). Non-linearity (fatigue, permanent deformations, cracks) is not taken into account.

3.1 Advanced viscoelastic characterization of bituminous materials

3.1.1 Experimental approach

Complex modulus tests on bitumen were performed at the EIFFAGE Travaux Publics laboratory using a Dynamic Shear Rheometer (DSR) over a frequency range from 1 to 100Hz and a temperature range from -30°C to 70°C. Equations (1) and (2) are used to determine complex shear modulus $G^*(\omega)$.

$$G^*(\omega) = \frac{\tau^*}{\gamma^*} = \left|G^*(\omega)\right| e^{j\phi_G} = \frac{\tau_0}{\gamma_0}.e^{j(\phi_\tau - \phi_\gamma)} \quad (1)$$

$$G_1 = \left|G^*\right|.\cos(\phi_G) \text{ and } G_2 = \left|G^*\right|.\sin(\phi_G) \quad (2)$$

where:

$\tau(t) = \tau_0.\sin(\omega t + \phi_\tau)$ is the shear stress;

$\gamma(t) = \gamma_0.\sin(\omega t + \phi_\gamma)$ is the shear strain;

ϕ_G is the phase angle between shear strain and shear stress (phase angle of complex modulus).
As behaviour is supposed isotropic, relation (3) is considered. It allows to obtain E*. For bitumen, a constant Poisson's ratio "ν" equal to 0.5 is considered (incompressibility), which is an approximation as shown by [15]. In this case, $\phi_E = \phi_G$.

$$E^*(\omega) = \frac{G^*(\omega)}{2(1+\nu)} \tag{3}$$

Complex modulus tests on bituminous asphalts were performed in tension/compression mode to characterize linear viscoelastic behaviour in the small strain domain ($\varepsilon < 10^{-4}$). Test principle is described in Figure 2. It should be noted that radial strain measurements (ε_r) are added to classical axial stress (σ_z) and strain measurements (ε_z) (Figure 2). Measured sinusoidal signals (Figure 2) are expressed in complex form (equation (4)).

$$\begin{cases} \sigma_z^* = \sigma_{0z}.e^{j(\omega t)} \\ \varepsilon_z^* = \varepsilon_{0z}.e^{j(\omega t + \phi_{\varepsilon_z})} \\ \varepsilon_r^* = \varepsilon_{0r}.e^{j(\omega t + \phi_{\varepsilon_r})} \end{cases} \tag{4}$$

Where σ_{0z}, ε_{0z} and ε_{0r} are amplitudes and 0, $\phi_{\varepsilon z}$ and $\phi_{\varepsilon r}$ phase lags of respectively axial stress, axial strain and radial strain.
Complex Young's modulus E* and complex Poisson's ratio ν* are then obtained using equations (5) and (6). They are defined with their norm and phase angle, respectively |E*| and ϕ_E for complex Young's modulus and |ν*| and ϕ_ν for complex Poisson's ratio.

$$E^* = \frac{\sigma_z^*}{\varepsilon_z^*} = |E^*| e^{j\phi_E} = \frac{\sigma_{0z}}{\varepsilon_{0z}}.e^{j(\phi_{\varepsilon_z})} \tag{5}$$

$$\nu^* = -\frac{\varepsilon_r^*}{\varepsilon_z^*} = |\nu^*| e^{j\phi_\nu} = -\frac{\varepsilon_{0r}}{\varepsilon_{0z}}.e^{j(\phi_{\varepsilon_r} - \phi_{\varepsilon_z})} \tag{6}$$

With the postulated hypothesis of isotropy, three-dimensional (3D) linear viscoelastic behaviour is completely determined by E* and ν*.

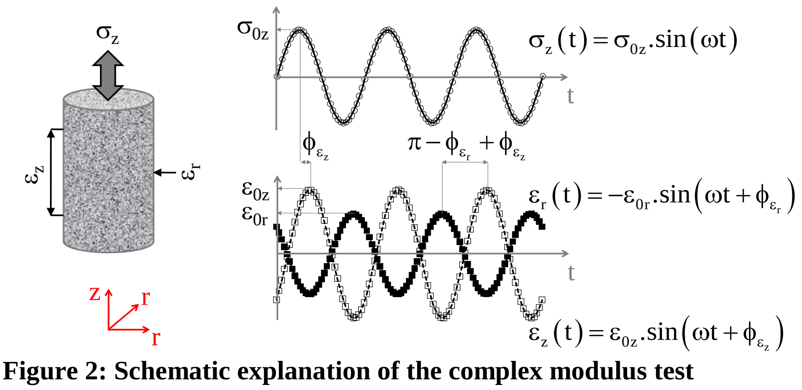

Figure 2: Schematic explanation of the complex modulus test

Measurements were made at 9 different temperatures (from -30°C to 50°C), sweeping 7 frequencies from 0.01Hz to 10Hz. From experimental data, the Time Temperature Superposition Principle (TTSP) is considered as a first approximation (some discrepancy appears at very low frequencies and/or for high temperatures polymer modified materials). In this paper, complex Young's modulus E* and complex Poisson's ratio ν* master curves are plotted at a reference temperature (T_{ref}) of 10°C. The classical WLF law (William, Landel and Ferry) [16] is used to fit shift factors a_T (equation (7)).

$$\log(a_T) = -\frac{C_1(T - T_{ref})}{C_2 + T + T_{ref}} \tag{7}$$

Where T is the considered temperature, T_{ref} is the reference temperature and C_1 and C_2 are constants depending on the material.

3.1.2 Viscoelastic modelling using the 2S2P1D model

The 2S2P1D (2 Springs, 2 Parabolic, 1 Dashpot) model, introduced in 2003 [9] and developed at the DGCB, consists of a generalization of the Huet-Sayegh model [17]. It is valid for any bituminous material: bitumen, mastic or asphalt [7] [9] [10]. This model is based on a simple combination of physical elements (spring, dashpot and parabolic element). The analogical representation of the 2S2P1D model is given in Figure 3. The considered version of the 2S2P1D model in 3D is able to simulate three-dimensional isotropic behaviour of bituminous materials.

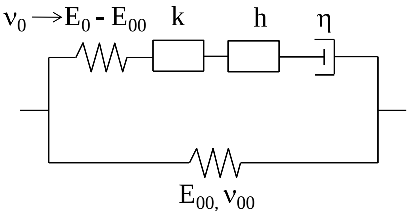

Figure 3: Representation of 2S2P1D model

At a given temperature, the introduced 2S2P1D model has 9 constants. Complex modulus and complex Poisson's ratio are respectively given by expressions (8) and (9).

$$E^*_{2S2P1D}(j\omega\tau) = E_{00} + \frac{E_0 - E_{00}}{1 + \delta(j\omega\tau)^{-k} + (j\omega\tau)^{-h} + (j\omega\beta\tau)^{-1}} \tag{8}$$

$$\nu^*_{2S2P1D}(j\omega\tau) = \nu_{00} + (\nu_0 - \nu_{00}) \cdot \frac{E^*_{2S2P1D}(\omega) - E_{00}}{E_0 - E_{00}} \tag{9}$$

Where:
j is the complex number defined by $j^2 = -1$
ω is the pulsation, $\omega = 2\pi f$, (f is the frequency)
k, h: exponents such as $0 < k < h < 1$
δ: constant
E_{00}: static modulus when $\omega \to 0$
E_0: glassy modulus when $\omega \to \infty$
ν_{00}: static Poisson's ratio when $\omega \to 0$
ν_0: glassy Poisson's ratio when $\omega \to \infty$
η: Newtonian viscosity of the dashpot, $\eta = (E_0 - E_{00})\beta\tau$
τ: characteristic time, whose value varies only with temperature (equation (10))

$$\tau(T) = a_T(T).\tau_0 \tag{10}$$

Where a_T is the shift factor at the temperature T.
At a given temperature, 9 constants (E_{00}, E_0, δ, k, h, β, τ_0, ν_{00}, ν_0) are required to completely characterize linear viscoelastic properties of considered material. τ evolution is approximated by a WLF-type law (equation (7)) [16]. In this paper $\tau_0 = \tau(T_{ref})$ is determined at the reference temperature $T_{ref} = 10°C$. When temperature effect is considered, the number of constants amounts to 11 including the 2 WLF constants (C_1 and C_2 calculated at the reference temperature).

3.2 ENTPE SHStS transformation

A lot of work has already been done and presented in the literature to relate bitumen and asphalt moduli for a given asphalt design ([1] [3] [4] [6] [7] [8] [9] among others).
In this paper, the obtained relationship between bitumen and asphalt complex moduli, based on the developments made in DGCB by Di Benedetto and Olard (for both phase angle and norm of the complex moduli), is proposed and extended in the three-dimensional case. Even though this relationship was built with the help of 2S2P1D model, presented in section 3.1.2, it is independent of any rheological model.
In addition, this transformation is completely reversible and allows treatment of both forward and reverse problems.
The following relationship between asphalt and bitumen complex moduli is proposed (equation (11)).

$$E^*_{asphalt}(\omega,T) = E_{00\_asphalt} + \left[E^*_{bitumen}(10^{\alpha}\omega,T)\text{-}E_{00\_bitumen}\right]\frac{E_{0\_asphalt} - E_{00\_asphalt}}{E_{0\_bitumen} - E_{00\_bitumen}} \tag{11}$$

$E_{00\_asphalt}$ and $E_{0\_asphalt}$ (resp. $E_{00\_bitumen}$ and $E_{0\_bitumen}$), more widely known as "static modulus" and "glassy modulus", respectively correspond to the minimum and maximum asymptotic values of the norm of complex modulus of asphalt (resp. of bitumen), respectively at very low frequencies and high frequencies. The additional parameter α depends on the considered asphalt design and/or ageing during mixing.
Considering that $E_{0\_bitumen}$ (resp. $E_{0\_asphalt}$) is much higher than $E_{00\_bitumen}$ (resp. $E_{00\_asphalt}$), equation (11) can thus be simplified in first approximation by equation (12).

$$E^*_{asphalt}(\omega,T) = E_{00\_asphalt} + E^*_{bitumen}(10^{\alpha}\omega,T)\frac{E_{0\_asphalt}}{E_{0\_bitumen}} \tag{12}$$

If the bitumen complex modulus is known at a given temperature T, equation (11) gives the asphalt complex modulus at this temperature T considering only three constants: $E_{00\_asphalt}$, $E_{0\_asphalt}$ and α.
If Time-Temperature Superposition Principle (TTSP) is verified for bitumen, then the following property can be added (idem for asphalts):

$$E^*_{bitumen}(10^{\alpha}\omega,T) = E^*_{bitumen}(10^{\alpha}\omega a_T(T),T_{ref}) \tag{13}$$

Where $a_T(T)$ is the shift factor at temperature T for bitumen and T_{ref} is the reference temperature.
It should be underlined that equation (11) is very simple and covers the whole frequency-temperature range. Indeed, equation (11) corresponds to a simple geometric transformation of the bitumen curve in the Cole-Cole plane, called ENTPE SHStS (for "Shift – Homothety – Shift – time Shift") transformation. Figure 4 explains how to practically obtain asphalt modulus from the bitumen one.

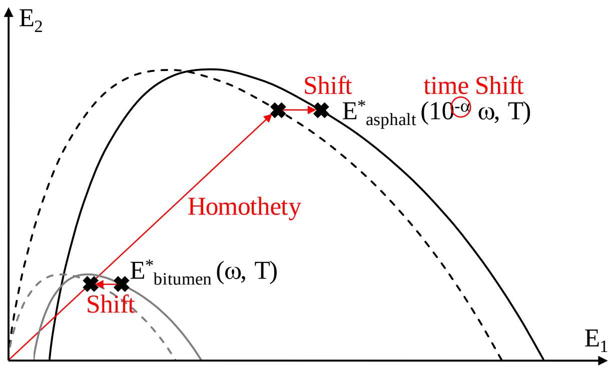

Figure 4: One-dimensional schematic of SHStS transformation in Cole-Cole plane

Starting from bitumen complex modulus $E^*_{bitumen}(\omega,T)$ at a pulsation ω and a temperature T, three steps have to be carried out to obtain asphalt modulus $E^*_{asphalt}(10^{-\alpha}\omega,T)$ at a pulsation $10^{-\alpha}\omega$ and the same temperature T:
i) a negative shift along the real axis of $E_{00\_bitumen}$ value (we also can consider $E_{00\_bitumen} \approx 0$ and skip this step if the frequency is not too low);

ii) an homothetic expansion from the origin with a ratio of $\dfrac{E_{0\_asphalt} - E_{00\_asphalt}}{E_{0\_bitumen} - E_{00\_bitumen}}$;

iii) a positive shift along the real axis of $E_{00\_asphalt}$ value.

As already shown by [7] and [10], equation (11) which is independent of any rheological model appears as a powerful predicting tool for asphalt modulus prediction from bitumen modulus. Complex modulus of any bitumen is sufficient to predict complex modulus of the corresponding asphalt. Indeed, static and glassy moduli of the corresponding asphalt design are known. If another asphalt composition is considered, $E_{00\_asphalt}$ (resp. $E_{0\_asphalt}$) could be obtained in a simple way by performing complex modulus tests at high temperatures and low frequencies (resp. low temperatures and high frequencies). Consequently, tremendous asphalt testing work could be saved, at least for the purpose of first estimates in the small strain domain (linear viscoelasticity).

The generalization to the three-dimensional case of the previous developments was more recently studied by [13] [15] [18] [19] [20] [21] [22]. The generalization keeps the general concept and structure of the unidirectional case and can be schematized by Figure 5. Equation (14) is used to predict asphalt complex Poisson's ratio evolution from bitumen experimental values. Equation (14) can be simplified as a first approximation by equation (15).

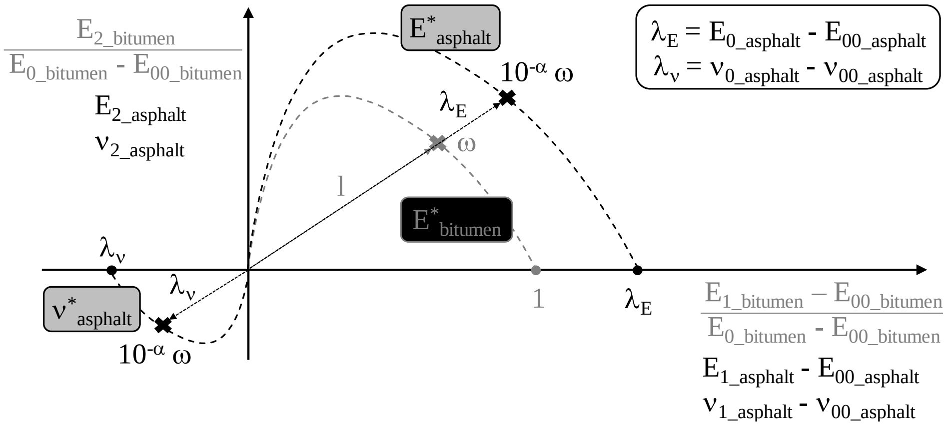

Figure 5: Three-dimensional schematic of SHStS transformation in Cole-Cole plane with normalized axis

$$\nu^*_{asphalt}(\omega, T) = \nu_{00\_asphalt} + \left(\nu_{0\_asphalt} - \nu_{00\_asphalt}\right).\frac{E^*_{bitumen}(10^{\alpha}\omega, T) - E_{00\_bitumen}}{E_{0\_bitumen} - E_{00\_bitumen}} \tag{14}$$

$\nu_{00\_asphalt}$ and $\nu_{0\_asphalt}$ respectively correspond to the minimum and maximum asymptotic values of the norm of complex Poisson's ratio of asphalt, respectively at very low and high frequencies.

$$\nu^*_{asphalt}(\omega, T) = \nu_{00\_asphalt} + \left(\nu_{0\_asphalt} - \nu_{00\_asphalt}\right).\frac{E^*_{bitumen}(10^{\alpha}\omega, T)}{E_{0\_bitumen}} \tag{15}$$

Finally, if bitumen complex modulus is known at a given temperature T, asphalt three-dimensional complex behaviour in the linear domain at this temperature T is completely defined considering only five constants: $E_{00\_asphalt}$, $E_{0\_asphalt}$, $\nu_{00\_asphalt}$, $\nu_{0\_asphalt}$ and α.

4 APPLICATION TO ROAD MATERIALS

This section focuses on the validation of both forward (section 4.1) and reverse (section 4.2) problems using ENTPE SHStS transformation proposed in equations (11) and (14) (respectively for complex modulus and complex Poisson's ratio). With this intention, a study on two bituminous asphalts produced with the same asphalt design (continuous 0/10 mm aggregates grading with 6% bitumen content (by aggregate weight) was carried out:
- E5070 asphalt produced with a 50/70 penetration grade pure bitumen called B5070;
- Polymer-Modified Asphalt (PMA) produced with a highly Polymer-Modified Bitumen (PMB) (more than 7% of SBS content with cross linking procedure).

4.1 Forward problem

Figure 6 (resp. Figure 7) represents complex modulus and complex Poisson's ratio experimental values of E5070 (resp. PMA) asphalt and the corresponding predicted values, obtained using equations (11) and (14), considering experimental data from B5070 (resp. PMB) bitumen and constants from 2S2P1D model (excepted α obtained by fit) and listed in Table 1.

Figure 6 reveals that ENTPE SHStS transformation successfully simulates E5070 asphalt complex modulus E* and complex Poisson's ratio ν* (for norm and phase angle) from experimental data issued form pure bitumen B5070 on a large range of frequencies and temperatures.
In Figure 7, it can be observed that PMA and PMB do not conform very well to TTSP at high temperatures. This is an expected result, due to the high content of polymer. In order not to overload the formalism, the simplification of considering TTSP respected is introduced in the modelling tool. Nevertheless, predicted curves correctly describe the evolution of complex modulus E* and of complex Poisson's ratio ν*. This observation is particularly valid for low temperatures, where TTSP is well respected.

Table 1: Constants used to predict isotropic linear viscoelastic behaviour of considered bituminous materials

Bituminous materials	$E_{0\_bitumen}$	$E_{00\_bitumen}$	$E_{0\_asphalt}$	$E_{00\_asphalt}$	$\nu_{0\_asphalt}$	$\nu_{00\_asphalt}$	α
B5070 & E5070	1800 MPa	0 MPa	36000 MPa	10 MPa	0.22	0.50	2.10
PMB & PMA	3250 MPa	0.006 MPa	41500 MPa	15 MPa	0.30	0.46	3.33

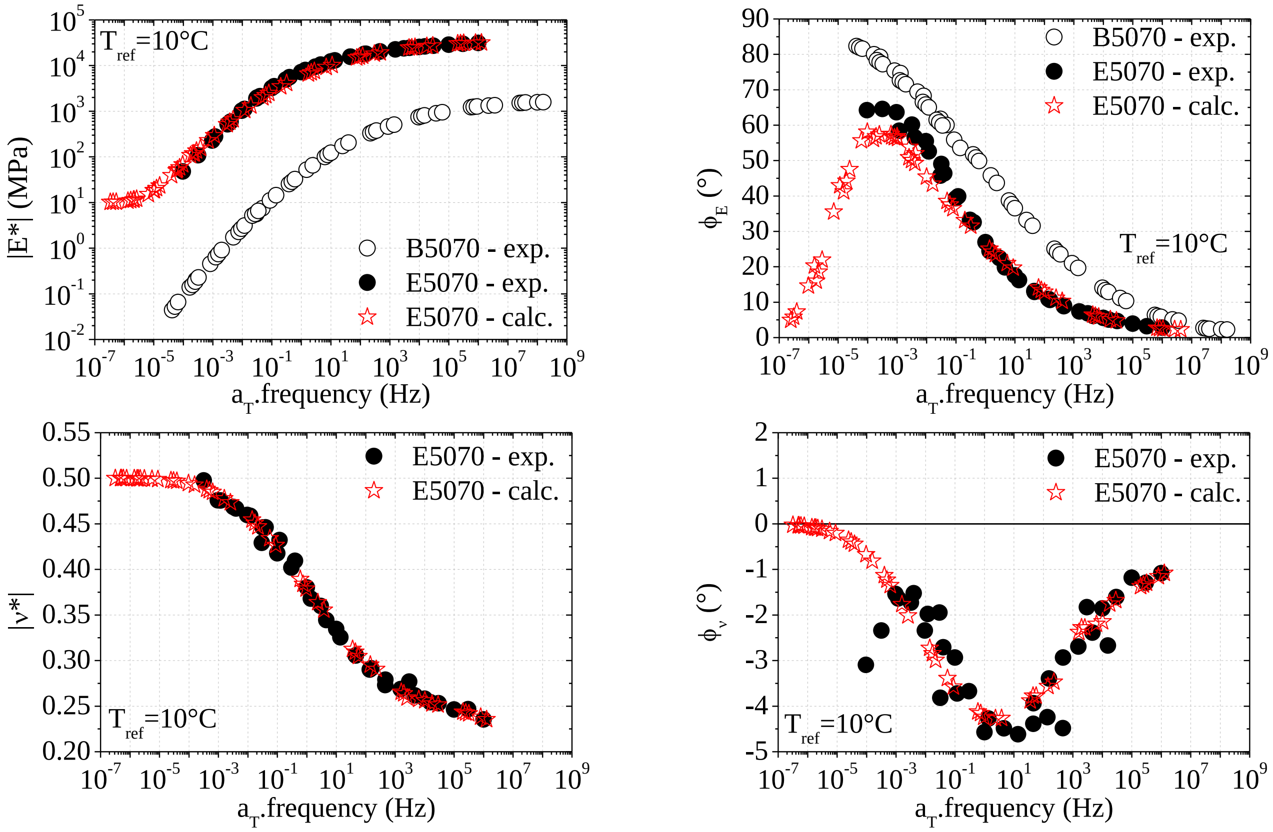

Figure 6: Experimental data from E5070 asphalt and prediction from equations (11) and (14) using experimental data of the introduced B5070 bitumen, at a reference temperature T_{ref}=10°C.
Above Left: norm of complex Young's modulus |E*|; Above Right: complex modulus' phase angle ϕ_E
Below Left: norm of complex Poisson's ratio |ν*|; Below Right: complex Poisson's ratio phase angle ϕ_ν

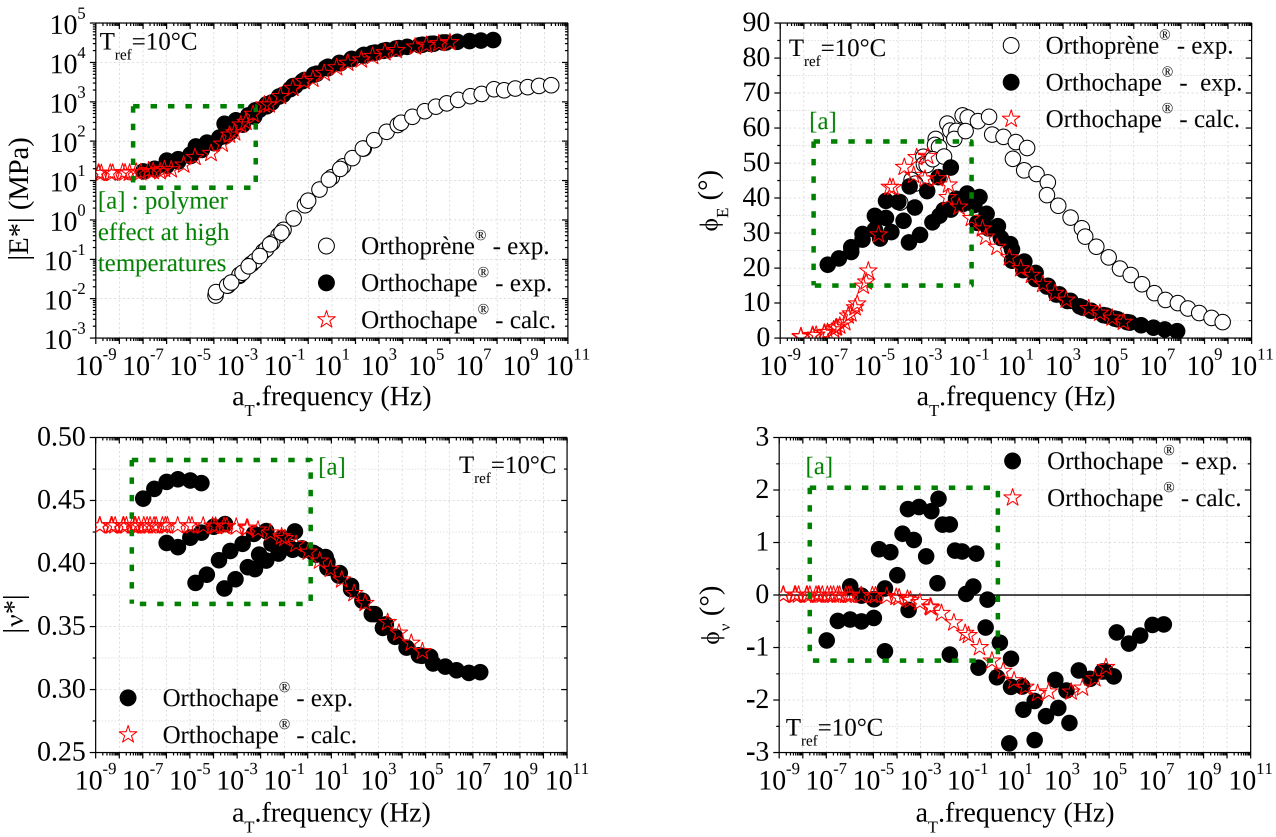

Figure 7: Experimental data from PMA and prediction from equations (11) and (14) using experimental data of the introduced PMB, at the reference temperature T_{ref}=10°C.
Above Left: norm of complex Young's modulus |E*|; Above Right: complex modulus' phase angle ϕ_E
Below Left: norm of complex Poisson's ratio |ν*|; Below Right: complex Poisson's ratio phase angle ϕ_ν

4.2 Inverse problem

Dealing with inverse problem can be particularly helpful for study of RAP materials. SHStS transformation allows predicting bitumen complex modulus from RAP complex modulus.

As a example, Figure 8 (resp. Figure 9) represents complex modulus experimental values of B5070 (resp. PMB) bitumen and the corresponding predicted values, obtained using equations (11) and (14) (which are completely reversible) considering experimental data from E5070 (resp. PMA) asphalt and constants listed in Table 1.
Similar conclusions as for forward problem can be drawn. Complex modulus prediction of pure bitumen using ENTPE SHStS transformation gives good simulation. Considering PMB and PMA, due to the high polymer content, complex modulus prediction at high temperatures is not perfect. However predicted curves adequately describe the evolution of complex modulus E*. This observation is validated for low temperatures, where TTSP is well respected.

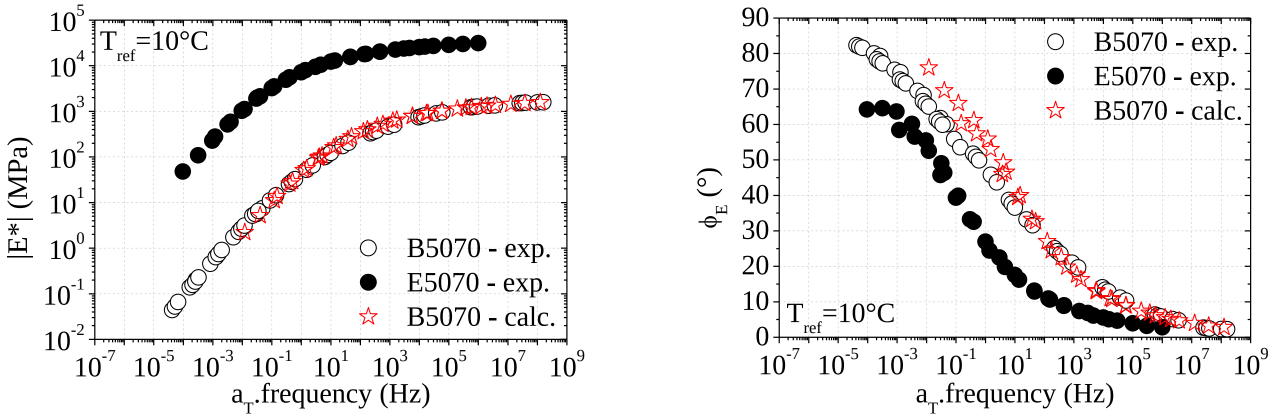

Figure 8: Experimental data from B5070 bitumen and prediction from equation (11) using experimental data of the introduced E5070 asphalt (also plotted), at the reference temperature T_{ref}=10°C.
Left: norm of complex Young's modulus |E*|; Right: complex modulus' phase angle ϕ_E

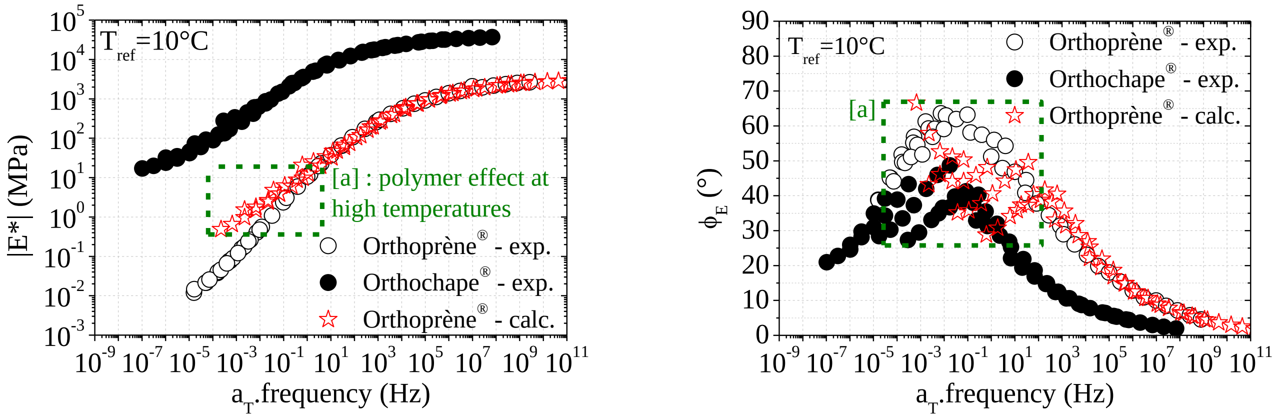

Figure 9: Experimental data from PMB and prediction from equation (11) using experimental data of the introduced PMA (also plotted), at the reference temperature T_{ref}=10°C.
Left: norm of complex Young's modulus |E*|; Right: complex modulus' phase angle ϕ_E

4.3 Summary

As already established by our team, the shift factor a_T is a bitumen characteristic. Its value remains the same (as a first approximation) for any mixture produced with the considered bitumen regardless of the added solid aggregates (mastic or asphalt) [2] [5] [11] [12] [13]. Figure 10 confirms this observation for E5070 mix made with 6% of B5070 pure bitumen.
However, considering PMA made with 6% of PMB, differences appear at high temperatures (at T>30°C, where the TTSP is not well-verified) due to polymer effect. This might explain the deviation observed between experimental and predicted values (for E* and ν*).

As introduced by [13], complex modulus values can be plotted in a normalized Cole-Cole diagram to obtain a unique curve for asphalt and its constitutive bitumen. This representation is proposed for the two studied materials in Figure 11. A unique curve is observed.

Finally, these developments are complementary to those realized by Olard and Di Benedetto [7] and Olard [9]. As illustrated in Figure 12, α constant used for SHStS transformation, can be determined considering logarithms of $\tau_{0\_bitumen}$ and $\tau_{0\_asphalt}$ (issued from equation (10)). For a reference temperature of 10°C respectively for bitumens and asphalts, $\tau_{0\_bitumen}$ and $\tau_{0\_asphalt}$ are well correlated ($r^2 = 0.89$) using equation (16).

$$\tau_{0\_asphalt} = 10^{\alpha}.\tau_{0\_bitumen} \qquad (16)$$

with α = 2.764, probably depending on asphalt design and ageing during mixing .

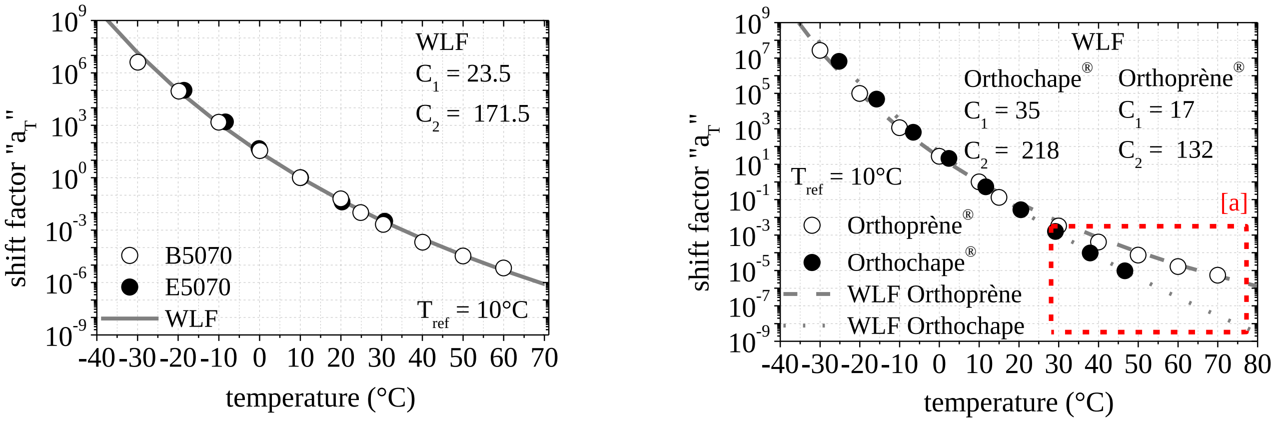

Figure 10: Experimental shift factors a_T and comparison with WLF simulation (equation (7))
Left: E5070 asphalt and B5070 bitumen; Right: PMA and PMB

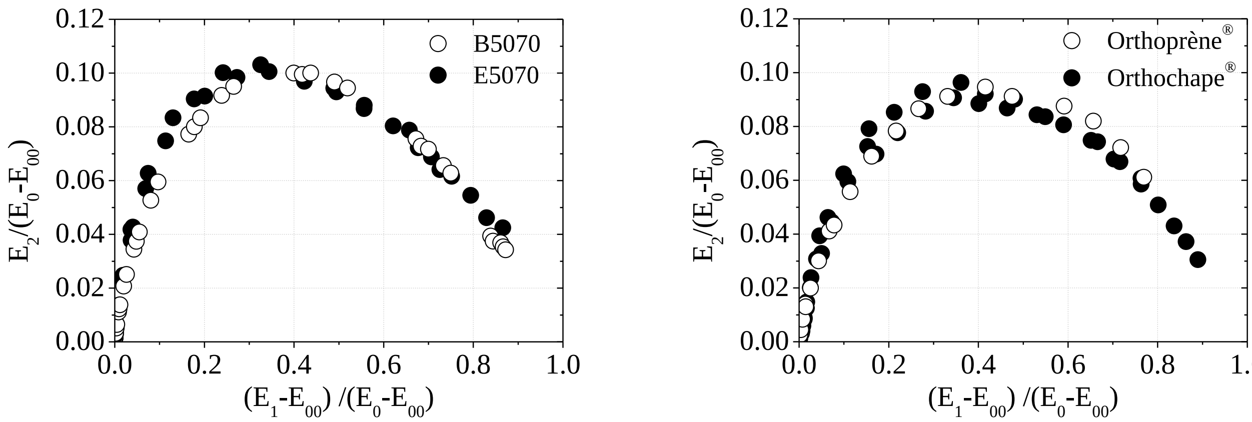

Figure 11: Cole-Cole diagram with normalized axis
Left: E5070 asphalt and B5070 bitumen; Right: PMA and PMB

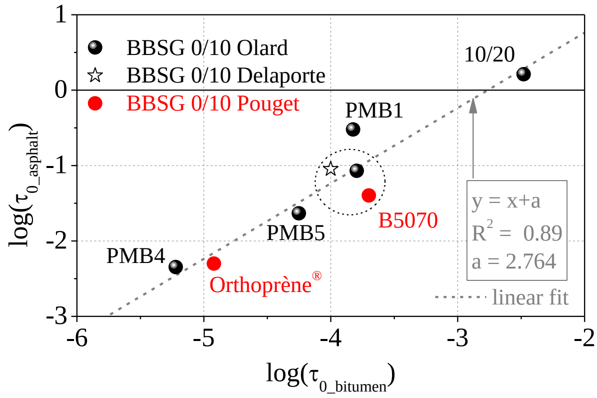

Figure 12: Relationship between $\log(\tau_{0\_bitumen})$ and $\log(\tau_{0\_asphalt})$ determined at 10°C for asphalt designs using the same grading shape

5 CONCLUSION

A rational approach, which consists in comparing the properties of bitumens and asphalts only in the small strain amplitude domain (where linear viscoelastic behaviour is observed), was considered in this paper. The aim of this work was to seek both handy and pertinent relations between rheological properties of bitumens and asphalts in the linear viscoelastic domain. Pertinent rheological modelling based on physical analogical elements was considered. Viscoelastic behaviour of bitumens and asphalts was evaluated using complex modulus tests.

Pure unmodified bitumens and associated asphalt formulations respect the Time-Temperature Superposition Principle (TTSP). Construction of polymer-modified bitumen and asphalt master curves relies on the so called "Partial Time-Temperature Superposition Principle" (PTTSP). The PTTSP is herein considered as an effective approximated approach for analysing viscoelastic data in the case of PMB's.

In addition, simple relations (equations (11) and (14)) have been proposed to obtain three-dimensional isotropic linear viscoelastic behaviour of asphalt from bitumen complex modulus (forward problem). They are called ENTPE SHStS transformation, that is independent of any rheological model. The relation between bitumen and asphalt complex moduli does not depend on any considered model and can be applied to any existing model (2S2P1D model or another model) or more directly and simply to bitumen experimental data. If bitumen complex modulus is known, only five parameters (α, $E_{00\_asphalt}$, $E_{0\_asphalt}$, $\nu_{00\_asphalt}$ and $\nu_{0\_asphalt}$) need to be determined to obtain asphalt three-dimensional isotropic linear viscoelastic behaviour. From the literature, $E_{00\_asphalt}$ and $E_{0\_asphalt}$ highly depend on asphalt composition. The additional parameter α might depend on the considered asphalt design and/or ageing during mixing.

Equations (11) and (14) are completely reversible. They allow predicting bitumen complex modulus from asphalt complex modulus. This approach is known as inverse problem. Satisfactory results are obtained as well for forward than reverse problems for materials made from pure unmodified bitumen and PMB at low temperatures (< 30°C), where TTSP is respected.

It must be noted that equations (11) and (14) do not suppose the Time-Temperature Superposition Principle. If this property holds for the bitumen, it will appear as automatically verified for the corresponding asphalt.

Finally, ENTPE SHStS transformation is a powerful predicting tool which can be used for any given bitumen, provided that coefficient α and static and glassy moduli (also Poisson's ratio in the three-dimensional case) of the considered asphalt design are known. Briefly, if bitumen *i* and the corresponding *i* asphalt –for a given asphalt design– have been tested, complex modulus of bitumen *j* can be then sufficient to predict three-dimensional isotropic linear viscoelastic behaviour of the corresponding *j* asphalt, for the considered asphalt design. This result is of prime importance since a tremendous amount of asphalt testing work could be saved.

REFERENCES

[1] Lytton, R.L., Uzan, J., Fernando, E.G., Roque, R., Hiltunen, D., Stoffels, S.M. "Development and Validation of Performance Prediction Models and Specifications for Asphalt Binders and Paving Mixes", SHRP-A-357, Strategic Highway Research Program, National Research Council, Washington DC, 1993.

[2] Boutin, C., De La Roche, C., Di Benedetto, H., and Ramond, G. "De la rhéologie du liant à celle de l'enrobé bitumineux, Théorie de l'homogénéisation et validation expérimentale" Eurobitume Workshop, 1995. [in French].

[3] Franken, L. and Vanelstraete, A. "Relation between mix stiffness and binder complex modulus", The Rheology of Bituminous Binders, European Workshop, Brussels, 5-7 April 1995.

[4] Franken, L. and Vanelstraete, A. "Complex moduli of bituminous binders and mixtures : interpretation and evaluation", Eurasphalt and Eurobitume, 1996.

[5] Di Benedetto, H., and Neifar, M. "Coefficients de dilatation et de contraction thermiques d'un enrobé bitumineux avec et sans chargement mécanique." 5th Interntional RILEM Symposium, Lyon, pp. 421-428, 1997. [in French].

[6] Zeng, M., Bahia, H.U., Zhai, H., Anderson and M.R., Turner, P., "Rheological modeling of modified asphalt binders and mixtures", Annual Meeting of the Association of Asphalt paving Technologists, 2001.

[7] Olard, F. and Di Benedetto, H. "General 2S2P1D model and relation between the linear viscoelastic behaviors of bituminous binders and mixes", International Journal Road Materials and Pavement Design, Vol. 4, pp. 185-224, 2003.

[8] Olard, F., Di Benedetto, H., Eckmann, B., Triquigneaux, J-P. "Linear viscoelastic properties of bituminous binders and mixtures at low and intermediate temperatures", International Journal Road Materials and Pavement Design, Volume 4, Issue 1, 2003.

[9] Olard, F. "Comportement thermomécanique des enrobés bitumineux à basses températures. Relations entre les propriétés du liant et de l'enrobé", PhD Thesis, ENTPE-INSA Lyon, 2003. [In French]

[10] Di Benedetto, H. Olard, F., Sauzéat, C. and Delaporte, B. "Linear viscoelastic behaviour of bituminous materials : from binders to mixes", International Journal Road Materials and Pavement Design, vol.5, pp. 163-202, 2004.

[11] Delaporte, B., Di Benedetto, H., Sauzéat, C., and Chaverot, P. "Linear viscoelastic properties of mastics : results from a new ASR, and modelling." Bearing Capacity of Roads Railways and Airfileds, Trondheim, 2005.
[12] Delaporte, B., Di Benedetto, H., Chaverot, P., and Gauthier, G. “Linear Viscoelastic Properties of Bituminous Materials : from Binders to Mastics” Journal of the Association of Asphalt Paving Technologists, Vol. 76, p. 455-494, 2007.
[13] Di Benedetto, H., Delaporte, B. and Sauzéat, C. “Three-dimensional linear behavior of bituminous materials : experiments and modeling”, International Journal of Geomechanics (ASCE), Volume 7, Issue 2, pp. 149-157, 2007.
[14] Velasquez, R., Falchetto, A. and Marasteanu, M. “From Mixtures to Binders Can the Inverse Problem be Solved?”, Road Materials and Pavement Design, Vol. 11, Special Issue EATA, pp. 225-249, 2010.
[15] Nguyen, H.M., Pouget, S., Di Benedetto, H., Sauzéat, C. “Time-Temperature Superposition Principle for bituminous mixtures”, European Journal of Environmental and Civil Engineering, Vol. 13, n°9, pp. 1095-1107, 2009.
[16] Ferry, J.D. Viscoelastic Properties of Polymers, John Wiley and Sons, New York, 680 p., 1980.
[17] Huet, C. “Etude par une méthode d’impédance du comportement viscoélastique des matériaux hydrocarbonés”, Faculté des sciences de Paris, Paris, 69 p., 1963. [in French]
[18] Pouget, S., Sauzéat, C., Di Benedetto, H., Olard, F. “From the Behavior of Constituent Materials to the Calculation and Design of Orthotropic Bridge Structures”, Road Materials and Pavement Design, Vol. 11, Special Issue EATA, pp. 111-144, 2010.
[19] Pouget S., Sauzéat C., Di Benedetto H., Olard F. “Numerical simulation of the five-point bending test designed to study bituminous wearing courses on orthotropic steel bridge”, Materials and Structures, Vol. 43, N° 3, pp. 319-330, 2010.
[20] Pouget, S. "Influence des propriétés élastiques ou viscoélastiques des revêtements sur le comportement des ponts à dalle orthotrope" PhD ENTPE-INSA, 254 p., 2011. [in French]
[21] Pouget S., Sauzéat C., Di Benedetto H., Olard F. “Viscous energy dissipation in asphalt pavement structures and implication on vehicle fuel consumption”, Journal of Materials in Civil Engineering, 2011. [accepted]
[22] Tiouajni, S., Di Benedetto, H., Sauzéat, C., Pouget, S. “Approximation of linear viscoelastic model by generalized Kelvin Voigt or generalized Maxwell Models: Application to bituminous materials”, Road Materials and Pavement Design (RMPD), 34 p., 2011. [accepted]