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VISCOELASTIC PROPERTIES OF BITUMEN BLENDS OBTAINED FROM PURE AND RAP-EXTRACTED BINDERS

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ABSTRACT

The main issue with pavement recycling procedure is the evaluation of the influence of aged asphalt binder in Reclaimed Asphalt Pavement (RAP) material on final properties of blended binder in the new mixture. The traditional approach relies on the use of either blending charts or empirical laws, such as the "log-log" rule. The problem with this kind of solutions is that their outcome consists of simple grading parameter-based temperatures, whereas a true evaluation of linear viscoelastic properties is still missing.
The study presented in this paper is part of a wider ongoing research effort in the framework of a PhD thesis, in collaboration between Université de Lyon/Ecole Nationale des Travaux Publics de l'Etat (ENTPE), EIFFAGE Travaux Publics and Beyond Petroleum (BP). The paper focuses on the influence of a binder extracted from RAP material on different bitumens, when blended together, in terms of linear viscoelastic properties of the final blend.
Three unaged binders provided by BP and a binder extracted from a well-known RAP material, provided by EIFFAGE Travaux Publics were blended in different proportions (20%, 40% and 60% RAP-extracted binder in final blend). Experimental plan consists, therefore, of thirteen different binders.
Complex modulus (G) tests were performed on binders using a DSR at the EIFFAGE Travaux Publics research centre. Prediction of G* of blended binders from initial binder proportions is proposed on the whole temperature and frequency range. In addition, 2S2P1D model, previously proposed by ENTPE, was used to model behavior of all bitumens and complete the analysis.*

Keywords: bitumen, blending, RAP, viscoelastic modeling, complex modulus

1. INTRODUCTION

Environmental and economical reasons encourage extensive use of Reclaimed Asphalt Pavement (RAP) materials for construction and maintenance of road infrastructures. However, the influence of aged bitumen in RAP material on final properties of blended bitumen in the new material is still a matter of investigation. Traditional methods to approach this issue still rely on blending charts [1] or totally empirical laws, such as the so-called "log-log" rule [2]. Complete and reliable evaluation and prediction of linear viscoelastic properties are still missing.
The presented study is part of a wider ongoing research project in the framework of a PhD thesis, in collaboration between Université de Lyon/Ecole Nationale des Travaux Publics de l'Etat (ENTPE), EIFFAGE Travaux Publics and Beyond Petroleum (BP) France. The paper focuses on the influence of the percentage of aged bitumen on viscoelastic properties of blends, produced by mixing a RAP-extracted bitumen (provided by EIFFAGE Travaux Publics) with pure bitumens (provided by BP). Dynamic Shear Rheometer (DSR) complex modulus tests were performed on thirteen different materials. 2S2P1D (2 Springs, 2 Parabolic, 1 Dashpot) model [3-4], developed at ENTPE, is used to model experimental results. Complex modulus of bitumen blends is predicted over the whole frequency and temperature range from initial proportions of single components.

2. MATERIALS AND METHODS

2.1. Materials

The experimental plan considers various blends in different proportions of three unaged unmodified neat bitumens with a bitumen extracted from a well known RAP material. The three base bitumens are:
- a 15/25 penetration hard paving grade bitumen;
- a 35/50 penetration paving grade bitumen;
- a 70/100 penetration paving grade bitumen.

Penetration and Ring-Ball Temperature (T_{RB}) tests were performed on the RAP-extracted bitumen in order to characterize it. Characteristic penetration and T_{RB} values were, respectively, 10.3 dmm and 71.2 °C.
Blending proportions of RAP bitumen were chosen in order to simulate real blending proportions between components of the corresponding asphalt mixtures produced in the framework of the ongoing study. In these mixtures, RAP material content is equal to 20%, 40% and 60% by weight of the total mixture without fresh bitumen (RAP material + added aggregates). For simplicity, corresponding bitumen blends are hereafter named according to the fresh binder base and the percentage of RAP material added during the production of the mixture (example: 70-100 + 40% RAP). Actual blending percentages of blends corresponding to mixtures containing 20%, 40% and 60% of RAP material are, respectively, equal to 18.7%, 37.8% and 57.0% by weight of the final blend.
A total number of thirteen bitumens were tested (Table 1).

2.2 Methods

Complex modulus tests were performed on all bitumens using a Dynamic Shear Rheometer apparatus (DSR), at eleven temperatures ranging from -30°C to +70°C and over a whole range of frequencies ranging from 0.01 Hz to 30 Hz. E^* values were obtained from G^* measured values by applying an arbitrary Poisson's ratio equal to 0.5 (therefore, $E^* = 3\,G^*$).
2S2P1D model was applied in order to analyze experimental results. Figure 1a shows a schematic representation of the model, consisting of two elastic (spring) elements, two parabolic creep elements and one viscous (dashpot) element, each one associated with a corresponding constant of the following equation:

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

where:
ω is the pulsation, so that $2\pi\omega$ is equal to the frequency;
τ is the characteristic time, function only of temperature and accounting for the Time-Temperature Superposition Principle, approximated by WLF equation [5];
E_0 is the value of the complex modulus when $\omega\tau \rightarrow \infty$;
E_{00} is the value of the complex modulus when $\omega\tau \rightarrow 0$, generally equal to 0 in the case of pure bitumens;
δ, k and h are dimensionless constants;
β is a dimensionless parameter, so that Newtonian viscosity η is described by

$$\eta = (E_0 - E_{00})\beta\tau \quad (2)$$

Figure 1b shows the meaning on a general Cole-Cole curve of a bitumen of six of the seven constants (E_0, E_{00}, δ, k, h and β) needed to describe the linear viscoelastic behavior of the material.

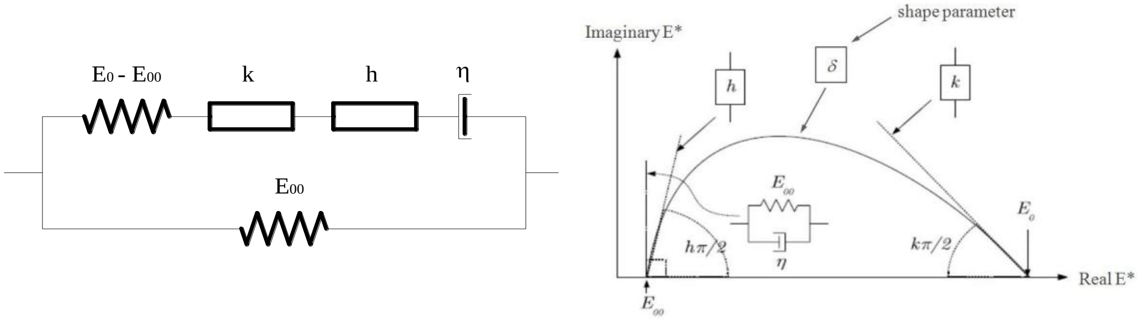

Figure 1: (a, left) Schematic representation of 2S2P1D model (constitutive elements and associated parameters); (b, right) Meaning of 2S2P1D parameters associated with constitutive elements of the model on a general Cole-Cole curve of a bitumen

3. RESULTS

Experimental data were modeled using 2S2P1D model: Black, Cole-Cole and complex modulus master curves (at a 15 °C reference temperature) were built for all materials. As an example, curves for 35-50 bitumen with 20% RAP are reported in Figure 2. Values of 2S2P1D model parameters for all bitumens are shown in Table 1. Values of τ are evaluated at a reference temperature equal to 15 °C.

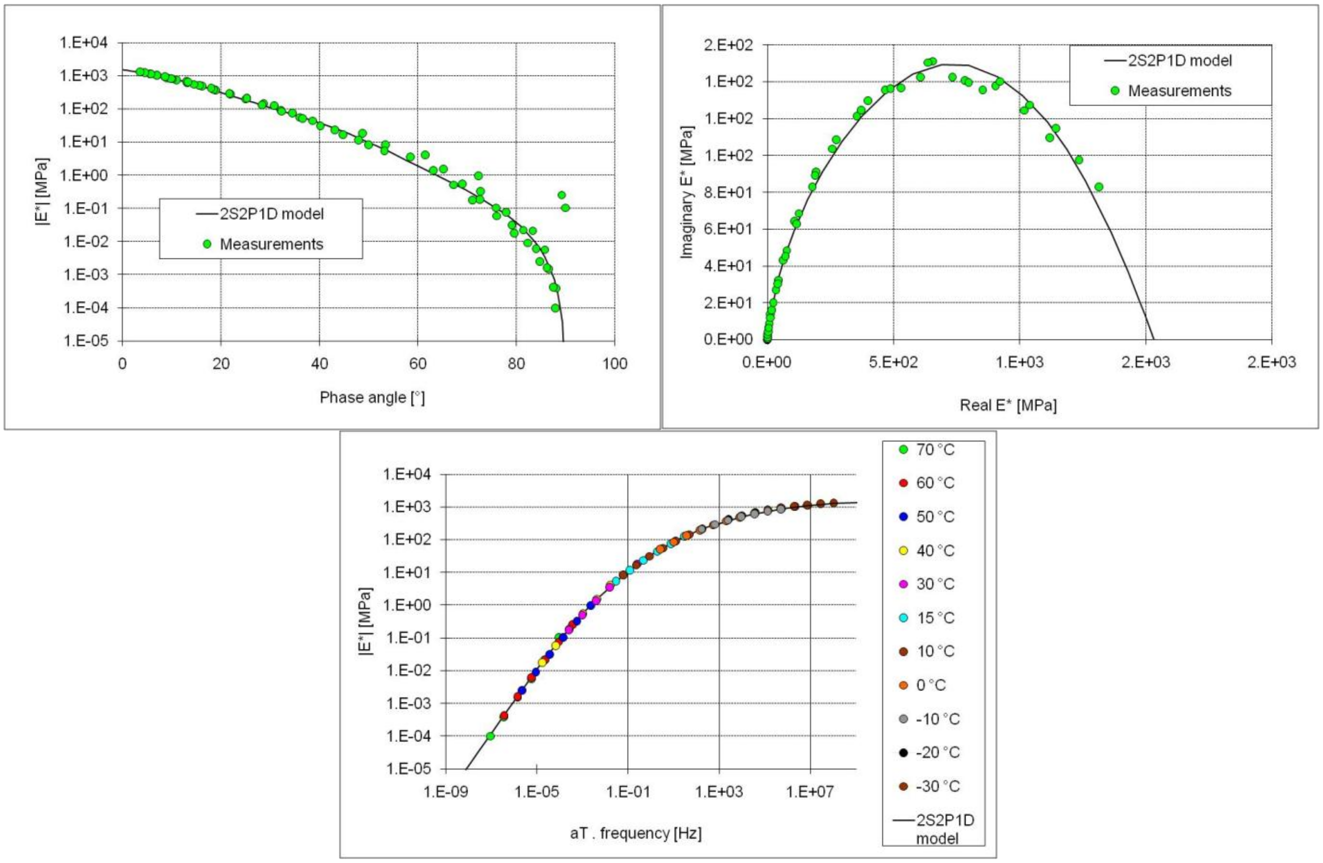

Figure 2: (a, top left) 35-50 +20% RAP bitumen Black curve; (b, top right) 35-50 +20% RAP bitumen Cole-Cole curve; (c, bottom) 35-50 + 20% RAP bitumen complex modulus master curve at 15°C.

Table 1: 2S2P1D model parameters of all pure bitumen and blends

bitumen blend	% RAP	E_{00}[MPa]	E_0 [MPa]	k	h	δ	τ [s]	β
15/25	0	0	1500	0.220	0.580	4.50	1.00E-03	750
15/25 + 20% RAP	18.7	0	1780	0.220	0.580	4.70	1.70E-03	700
15/25 + 40% RAP	37.8	0	1640	0.220	0.585	4.80	2.20E-03	550
15/25 + 60% RAP	57.0	0	1650	0.221	0.590	4.90	4.50E-03	450
35/50	0	0	1500	0.242	0.590	4.10	1.60E-04	230
35/50 + 20% RAP	18.7	0	1540	0.235	0.600	4.40	6.50E-04	220
35/50 + 40% RAP	37.8	0	1690	0.232	0.600	4.60	1.25E-03	250
35/50 + 60% RAP	57.0	0	1630	0.230	0.600	4.80	2.40E-03	250
70/100	0	0	1650	0.235	0.575	3.40	1.50E-05	250
70/100 + 20% RAP	18.7	0	1550	0.235	0.580	3.80	7.30E-05	250
70/100 + 40% RAP	37.8	0	1620	0.230	0.590	4.10	2.20E-04	250
70/100 + 60% RAP	57.0	0	1810	0.227	0.600	4.50	5.50E-04	250
RAP bitumen	100	0	1850	0.221	0.610	5.20	1.10E-02	220

E_0 values appear lower than expected. Standard literature values are approximately equal to 2.1 to 3 GPa for all bitumens [6], while obtained experimental data show values lower than 2 GPa. Further investigation is ongoing in order to verify the cause of this discrepancy with literature. However, the objective of the study being observing the effects of blending pure and RAP-extracted bitumens in terms of viscoelastic behavior of resulting blends, a systematic potential quantitative error can be ignored.

In order to evaluate the influence of RAP-extracted bitumen content, complex shear modulus and phase angle master curves at 15°C (isotherms) and 10 Hz (isochrones) for all blends prepared with 35-50 bitumen are shown in Figure 3, as an example.

As expected, master curves progressively approach those corresponding to pure RAP-extracted bitumen with the increase of its content in the blend. The same tendency, although less consistently, is observed in Cole-Cole curves (Figure 4).

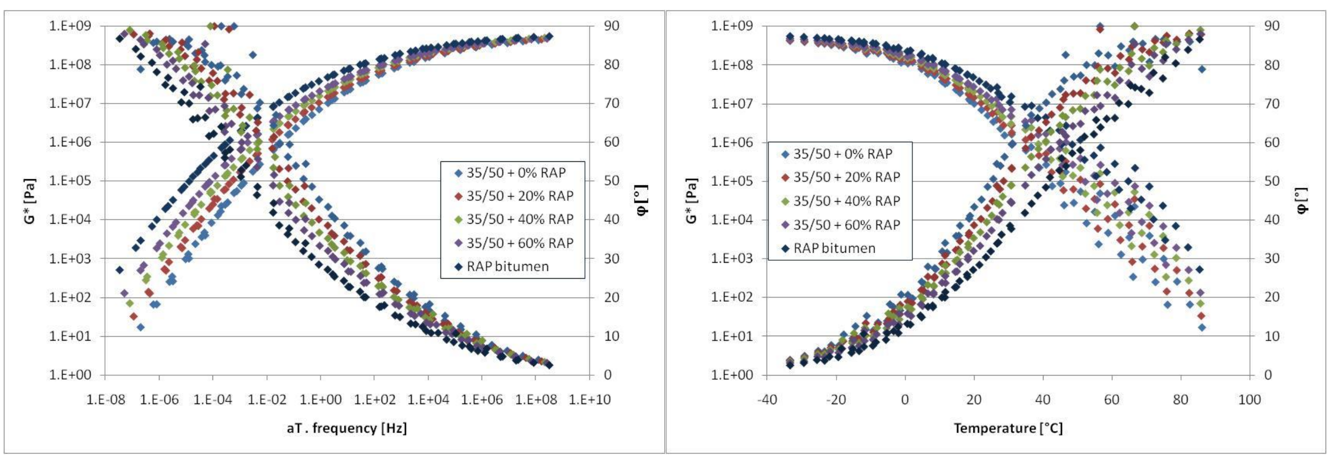

Figure 3: (a, left) Complex shear modulus and phase angle master curves at 15°C for all blends of 35-50 and RAP-extracted bitumens; (b, right) Complex shear modulus and phase angle isochrones master curves at 10 Hz for all blends of 35-50 and RAP-extracted bitumens.

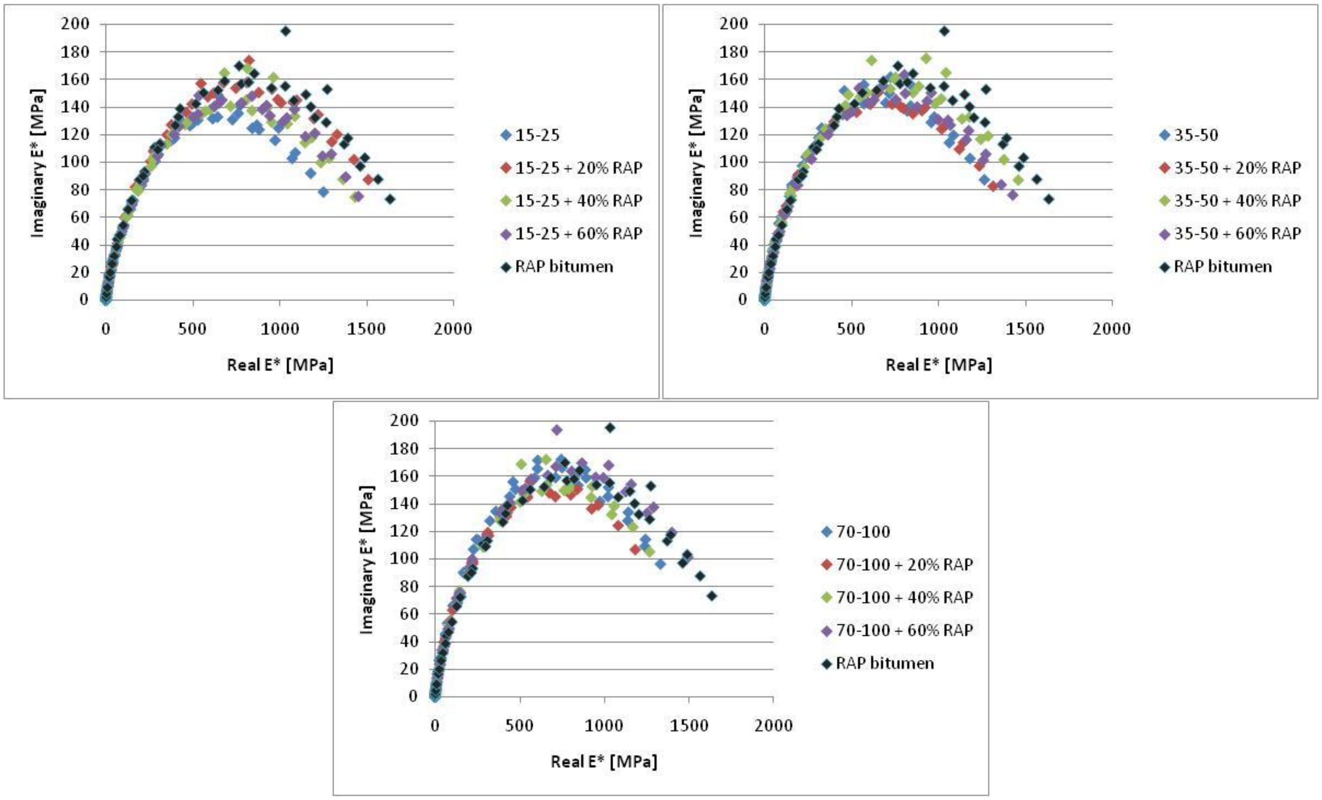

Figure 4: Cole-Cole curves for all blends of 15-25 (a, left), 35-50 (b, right) and 70-100 (c, bottom) bitumens with RAP-extracted bitumens.

The observations made for Cole-Cole and master curves are confirmed by 2S2P1D parameter values used to fit experimental data, listed in Table 1. Particularly, E_{00} is equal to 0 MPa for all bitumens, while E_0 and τ show a remarked tendency with the increase of the percentage of RAP bitumen in the blend, as shown in Figures 5 and 6.

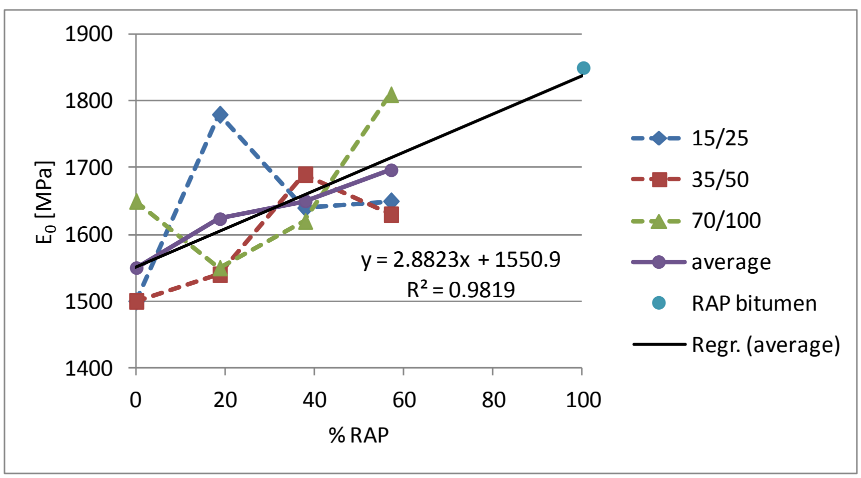

Figure 5: E_0 tendency with RAP-extracted bitumen content

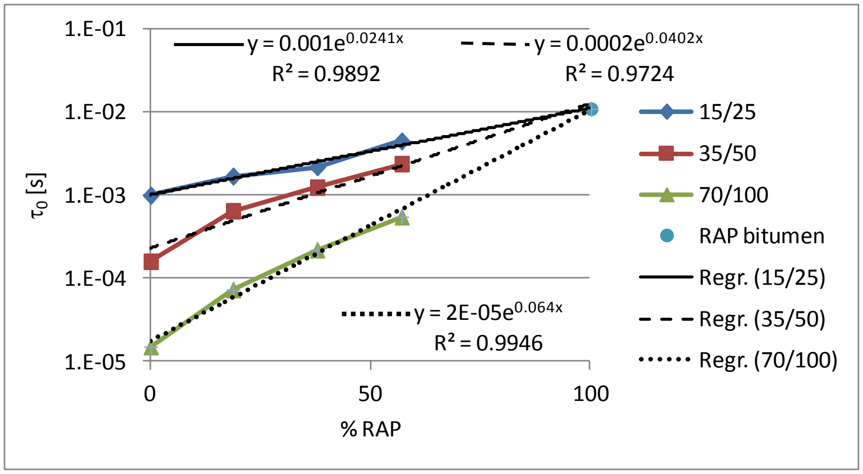

Figure 6: τ tendency with RAP-extracted bitumen content

As already stated, literature suggests than complex modulus of all bitumens tend to a unique value approximately equal to 2.1 to 3 GPa at low temperature and/or high frequencies, corresponding to a glassy plateau of the master curve. However, experimental data collected in the study show considerably lower values of E_0. Moreover, different blends show slightly different E_0. As it can be observed in Figure 5, the variation of this parameter with RAP-extracted bitumen content is neither smooth nor monotone, as it would be expected, and a classification of different blends produced by mixing different base bitumens with the same amount of RAP-extracted bitumen is impossible. However, the average value of the E_0 parameter for each triplet of blends at the same RAP-extracted bitumen content shows a clear overall tendency. The variation of the average parameter is closely fitted by a linear relationship with the percentage of RAP-extracted bitumen content in the final blend, including the final value corresponding to pure RAP bitumen.

A similar remark is valid for the characteristic time (Figure 6), which is related to temperature sensitivity. The variation of τ with RAP-extracted bitumen content, in logarithmic scale, follows a linear trend. This is valid even for each single pure bitumen base. In fact, each triplet of blends for the same RAP bitumen content shows the same classification among different blends that is valid for the three pure bases. When increasing the percentage of RAP bitumen in the blend, characteristic times increase, tending towards the value of pure RAP-extracted bitumen.

Equations 3 and 4 describe the variation of, respectively, E_0 and τ.

$$E_{0,x\%} = E_{0,0\%} + x\left(E_{0,RAP} - E_{0,0\%}\right) \quad (3)$$

$$\log\tau_{x\%} = \log\tau_{0\%} + x\left(\log\tau_{RAP} - \log\tau_{0\%}\right) \quad (4)$$

where x is the percentage of RAP-extracted binder in the blend.

Equation 3 has been rewritten in a more general form (Equation 5) and applied to the remaining four constants of 2S2P1D model (E_{00} is null for bitumens).

$$A_{x\%} = A_{0\%} + x\left(A_{RAP} - A_{0\%}\right) \quad (5)$$

Equations 4 and 5 have been used to simulate a prediction of 2S2P1D parameters for all blends, in order to evaluate the validity of the observed tendencies. Table 2 shows all experimental and predicted values. Figure 7 shows correlation plots for E_0, τ and β: 95% confidence interval bars are showed.

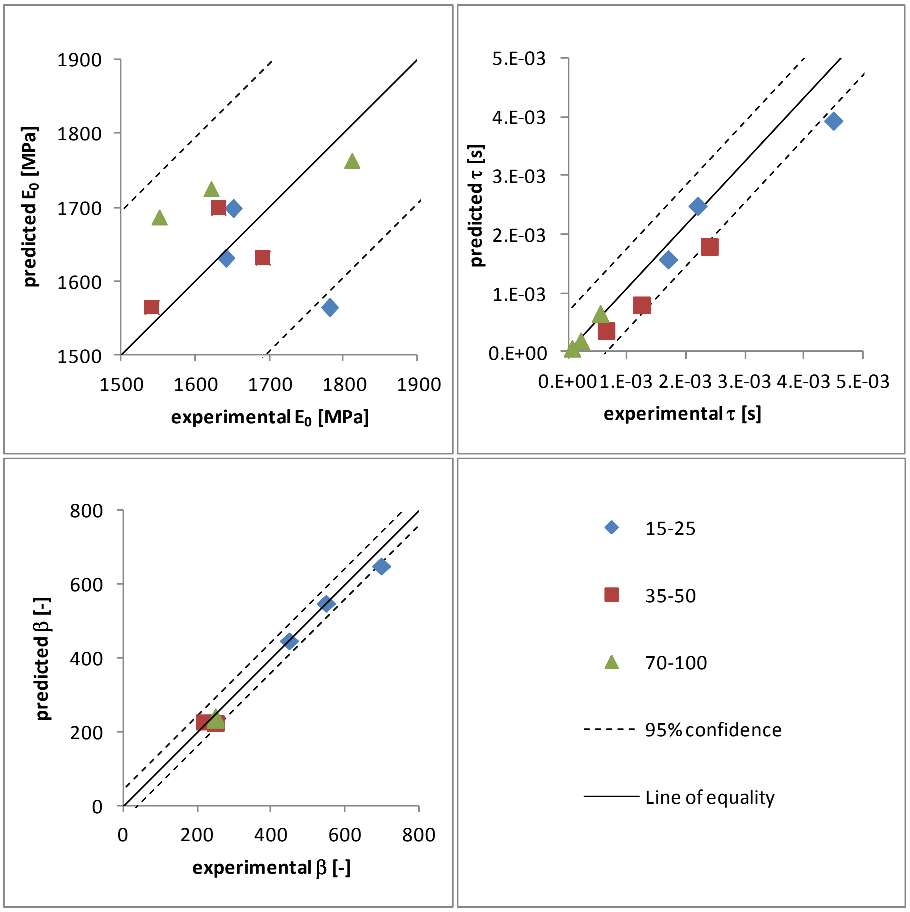

Figure 7: Correlation plots for E_0, τ and β

Table 2: Experimental and predicted 2S2P1D model parameters of all bitumen blends

bitumen blend	E_0 [MPa]		k		h		δ		τ [s]		β	
	exp.	pred.	exp.	pred.	exp.	pred.	exp.	pred.	exp.	pred.	exp.	pred.
15/25	1500	-	0.220	-	0.580	-	4.50	-	1.00E-03	-	750	-
15/25 + 20% RAP	1780	1565	0.220	0.220	0.580	0.586	4.70	4.63	1.70E-03	1.57E-03	700	651
15/25 + 40% RAP	1640	1632	0.220	0.220	0.585	0.591	4.80	4.76	2.20E-03	2.48E-03	550	550
15/25 + 60% RAP	1650	1700	0.221	0.221	0.590	0.597	4.90	4.90	4.50E-03	3.92E-03	450	448
35/50	1500	-	0.242	-	0.590	-	4.10	-	1.60E-04	-	230	-
35/50 + 20% RAP	1540	1565	0.235	0.238	0.600	0.594	4.40	4.31	6.50E-04	3.53E-04	220	228
35/50 + 40% RAP	1690	1632	0.232	0.234	0.600	0.598	4.60	4.52	1.25E-03	7.92E-04	250	226
35/50 + 60% RAP	1630	1700	0.230	0.230	0.600	0.601	4.80	4.73	2.40E-03	1.78E-03	250	224
70/100	1650	-	0.235	-	0.575	-	3.40	-	1.50E-05	-	250	-
70/100 + 20% RAP	1550	1687	0.235	0.232	0.580	0.582	3.80	3.74	7.30E-05	5.15E-05	250	244
70/100 + 40% RAP	1620	1726	0.230	0.230	0.590	0.588	4.10	4.08	2.20E-04	1.82E-04	250	239
70/100 + 60% RAP	1810	1764	0.227	0.227	0.600	0.595	4.50	4.43	5.50E-04	6.45E-04	250	233
RAP bitumen	1850	-	0.221	-	0.610	-	5.20	-	1.10E-02	-	220	-

Values for E_0 are affected by the possible systematic experimental error, therefore, at the moment, this parameter is not taken into account for analysis and prediction of material behavior. However, only one predicted value lies outside of the 95% confidence interval with respect to experimental data, as showed in Figure 7. Characteristic time τ exhibits excellent correlation between experimental and modeled values: thus, temperature sensitivity of the material is strictly dependent on RAP-extracted bitumen content of the blend and it varies linearly (in logarithmic scale) with it.
Nevertheless, all predicted parameters have been reimplemented in 2S2P1D model and resulting Black, Cole-Cole and complex modulus master curves have been compared to those built by using experimental values. As an example, curves for 35-50 bitumen with 20% RAP are reported in Figure 8. No sensible difference can be observed, except for Cole-Cole curves. However, this small discrepancy is due to the different values of E_0: curves built by using the predicted set of values for all 2S2P1D but E_0 superimpose almost exactly, as in the case of Black and complex modulus master curves. Accurate prediction of complex modulus values over the whole frequency and temperature range is therefore possible.

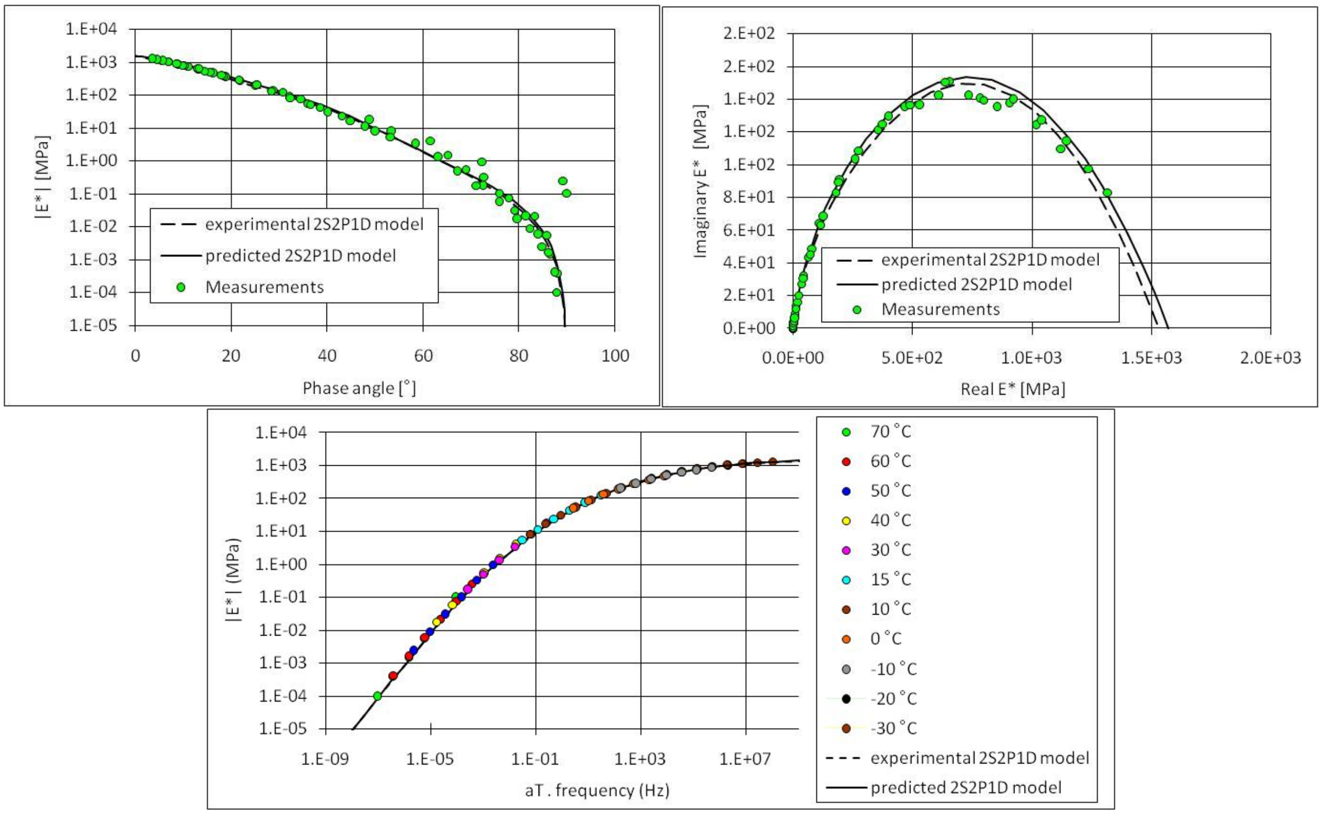

Figure 8: Comparison between curves built using predicted and experimental 2S2P1D parameters for 35-50 +20% RAP bitumen: (a, top left) Black curve; (b, top right) Cole-Cole curve; (c, bottom) complex modulus master curve at 15°C.

4. CONCLUSIONS

Thirteen different bitumen blends were produced, using three pure bitumen bases and a RAP-extracted bitumen. Viscoelastic behavior of all materials was investigated, performing DSR complex modulus tests at different temperatures and frequencies. 2S2P1D model was used to analyze experimental data. Blends were compared between them, according to their RAP-extracted bitumen content. Progressive variations have been observed for 2S2P1D constants with the increase of RAP bitumen content in the blends: in particular, parameters E_∞ and τ show significant variations and appear to follow, respectively, linear and logarithmic trends. This hypothesis has been confirmed by simulating a prediction of all 2S2P1D model constants of all blends and recalculating their Black, Cole-Cole and complex modulus master curves. Comparison between experimental and predicted model constants and curves shows satisfactory accordance. Prediction of viscoelastic behavior of blends produced with pure and RAP-extracted bitumens is therefore possible over the whole frequency and temperature range.
Future work will focus on further investigation of prediction of linear viscoelastic behavior of bitumen blends. In particular, since the proposed approach is based on 2S2P1D model, one of the main future objectives is to find a simple procedure independent of any specific rheological model. A similar approach will be attempted on mixtures.

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