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Prediction of LVE behavior of mixtures containing RAP from properties of base constituents

Salvatore Mangiafico [a],*, Cédric Sauzéat [a], Hervé Di Benedetto [a],
Simon Pouget [b], François Olard [b], Luc Planque [c]

[a] Université de Lyon/ENTPE (LGCB)/LTDS (CNRS UMR 5513), rue Maurice Audin, 69518 Vaulx-en-Velin Cedex, France
[b] EIFFAGE Infrastructures – Direction R&D, 8 rue du Dauphiné CS74005, 69964 Corbas Cedex, France
[c] BP France – Service Bitumes, Immeuble Le Cervier A, 12 av. des Béguines, 95866 Cergy Pontoise Cedex, France

Abstract

Considerable research efforts are made to develop methods to predict mechanical behavior of bituminous mixtures from properties of basic components. In particular, such methods would be most useful for the design of mixtures containing Reclaimed Asphalt Pavement (RAP) material. The objective of the study is the simulation of Linear ViscoElastic (LVE) behavior of bituminous mixtures containing RAP from LVE properties of base constituents.

Five mixtures were produced and tested, a reference mixture produced only with 35/50 binder, a mixture containing 100% RAP and three mixtures produced with 35/50 binder and different RAP contents (20%, 40% and 60%). All mixtures had the same granular size distribution curve. Complete LVE characterization was carried out on all materials. DSR and Tension/Compression (T/C) tests were performed on base and RAP-extracted binders (from -30 °C to +70 °C and from 0.01 Hz to 30 Hz). T/C tests were carried out on mixtures (from -25 °C to 40 °C and from 0.001 Hz to 10 Hz). Test results on both binders and mixtures were successfully fitted with 2S2P1D (2 Springs, 2 Parabolic elements, 1 Dashpot) model.

LVE behavior of mixtures containing RAP was simulated by using as input data only LVE properties of base binders (35/50 and RAP-extracted binders) and of the reference mixture (produced with 35/50 binder, without RAP). In order to do this, two existing procedures, previously developed at the ENTPE, were used conjunctly. The first procedure was applied to predict LVE behavior of binder blends of pure base and RAP-extracted binders over the whole range of frequency and temperature. This procedure allows estimating 2S2P1D parameters of binder blends from those of base bitumens, according to their proportions in the blend. Therefore, LVE properties of blends can be predicted over the whole range of frequency and temperature. The second procedure

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* Corresponding author. Tel.: +33-(0)4-7204-7264; fax: +33-(0)4-7204-7156.
E-mail address: salvatore.mangiafico@entpe.fr

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used is SHStS (Shift, Homothety, Shift in time, Shift) transformation. This analytical tool is useful to determine the relationship between LVE behavior of mixtures and their corresponding binders. Experimental data of pure 35/50 binder and its corresponding mixture (without RAP) were used to calibrate SHStS transformation, depending mainly on aggregate skeleton. LVE behavior of mixtures produced with RAP was then estimated from simulations of LVE properties of blends, having the same proportions of base binders, obtained with the first procedure.

Simulations of LVE behavior of mixtures containing RAP were finally compared to T/C test data. Successful correspondence was found between predicted and experimental results. Small discrepancies observed can be reasonably attributed to incomplete blending of base and RAP binders within the mixture. Therefore, as a first approximation, the proposed procedure can be used to predict LVE behavior of mixtures produced with RAP, over the whole range of frequency and temperature, from LVE properties of base binders and of a reference mixture (with the same granular size distribution) are known.

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Keywords: Binder; mixture; complex modulus; LVE behavior; blending; prediction; RAP

1. Introduction

The use of RAP (Reclaimed Asphalt Pavement) in bituminous mixtures is a widespread solution in road paving industry. Besides the evident advantages from the environmental point of view, as shown in literature, the incorporation of RAP within mixtures can have beneficial effects for mechanical properties (Visintine et al., 2013; Widyatmoko, 2008, among others). Generally, for RAP contents higher than 20%, an increase of stiffness is observed, due to the aged binder contained in RAP (Li et al., 2008; McDaniel et al., 2000, among others). However, a reliable method to estimate mechanical properties of mixtures produced with RAP without extensive laboratory work is still missing. Several models (Bari and Witczak, 2006; Christensen et al., 2003; Heukelom and Klomp, 1964; Witczak and Fonseca, 1996) exist to estimate mixture properties from their mixture design and base binder properties, but their output is limited in terms of temperature-frequency combinations (i.e., they cannot predict complete LVE behavior of materials, but only mechanical properties at specific temperatures and frequencies).

The objective of this paper is to propose a method to estimate LVE properties of mixtures containing RAP over the whole range of temperature and frequency, only from properties of base constituents and their proportions. The procedure consists in the joint applications of two analytical tools previously developed at ENTPE. First, a previously blending law (Mangiafico et al., 2014) is used to estimate complete LVE properties of a binder blend composed of the fresh binder and the binder contained in the RAP used for mixture production, in the same proportions as in the final mixture. Then, the SHStS transformation (Di Benedetto et al., 2004; Olard and Di Benedetto, 2003) is applied to predict complete LVE behavior of mixture from the estimated properties of the binder blend. An experimental campaign was carried out to obtain input data for base components and real experimental results for three mixtures produced with the same fresh binder and RAP material, at different RAP contents. Predicted LVE properties of mixtures were then compared to actual experimental data, showing satisfactory correspondence.

2. Experimental campaign

2.1. Materials

The experimental plan of the study consists of both bituminous mixtures and binders.

Five HiMA (High Modulus Asphalt, EN 13108-1:2007) bituminous mixtures were produced (Table 1). Four of them were produced using a 35/50 pen grade straight bitumen, with different RAP (Reclaimed Asphalt Pavement) contents (0%, 20%, 40% and 60% by weight of RAP and aggregates, corresponding to, respectively, 0%, 18.7%, 37.8% and 57.0% by weight of final mixture). The fifth mixture (100% RAP) was produced exclusively using RAP (RAP binder was extracted and used to coat RAP aggregates). Common characteristics of all mixtures are:

- same grading curve (Figure 1)
- same silica-limestone aggregates, from a unique lot;
- 5.35% total binder content (by weight of total mixture).

Table 1. Materials used in the study.

Material	RAP content	Binder	Mixture	Voids in mixture
35/50	0%	X	X	3.7%
35/50 +20% RAP	18.7%	X (blend)	X	4.1%
35/50 + 40% RAP	37.8%	X (blend)	X	3.2%
35/50 + 60% RAP	57.0%	X (blend)	X	2.3%
100% RAP	100%	X	X	1.4%

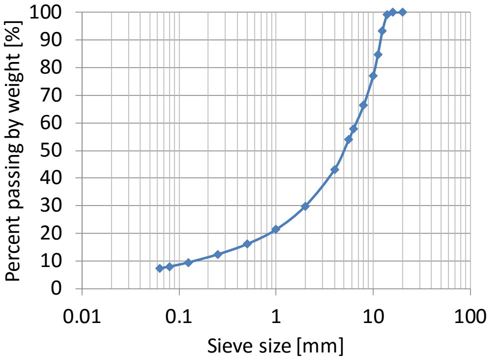

Fig. 1. Grading curve of mixtures used in the study.

All mixtures were produced at equiviscosity temperatures (with a 10 °C tolerance), according to EN 12697-35:2004+A1:2007. In any case, production temperature was limited to 185 °C. For mixtures 35/50 + 20% RAP, 35/50 + 40% RAP and 35/50 + 60% RAP, the corresponding binder blend was produced. In order to do so, RAP-extracted binder and fresh 35/50 bitumen were perfectly mixed in laboratory (using an electric mixer) with the same proportions as in each of the three mixtures. Therefore, RAP contents indicated in Table 1 are also to be intended as binder replacement ratios of the corresponding binder blends.

Mixtures were compacted using a LPC-type roller compactor, according to EN 12697-33:2003+A1:2007. Cylindrical samples (150 mm high, with a 75 mm diameter) used for tests (see Section 2.2) were obtained by coring. One sample was tested for each mixture. Before testing, void content of each sample was verified. All values are reported in Table 1.

2.2. Experimental procedures

All materials used in the study, both mixtures and binders, were subjected to complex modulus tests. Regarding mixtures, Tension/Compression (T/C) tests were performed on cylindrical samples, by means of a hydraulic press (Figure 2). Cyclic sinusoidal loading was performed in strain control mode. Axial stress was calculated from axial force, measured with a load cell. Axial strain was monitored using three extensometers placed at 120 ° from each other in the central part of the sample. The average value of the three extensometer was considered. Surface temperature of samples was constantly measured during tests by means of a thermocouple. Radial displacements were also monitored, but these results were not used in the present study.

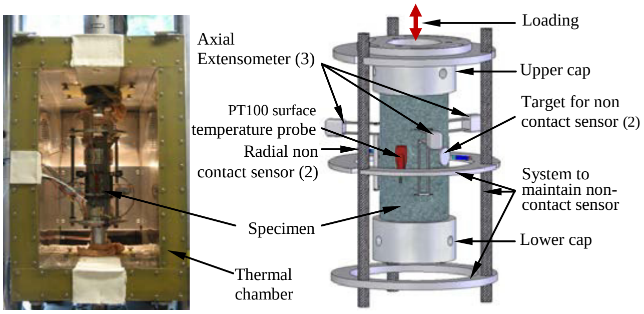

Fig. 2. (left) Tension-compression apparatus used for tests on mixtures; (right) Detailed scheme of sample and sensors.

Tests were performed at seven different temperatures (from -25 °C to +40 °C) and nine different loading frequencies (from 0.001 Hz to 10 Hz). Test temperatures were controlled by means of a thermal chamber.

Binders were subjected to two types of complex modulus tests. A DSR apparatus was used to perform tests at temperatures ranging from +10 °C to +70 °C, at frequencies ranging from 0.01 HZ to 30 Hz. For these tests, a plate-plate 8 mm diameter configuration was used, with a 2 mm gap. An arbitrary 0.5 Poisson's ratio was applied to convert $|G^*|$ to $|E^*|$ data (isotropic behavior was therefore assumed, therefore $|E^*| = 3|G^*|$). In order to cover the low temperature domain, a T/C apparatus was used to run tests at temperatures ranging from -30 °C to + 10 °C, at frequencies from 0.01 Hz to 30 Hz. These tests were performed on 20 mm long cylindrical samples with a 10 mm diameter. This kind of test gives access to $|E^*|$ values directly.

3. Analytical tools used in the study

3.1. LVE behavior of binders and mixtures: 2S2P1D model

$|E^*|$ data obtained for binders and mixtures were modeled using 2S2P1D (2 Springs, 2 Parabolic elements, 1 Dashpot) model (Olard and Di Benedetto, 2003). This analogical model (Figure 3) has a continuous spectrum and it can successfully approximate LVE behavior of bituminous materials by means of seven constants, according to the equation:

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

where ω is the pulsation, E_0 (glassy modulus) is the value of complex modulus when $\omega \rightarrow \infty$, E_{00} (static modulus) is the value of complex modulus when $\omega \rightarrow 0$ (generally, this parameter can be considered equal to zero for binders), δ, k and h are dimensionless constants, β is a parameter related to the Newtonian viscosity of the linear dashpot, η, as in

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

and τ is the characteristic time, depending on temperature and accounting for the time-temperature superposition principle by means of shift factors a_T as follows:

$$a_T = \frac{\tau}{\tau_0} \tag{3}$$

where τ0 is the value of τ at the chosen reference temperature.

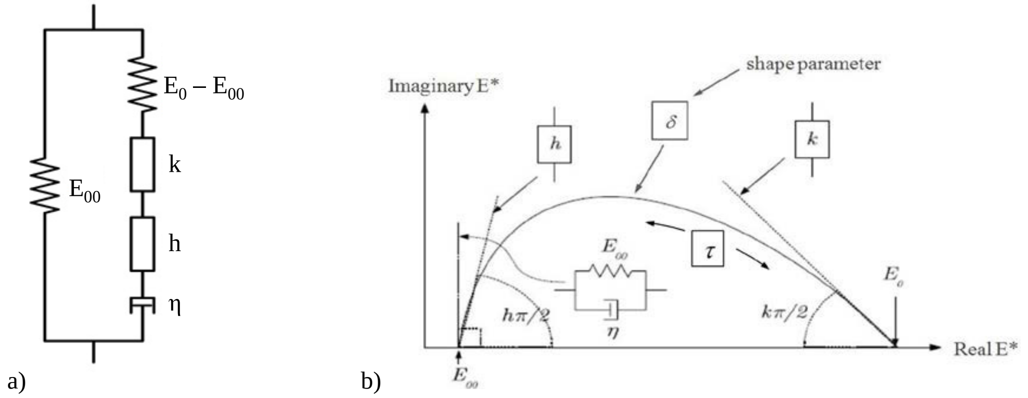

Fig. 3. (a, left) Analogical scheme of 2S2P1D model; (b, right) Influence of 2S2P1D parameter on Cole-Cole diagram.

3.2. Estimation of binder blend LVE behavior: binder blending law

Mechanical behavior of binder blends can be predicted using a blending law based on 2S2P1D model (Mangiafico et al., 2014). This method allows successfully estimating LVE properties of blends over the whole domain of frequency and temperature only from 2S2P1D parameters of base binders and blending proportions. 2S2P1D parameters of blends can be obtained from linear interpolation of parameters of base binders according to the following equation:

$$A_x = A_0 + x\left(A_{RAP} - A_0\right) \tag{4}$$

where A_x is the value of the desired 2S2P1D parameter (E_0, k, h, δ, β or $\log\tau_0$) of the blend, A_0 is the value of the parameter of the fresh binder, A_{RAP} is the value of the RAP binder and x is the RAP binder content in the blend.

3.3. From binder to mixture: SHStS transformation

The SHStS (Shift, Homothety, Shift, time Shift) transformation is a method to predict LVE behaviour of mixtures over the whole domain of frequency and temperature from LVE behaviour of corresponding binders and vice-versa (Di Benedetto et al., 2004; Olard and Di Benedetto, 2003). It is based on the concept that the time and temperature dependency of a bituminous mixture depends originates from the composing binder. This hypothesis is easily verifiable by plotting normalized complex moduli of a mixture and its corresponding binder on a Cole-Cole or Black diagram. The following equation describes the relationship and is independent of any specific rheological model and it yields the complex modulus E^*_{mix} of a mixture at temperature T and pulsation ω, as a function of complex modulus of the corresponding binder E^*_{binder} at the same temperature:

$$E^*_{mix}(\omega,T) = E_{00,mix} + \left[E^*_{binder}\left(10^{\alpha}\omega,T\right) - E_{00,binder}\right]\frac{E_{0,mix} - E_{00,mix}}{E_{0,binder} - E_{00,binder}} \tag{5}$$

where α is a parameter depending on the considered mix design. For operational purposes, parameter α was obtained as the logarithm of the ratio of characteristic times of mix and binder, as in:

$$10^{\alpha} = \frac{\tau_{0,mix}}{\tau_{0,binder}} \tag{6}$$

4. Results and analysis

4.1. Prediction of LVE behavior of binder blends

DSR and T/C test results obtained for all of the five binders of the study were successfully modelled using 2S2P1D model. Figure 4 shows an example of binder blend 35/50 + 60% RAP. In the three pictures, experimental data are reported as blue dots, while the 2S2P1D model fit is the dashed line. A reference temperature of 15 °C was chosen.

For the three binder blends of the study (35/50 + 20% RAP, 35/50 + 40% RAP and 35/50 + 60% RAP), LVE behavior was also simulated using the binder blending law described in Section 3.2. The 2S2P1D parameters obtained for fresh binder 35/50 and pure RAP binder were used to estimate values of parameters for the three blends, using equation (4). Satisfactory results were obtained for all of them. As an example, the simulated 2S2P1D model fit for binder 35/50 + 60% RAP is shown in Figure 4 as a continuous line. As for 2S2P1D calibrations, the reference temperature was fixed to 15 °C.

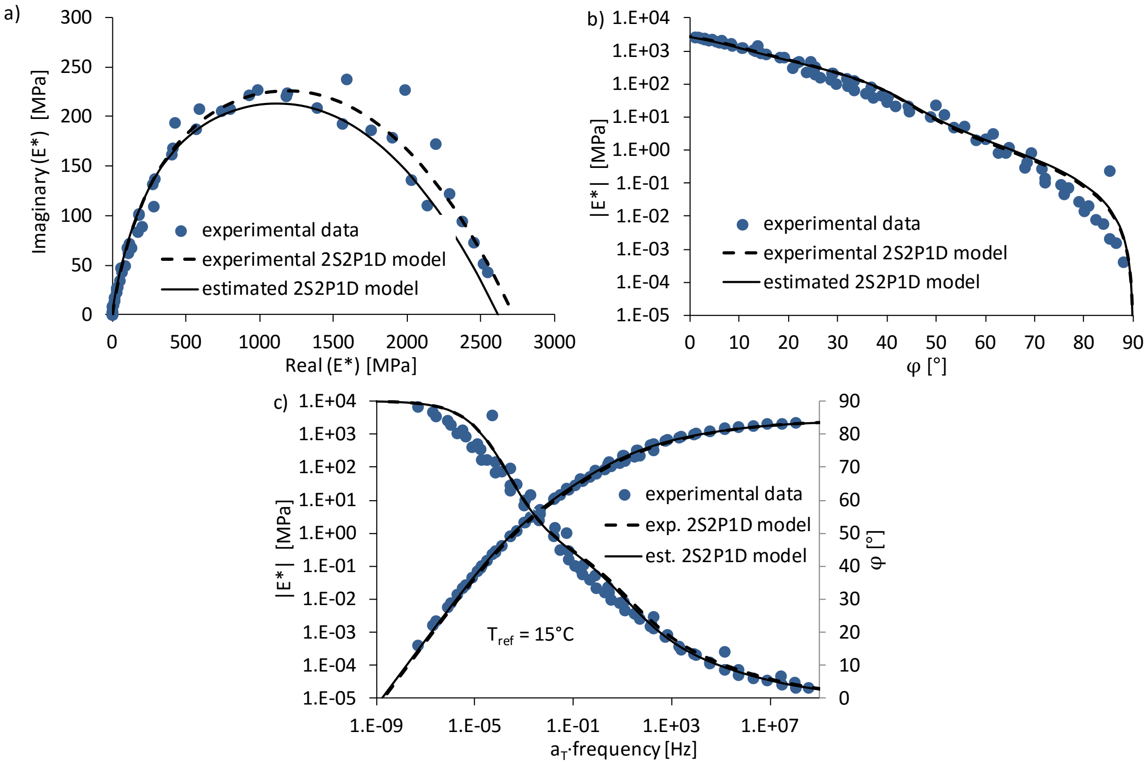

Fig. 4. Comparison of experimental results obtained from DSR and T/C tests on binder blend 35/50 + 60% RAP (blue dots), 2S2P1D model fitted on experimental data (dashed line) and predicted with binder blending law (continuous line): (a, top left) Cole-Cole diagram; (b, top right) Black diagram; (c, bottom) Complex modulus and phase angle master curves (Tref = 15 °C).

4.2. Prediction of LVE behavior of mixtures from corresponding binder blend simulations

Based on the simulated LVE behaviour obtained for the three binder blends (35/50 + 20% RAP, 35/50 + 40% RAP and 35/50 + 60% RAP), mechanical properties of the corresponding mixtures was predicted, using SHStS transformation. First, the transformation was performed for mixtures (and corresponding binders) 35/50 and 100% RAP, based on experimental data obtained from DSR and T/C tests for binders and T/C tests for mixtures. For all binders, E00 was set equal to zero. Since E00,mix, E0,mix and α depend mainly only on the mix design (in particular, on the grading curve of the mixture), the same values were used for the three predictions. Their values were chosen equal to the average values of mixtures 35/50 and 100% RAP. A summary of the parameters used is reported in Table 2.

Table 2. Parameters used for SHStS transformation.

Material	$E_{00,binder}$ [MPa]	$E_{0,binder}$ [MPa]	$E_{00,mix}$ [MPa]	$E_{0,mix}$ [MPa]	α [-]
35/50	0	2450	14	36000	3.52
100% RAP		2740	23	39100	3.88
35/50 +20% RAP	0	2504	19	37550	3.70
35/50 + 40% RAP		2560			
35/50 + 60% RAP		2615			

Obtained with blending law

Average values of 35/50 and 100% RAP

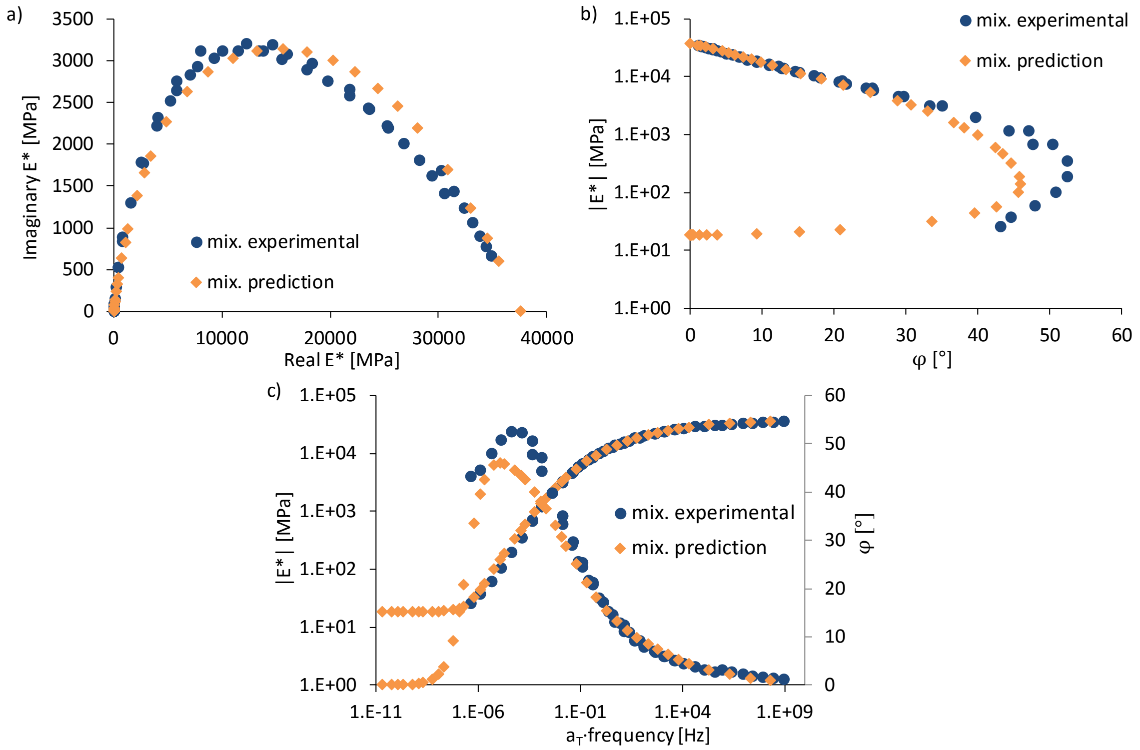

Fig. 5. Comparison of experimental results obtained from T/C tests on mixture 35/50 + 20% RAP (blue dots) and predicted behavior following the proposed procedure: (a, top left) Cole-Cole diagram; (b, top right) Black diagram; (c, bottom) Complex modulus and phase angle master curves.

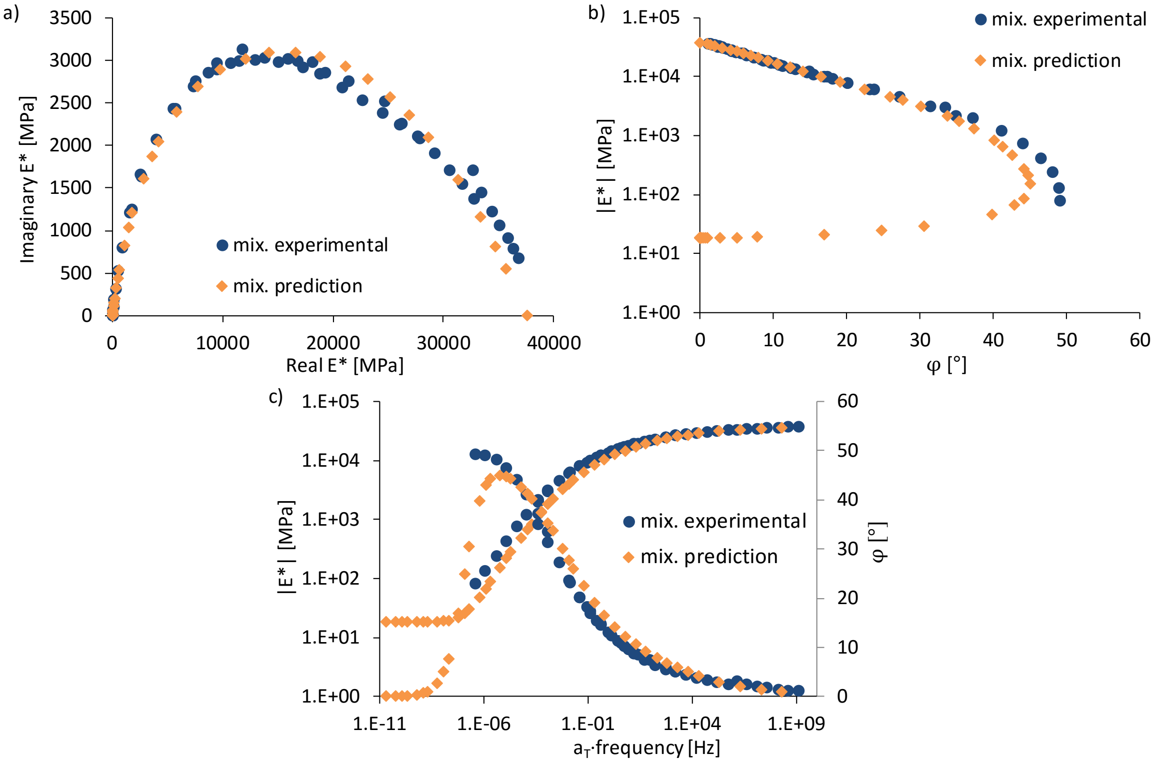

Fig. 6. Comparison of experimental results obtained from T/C tests on mixture 35/50 + 40% RAP (blue dots) and predicted behavior following the proposed procedure: (a, top left) Cole-Cole diagram; (b, top right) Black diagram; (c, bottom) Complex modulus and phase angle master curves.

Predicted LVE behaviour of the three mixtures was compared with experimental data obtained from T/C tests (Figures from 5 to 7). Satisfactory correspondence was found for all considered materials. Cole-Cole and Black diagrams show an excellent match between predicted and experimental data.

A small gap can be observed between for master curves of norm of complex modulus and phase angle of mixture 35/50 + 60% RAP (Figure 7). The gap is less important for mixture 35/50 + 40% RAP (Figure 6) and it is not observed for mixture 35/50 + 20% RAP (Figure 5). The reason for this small discrepancy is attributable to an incorrect translation of the master curves on the frequency axis. Within the SHStS method, this translation is operated during the "time shift", by means of parameter α. The fact that an average α was used for all transformations is not likely to be the cause of the observed discrepancy. For this reason, the cause of the observed gap between master curves originates in the estimation of $\tau_{0,\text{binder}}$. As already explained, this value is estimated by means of the blending law described in Section 3.2, which simulates LVE properties of a perfect blend. As already observed in literature, when common procedures are followed to produce a bituminous mixture containing RAP (as for the mixtures produced in the study), an incomplete blending occurs between RAP and fresh binder (Al-Qadi et al., 2009; Bonaquist, 2007; Eddhahak-Ouni et al., 2012; El Beze, 2008; Huang et al., 2005; McDaniel et al., 2000, among others). In previous research (Mangiafico, 2014; Mangiafico et al., 2013), it was observed that for mixtures containing RAP the variation of τ_0 values with RAP content deviates from the linear trend observed for the corresponding binder blends (perfectly blended). This observation was linked to the assumption of incomplete blending between RAP and fresh binder within the mixtures, for high RAP contents ($\geqslant$ 40%). In this study, since the value of $\tau_{0,\text{binder}}$ used is adapted to a blended binder, the application of a constant α for all transformations leads to an underestimation of $\tau_{0,\text{mixture}}$, which, in turn, generates the observed gap between master curves. However, the overall quality of the prediction does not appear to be undermined.

A slight underestimation of phase angle at intermediate temperatures and frequencies can be observed for mixtures 35/50 + 20% RAP and 35/50 + 40% RAP. This problem appears to be disappear with increasing RAP content. The choice of a lower value of $E_{00,mix}$ when performing the transformations solves this small issue.

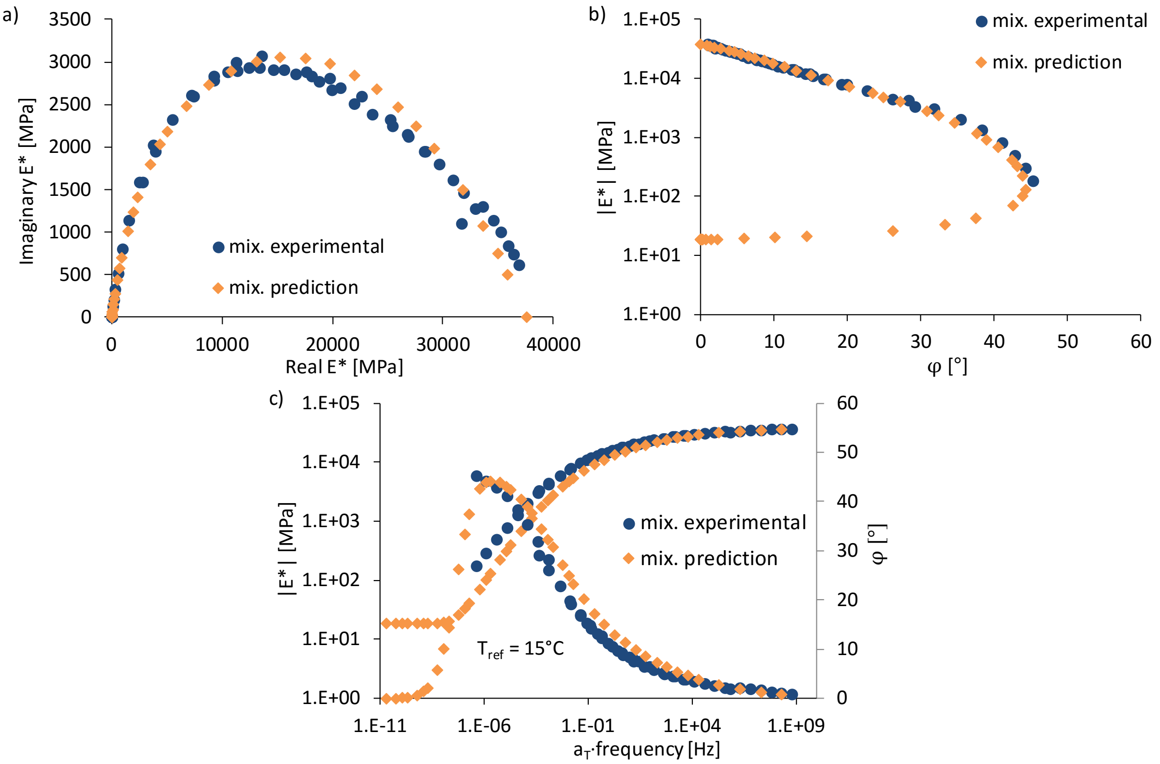

Fig. 7. Comparison of experimental results obtained from T/C tests on mixture 35/50 + 60% RAP (blue dots) and predicted behavior following the proposed procedure: (a, top left) Cole-Cole diagram; (b, top right) Black diagram; (c, bottom) Complex modulus and phase angle master curves.

5. Conclusions

A procedure is proposed to estimate LVE behavior of mixtures containing RAP over the whole range of temperatures and frequencies from properties and proportions of base constituents. The procedure consists in the joint application of two previously developed analytical tools.

Excellent correspondence was found between real experimental data and predicted LVE behavior for the three mixtures considered in the study, all produced with the same fresh binder and RAP material, with different RAP contents. A small gap in the horizontal axis was observed for the two mixtures with high RAP content ($\geqslant$ 40%). This gap can be attributable to an incomplete blending between fresh and RAP binders within the mixtures, as suggested by previous research. However, the quality of the prediction does not appear to be undermined.

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