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Modeling of the rheological properties of asphalt binder and asphalt mortar containing recycled asphalt material

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Abstract

The use of recycled materials in asphalt pavements increased significantly over the years, determining well known environmental and economic benefits. Many research agencies and road authorities evaluated the impact of Recycled Asphalt Pavement (RAP) on pavement performance. Nevertheless, the mechanism governing the interaction between virgin asphalt binder and aged RAP binder is not well understood. In this paper, the effect of RAP on the rheological properties of asphalt binders and mortars is experimentally evaluated, and theoretically modeled with the objective of defining a relationship between the linear viscoelastic (LVE) properties of binders and those of the corresponding mortars.Three asphalt binder types, obtained by blending a hard and a soft binder at three different percentages, were mixed with three different contents of a Selected fraction of Recycled Asphalt Pavement, called SRAP, for preparing the asphalt mortar samples. Dynamic Shear Rheomether tests were performed on binders and mortars to determining the complex modulus over a wide range of temperatures and frequencies. The rheological properties of the compound of virgin and RAP binder were evaluated by using a new approach based on a modified version of the Nielsen model, avoiding the extraction and recovery method.The results were then modelled by using the analogical 2S2P1D model, consisting of one spring, two parabolic and one-dashpot elements combined in series and then assembled together with a second spring in parallel. Based on test results, a simple experimental relationship between the characteristic times of the binder and the percentage of RAP in the mortar was found.

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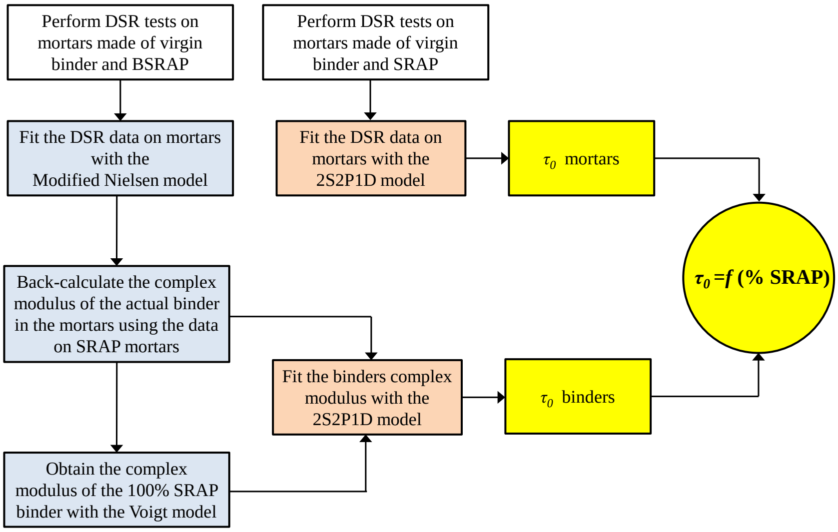
1. Introduction and objective of the research

The use of Recycled Asphalt Pavement (RAP) in asphalt mixtures is common practice in the pavement industry since almost three decades. In spite of a long experience in using RAP materials in Hot Mix Asphalt (HMA)the influence of the aged RAP binder on the final properties of the mixtures is still not well understood. Some of the methodologies available in literature address this issue either through the use of blending chart (McDaniel and Anderson 2001; Al Qadi et al., 2007) or empirical laws, such as the so-called "log-log" rule (EN 13108-1 2006). Other research efforts focused on design procedures, forensic evaluation, rheological and microstructural modeling (Zofka et al., 2005; Buttlar and Dave, 2005;CannoneFalchetto et al., 2014); however, most of them investigated blending either at the binder or at the mixture level without considering a critical intermediate phase such as asphalt mortar, for which comprehensive and reliable evaluation and prediction of linear viscoelastic properties are still missing.

In this research study, asphalt binder and asphalt mortar were investigated with the objective of determining a relationship between the linear viscoelastic (LVE) properties of binders and those of the corresponding mortars. For this purpose eighteen asphalt mortars were prepared mixing three different asphalt binders with Selected Recycled Asphalt Pavement (SRAP) material (particles smaller than 150μm).Dynamic Shear Rheometer (DSR) test were conducted on the prepared material (binder and mortars) in order to obtain the complex modulus and the phase angle master curves. The effect of RAP binder on the properties of asphalt binders and mortars was evaluated through rheological and analogical models. Specifically, the response of the combined virgin and RAP binders in the mortar was investigated and back-calculated with a new approach based on a modified version of the Nielsen model (Landel and Nielsen, 1993; Leandri et al., 2015), avoiding binder extraction and recovery. Then, the 2S2P1D model (2 Springs, 2 Parabolic elements, 1 Dashpot), developed at the Ecole Nationale des Travaux Publics de l'Etat (ENTPE) (Di Benedetto et al., 2004), was used to estimate a new expression linking the characteristic time to RAP content both for asphalt mortar and for the back-calculated binder rheological properties. Figure 1 provides the flow chart of the research approach used in this study.



SRAP: Selected Recycled Asphalt Pavement (particles smaller than 150 μm)
BSRAP: Burned Selected Recycled Asphalt Pavement (aggregate extracted by ignition from the SRAP)

Fig.1. Research approach.

2. Experiments

2.1. Materials

Eighteen different mortars were produced mixing the preheated SRAP and Burned SRAP (BSRAP, that represents the aggregate extracted by ignition from the SRAP) materials at 105 °C, with three different fresh binders, preheated at 160 °C and obtained by blending a Hard (H) and a Soft (S) binder at different percentages:

- 90%Hard+10%Soft, identified as 90H+10S;
- 80%Hard+20%Soft, identified as 80H+20S;
- 70%Hard+30%Soft, identified as 70H+30S.

The conventional binder properties, such as the Penetration grade and the softening point (EN 12591, 2009),are reported in Table 1along with the specific Performance Grade (PG) (AASHTO M320, 2010).Concerning the S binder, a viscosity of 8000 mm^2/s at 60 °C (ASTM D2170/D2170M, 2010) was measured and, therefore, due to its low consistence, it could not be characterized through traditional tests.

Table 1. Conventional test results for the different asphalt binders used.

Binder	**100H**	**90H+10S**	**80H+20S**	**70H+30S**
Pen 25 °C (dmm)	41.0	44.6	58.9	75.5
Softening point R&B (°C)	52.0	51.5	47.0	44.0
PG	64-16	64-16	64-16	58-22

The eighteen different asphalt mortars used in this research effort were prepared by mixing the three binder blends with various percentages V_p, (20%, 40% and 60%) of SRAP and BSRAP; these materials account for RAP particles smaller than 150μm (ASTM sieve #100). The use of the fine RAP fraction was selected to assure consistent reliability of the test procedure. It is good practice to prepare DSR specimens with a gap (thickness) at least ten times bigger than the actual maximum aggregate particle size (Liao et al., 2013); hence, larger aggregates were not considered, since this may potentially result in misleading measurements.

The asphalt binder content (AC) of SRAP was determined with a Soxhlet extractor and it was equal to 9.89% respect to the SRAP aggregate; therefore, the percentage of SRAP binder in mortars containing 20%, 40% and 60% SRAP was 5%, 10% and 14% by volume of mortar respectively, which correspond to 6%, 16% and 36% by volume of total binder (virgin and SRAP binder).

2.2. Tests

The three asphalt binders and the eighteen asphalt mortars were investigated using the DSR in the classical parallel-plate configuration (diameter=8mm; gap=2mm) in strain controlled mode. The strain levels reported in Table 2 were used; these values were obtained performing amplitude sweep tests in order to remain in the Linear Viscoelastic range (LVE).

Table 2. DSR strain level for asphalt binders and mortars.

Material	Temperature range	Strain
Asphalt binders	0 °C to +40 °C	γ=0.05%
V_p 20	0 °C to +40 °C	γ=0.05%
V_p 40	0 °C to +40 °C	γ=0.05%
V_p 60	0 °C to +40 °C	γ=0.005%

Frequency (from 0.2 to 20 Hz) and Temperature (from 0 to 40 °C) sweep tests were performed in order to obtain the master curves of both binders and mortars reported in the figures below.

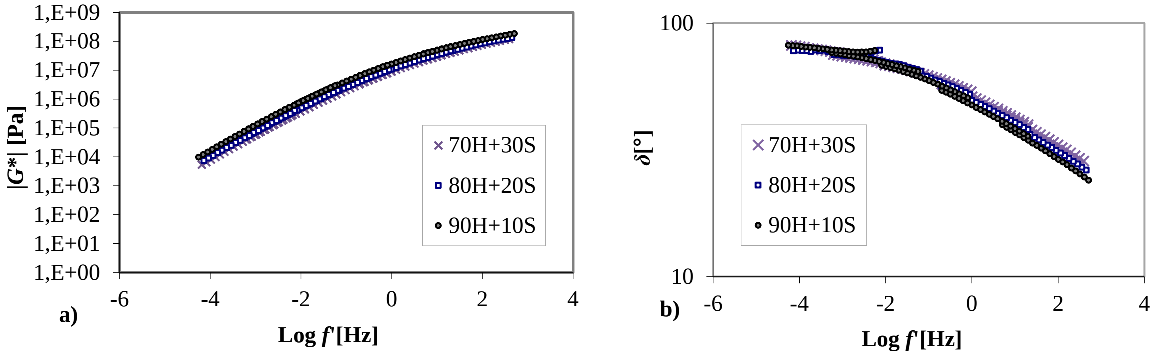


Fig. 2. Master curve of complex modulus (a) and of phase angle (b) for the three asphalt binders used.

Figure 3 shows complex modulus and phase angle master curves of different asphalt mortars containing the same percentage of SRAP (V_p=20%). In Figure 4complex modulus and phase angle master curves of mortars prepared with the same binder blend 80H+20S and different percentage of SRAP are presented.

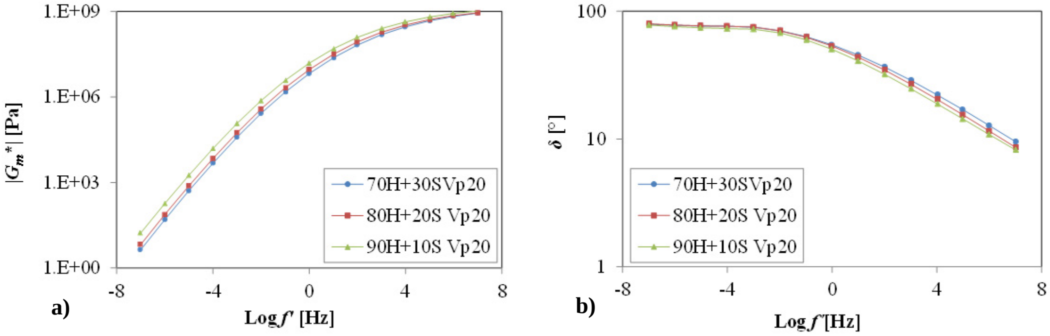


Fig. 3. Master curve of (a) complex modulus and (b) phase angle of different mortars for V_p=20%.

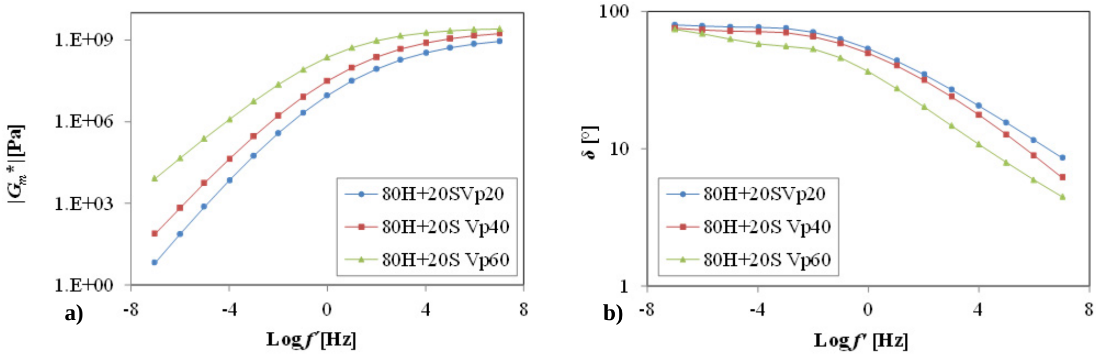


Fig. 4. Master curve of (a) complex modulus and (b) phase angle of mortars prepared binder blend 80H+20S and different V_p.

The master curves presented in Figures 3 and 4 suggest that SRAP has a significant stiffening effect on asphalt binder. This increment in stiffening is due to the hardening effect of the aged binder present in the SRAP and depends also on the volume percentage of SRAP particles added. This is especially true at low frequency where SRAP presents a dominant contribution acting as the aggregate skeleton in the asphalt mortar. Moreover, from Figure 3 it can be observed that the complex modulus decreases while the phase angle increases when the percentage of the S bitumen increases for the same V_p. This is due to the rejuvenating effect of the S binder.

3. Modeling

3.1. Modified Nielsen Model

The Modified Nielsen Model recently proposed by Leandri et al. (2015) was used to estimate the complex modulus of the binder composed by virgin and aged binder contained in the recycled material. The formulation of the model is reported in Equation (1):

$$\left(\frac{G_m^*}{G_b^*}\right) = \frac{1 + A \cdot B \cdot V_p}{1 - B \cdot \Psi \cdot V_p} - (a \cdot \ln(f) - b) V_p^c \tag{1}$$

where G_m^* is the complex modulus of the mortar (aggregate particles and binder); G_b^* is the complex modulus of the binder; V_p is the volume fraction of aggregate particles, calculated as the ratio of the particle volume over the composite (mortar) volume, in percentage; f is the frequency; a, b and c are coefficients that can be determined by a regression fitting method, considering all the BSRAP data at different V_p and different temperatures; A, B and Ψ are dimensionless model parameters. In particular coefficient A is an indicator of the physical chemical contribution to stiffening. Parameter B is a constant and accounts for the relative moduli of particles and asphalt binder phases, and the coefficient Ψ depends on the maximum volumetric packing fraction, which represents the maximum amount of particles that can be added to the matrix without the appearance of air voids. The detailed description of these parameters and the methods to calculate them can be found elsewhere(Leandri et al., 2015). Table 3 presents the parameters of the Modified Nielsen Model for the material used in the present study.

Table 3.Parameters of the modified Nielsen model.

Asphalt binder	***a***	***b***	***c***	***B***	V_p	Ψ	K_E
70%H+30%S	1.48	4.46	1.68	1	0.2	1.18	$4.57e^{0.0177\,T}$
					0.4	1.37	
					0.6	1.56	
80%H+20%S	1.30	4.06	1.20	1	0.2	1.18	$4.12\ e^{0.020\,T}$
					0.4	1.37	
					0.6	1.56	
90%H+10%S	1.14	3.41	1.20	1	0.2	1.18	$2.75\ e^{0.026\,T}$
					0.4	1.37	
					0.6	1.56	

Once the effective complex modulus of the combined virgin and RAP bindersin the mortar is back-calculated using the Modified Nielsen Model (Leandri et al., 2015), the actual RAP binder complex modulus can be determined using the simple Voigt model (Lakes, 2009) expressed by Equation (2):

$$G^*_{RAPbinder} = \frac{G_b^* - G_1^* V_1}{V_{RAPbinder}} \tag{2}$$

where $G^*_{RAPbinder}$ is the complex modulus of RAP binder; G_b^* is the complex modulus of the blend of virgin and RAP binders; G_1^* is the complex modulus of the virgin binder; $V_{RAP\ binder}$is the volume percentage of RAP binder in the bituminous blend; V_1 is the volume percentage of the virgin binder in the bituminous blend.

Based on the procedure described above, the master curves of the complex modulus of the asphalt binder consisting of 80H+20S and different percentages (0%, 6%, 16% and 36%) of RAP binder and of the back-calculated 100% RAP binder were calculated and they are reported in Figure 5.

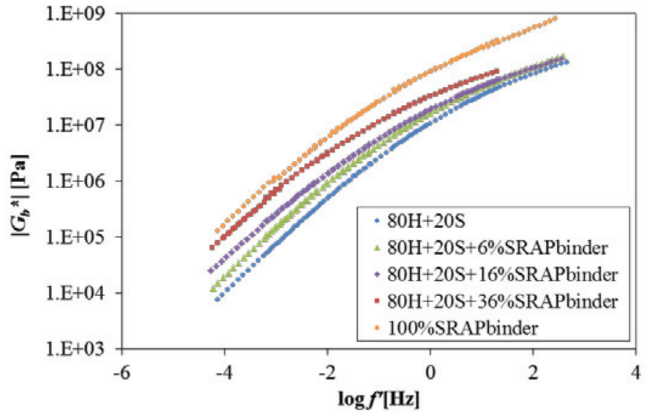


Fig. 5. Master curve of complex modulus of different bituminous blend of 80H+20S and RAP binder.

As shown in Figure 5 the stiffness of the asphalt binders is significantly affected by the recycled material content. As the percentage of RAP binder increases a substantial increase in G^* is observed especially at low frequency. This effect is associated to the much higher complex modulus of the RAP binder compared to the virgin material used.

3.2. 2S2P1D Model

The 2S2P1D model (2 springs, 2 parabolic elements, 1 dashpot) (Di Benedetto et al., 2004) is a rheological model which consists in a linear dashpot in series with the two parabolic elements and one spring of stiffness $G_{\cdot}$- G_0 assembled in parallel with a second spring (G_0). The mathematical expression of the model can be written as in Equation (3):

$$G^*(i\omega\tau) = G_0 + \frac{G_\infty - G_0}{1 + \delta(i\omega\tau)^{-k} + (i\omega\tau)^{-h} + (i\omega\beta\tau)^{-1}} \tag{3}$$

where i is the complex number defined by i^2=-1; ω is the angular frequency such that ω= 2pf_r and f_r is the reduced frequency; k and h are exponents such as $0<k<h<1$; d is a constant; G_0 is the shear modulus when $\omega \rightarrow 0$; G_∞ is the glassy shear modulus when $\omega \rightarrow \infty$; η is the Newtonian viscosity such that $\eta = (G_\infty - G_0)\beta\tau$; β is a constant; τi s the characteristic time $\tau(T) = a_T \cdot \tau_0$,where a_T is the shift factor at temperature T;$\tau_0=\tau(T_0)$ determined at the reference temperature T_0.

Therefore, seven constants (G_0, G_∞,d,k, h, β and τ) are needed to entirely determine the linear viscoelastic behavior of a specific material at a given temperature. For asphalt binders the experimental static modulus is close to zero and can be assumed as negligible; hence, the number of constants can be reduced to six.

In order to find the seven parameters of the *2S2P1D* model the sum of the square of the distance between the experimental complex modulus and the value obtained from Equation (3) at N points of pulsation ω(Cook and Weisberg, 1999; Di Benedetto et al., 2004) was minimized. In order to calibrate the model, the parameters, k, h and d were assumed to be the same both for asphalt binders and corresponding mortars, since these parameters depend only on the binder source as demonstrated in previous studies (Di Benedetto et al., 2004; Cannone Falchetto et al., 2014).

In Figure 6a a comparison between the back-calculated asphalt binder complex modulus, obtained with the modified Nielsen model, and 2S2P1D model fitting for 70H+30S binder with different percentage of SRAP binder, is shown. As previously stated 20% and 40% SRAP materials correspond to 6% and 16% of RAP binder, respectively. In Figure 6b the same Cole-Cole plot is reported for the mortars composed by 70H+30S and different percentage of SRAP (20% and 40%). As shown in the figures the model provides very good fitting of the back-calculatedvalues. In Table 4 all the 2S2P1D model parameters for asphalt binders and mortars are summarized.

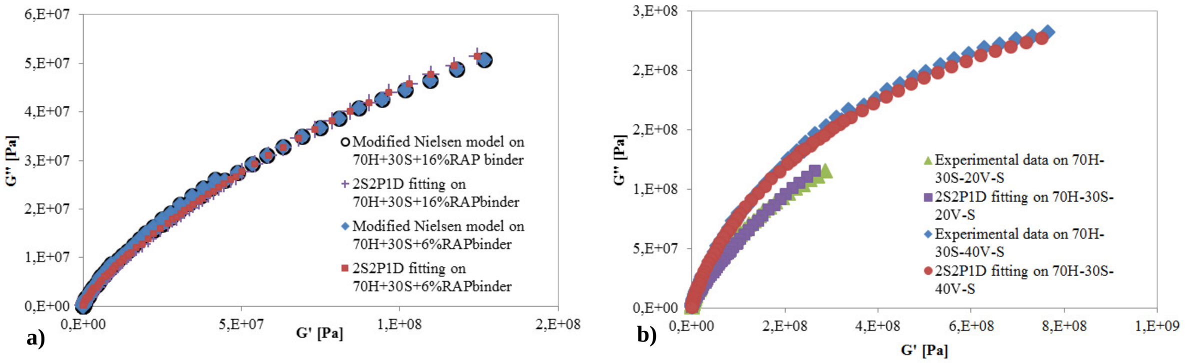


Fig. 6. a) Comparison between back-calculated complex modulus values and corresponding calibrated 2S2P1D model for 70H+30S binder at different RAP binder percentage; and b) comparison between experimental complex modulus data and corresponding calibrated 2S2P1D model for mortars composed by 70H+30S binder and different SRAP percentages.

Table 4. Parameters of the 2S2P1D model for all asphalt binders and corresponding mortars.

Material	δ	k	h	G_0 **(Pa)**	G_∞ **(MPa)**	β	**log(τ_0)**
70H+30S binder	2.61	0.19	0.56	0	600	143	-3.85
70H+30S+6% SRAP$_{binder}$	9.68	0.32	0.65	0	700	99.5	-3.47
70H+30S +16% SRAP$_{binder}$	5.59	0.25	0.64	0	800	174	-3.36
70H-30S-20V-S	9.68	0.32	0.65	400	1300	99.5	-3.35
70H-30S-40V-S	5.59	0.25	0.64	500	2300	174	-2.70
70H-30S-60V-S	2.61	0.28	0.58	700	2600	250	-2.21
80H+20S binder	3.13	0.22	0.56	0	1000	245	-3.84
80H+20S +6% SRAP$_{binder}$	5.55	0.25	0.65	0	1300	250	-3.73
80H+20S +16% SRAP$_{binder}$	13.6	0.32	0.73	0	1500	265	-3.59
80H-20S-20V-S	11.9	0.34	0.80	500	1500	250	-3.61
80H-20S-40V-S	13.6	0.32	0.73	650	2400	270	-2.98
80H-20S-60V-S	4.14	0.35	0.70	800	2700	300	-2.02
90H+10S binder	4.90	0.28	0.65	0	1000	43	-3.98
90H+10S +6% SRAP$_{binder}$	9.68	0.31	0.77	0	1400	250	-3.67
90H+10S+16% SRAP$_{binder}$	9.52	0.28	0.70	0	1600	270	-3.31
90H-10S-20V-S	9.68	0.31	0.77	550	1700	250	-3.54
90H-10S-40V-S	9.52	0.28	0.70	700	2500	270	-2.62
90H-10S-60V-S	3.67	0.29	0.66	1000	2800	300	-1.83

4. Relationship between characteristic time and RAP binder content

The relationship between characteristic time and RAP content was investigated in order to further understand the impact of recycled material on the rheological response of asphalt mortar. Figure 7a provides the evolution of the characteristic time as function of RAP binder content for back-calculated complex modulus of asphalt binders; Figure 7b represents the trend of the characteristic time of mortars versus the different volume fractionV_p, of SRAP (20, 40 and 60%). As shown in this figure the characteristic time presents a minimal increase for small RAP binder percentage, while above 50% it reaches significantly higher values. A similar trend is also in the case of mortars where the characteristic time presents limited changes for small SRAP content, while beyond 40% it starts increasing significantly.

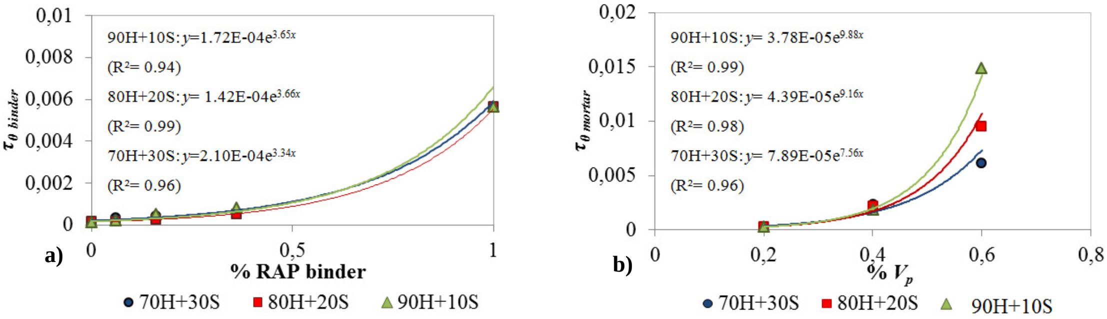


Fig. 7. Relationship between $\tau_{0binder}$ and RAP binder percentage (a), and between $\tau_{0mortar}$ and SRAP percentage (b).

Based on Figure 7 and 8, it can also be observed that the relationship between the characteristic time of asphalt binders and of mortars and SRAP percentage is exponential; in the case of asphalt binder it can be expressed by Equation (4):

$$\log \tau_0 = a \cdot e^{k \cdot \%RAP_{binder}} \tag{4}$$

Where *a* and *k* are fitting constants and *%RAP$_{binder}$* is the percentage of RAP binder. This Equation is equivalent to the one found by other authors (e.g. Mangiafico et al., 2013). Equation (4) is also valid for mortars when *%RAP$_{binder}$* is replaced by the volume percentage of SRAP, *%V$_{p,SRAP}$*:

$$\log \tau_0 = c \cdot e^{w \cdot \%V_{p,SRAP}} \tag{5}$$

where *c* and *w* are fitting constants.

5. Summary and conclusions

In this research, laboratory testing and rheological modeling were combined to evaluate the effect of a fine fraction of Recycled Asphalt Pavement (SRAP) on the mechanical behavior of asphalt binders and mortars. Shear complex modulus data were obtained with the Dynamic Shear Rheometer. Then, the modified Nielsen model and the 2S2P1D model were applied to the experimental data to determine a relationship between the linear viscoelastic (LVE) properties of binders and mortars, and the amount of recycled material. Based on the performed analysis the following conclusions can be drawn:

- A significant stiffening effect of the SRAP materials was experimentally found especially at low frequency, where the stiffer SRAP phase provides a dominant contribution.
- The properties of the asphalt binder in the mortar can be captured with the newly proposed Modified Nielsen Model. This is especially important when recycled material is used because it can potentially avoid the need of extraction and recovery process that can alter the binder properties.
- Based on the 2S2P1D model, it was found that characteristic time of the asphalt binder in the mortar depends on the recycled materials content according to an exponential function. A similar expression is valid also for the characteristic time of the corresponding mortar. This confirms previous findings of different authors.

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