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Steady shear viscosity of blends of fresh and RAP binders with rejuvenator: experimental and estimated results

A. Forton[a,b*], S. Mangiafico[a], C. Sauzéat[a], H. Di Benedetto[a], P. Marc[b]

[a] Université de Lyon/ENTPE, LTDS (UMR CNRS 5513), rue Maurice Audin, 69518 Vaulx-en-Velin Cedex, France;
[b] University Politehnica Timisoara, Piata Victoriei, 300006 Timisoara, Romania;
andrei.forton@student.upt.ro; salvatore.mangiafico@entpe.fr; cedric.sauzeat@entpe.fr;
herve.dibenedetto@entpe.fr; paul.marc@upt.ro
[*] corresponding author

Abstract

This paper focuses on the influence of the RAP-extracted binder and rejuvenator contents on the steady shear viscosity obtained as a linear viscoelastic property of different binder blends. One pure fresh 50/70 binder, a RAP-extracted binder and a rejuvenator of vegetal origin were mixed in different dosages. Steady shear viscosity (η_0) values at different temperatures (from 25°C to 85ºC) were determined from complex shear modulus results for all tested binders. In addition, $\eta_0(T)$ values of all binder blends were estimated from $\eta_0(T)$ values of base constituents by using two different approaches. Good correspondences with experimental results were found.

Keywords: RAP binder; rejuvenator; steady shear viscosity; binder blends; estimations.

Highlights

- Viscoelastic properties (steady shear viscosity) of several binders were studied.
- Steady shear viscosity η_0 at 85°C was determined from complex shear modulus results.
- $\eta_0(T)$ were calculated from $\eta_0(T_{ref} = 85°C)$ and a_T shift factor at temperature T.
- $\eta_0(T)$ of all binder blends were estimated with two different approaches.

1. Introduction

For economic and environmental reasons, the use of Reclaimed Asphalt Pavement (RAP) in the production of new bituminous mixtures HMA (hot-mix asphalt) [1], [2], [3], [4], [5] and WMA (warm-mix asphalt) [6], [7] has become a common strategy for the construction and maintenance of roads.

Due to the long-term aging process, the physical and rheological properties as well as the chemical structure of the RAP-bitumen suffer irreversible changes [8], [9]. For these reasons, in order to achieve an adequate workability and good mechanical performance of a new bituminous mixture containing RAP material, a softer bitumen [10], [11] or some rejuvenators [12], [13], [14], [15], [16], [17] could be used.

Many studies showed the efficiency of using vegetal oils by evaluating the conventional properties (such as penetration, ductility, Fraass temperature, ring and ball temperature), fatigue or complex modulus of final blends produced with these products, different RAP binders and different base fresh binders [1], [18], [19], [20], [21], [22].

The binder has a very complex thermomechanical behaviour that is influenced by the temperature, the speed and the of the load level. In a width range of loading the behaviour can be considered as linear viscoelastic [23]. The linear viscoelastic response of a binder is commonly analysed in terms of complex shear modulus.

Di Benedetto and Corté (2005) indicated different behaviors of bituminous materials based on the temperature (T) and the amplitude of the deformation (|ε|). As it can be observed in Figure 1, the following behaviors of binders can be distinguished: the brittle and the ductile domains, the linear elastic behavior (characterized by E and G), the linear viscoelastic (LVE) domain (characterized by E* and G*), the purely viscous Newtonian behavior (characterized by the viscosity η), the fragile rupture (characterized by the toughness K_c) and the non-linear domain.

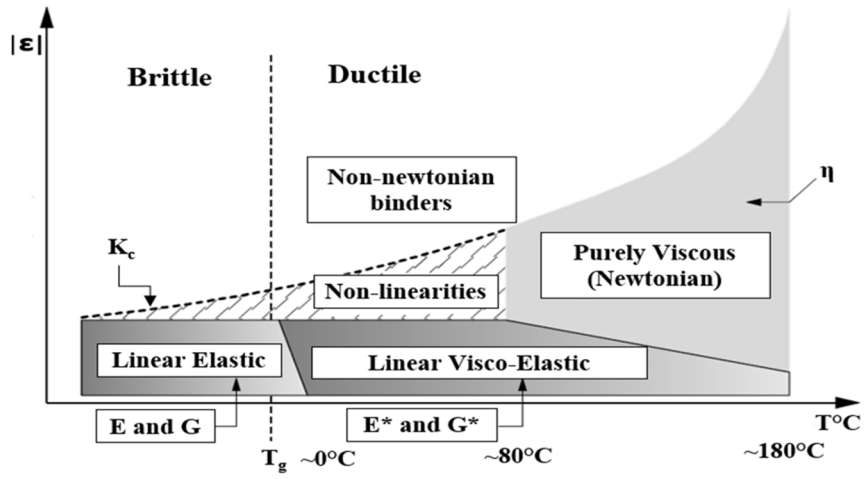

Figure 1. Binder behaviors as a function of T and |ε| [23].

The relation between temperature and viscosity is very important in the context of determining and evaluating some characteristics such as adhesion, rheology, durability, etc. of binders.

Therefore, the characterization and the understanding of the viscoelastic behaviour of binders it can be considered essential in the design process of a bituminous mixture due to the fact that the binder has an important influence on the mechanical response of the bituminous mixture [7].

Complex shear modulus (G^*) together with the steady and complex shear viscosities are the most important rheological properties, used to characterize the linear viscoelastic behaviour of binders. Viscosity is a fundamental characteristic property of binders and rejuvenators and it can be determined by several methods [24], [25], [26].

The complex viscosity (η^*) determined by oscillatory test is defined as the ratio between the complex shear modulus G^* and the angular frequency ω, multiplied by i (i^2=-1).

Steady shear viscosity (η_0) at a given temperature corresponds to the limit of the norm of the complex viscosity $|\eta^*|$ when angular frequency ω tends towards zero.

The objective of this paper is to study the properties of several binder blends between one type of fresh binder, a RAP binder with/without a rejuvenator of vegetal origin by evaluating the steady shear viscosity at different temperatures ($\eta_0(T)$). The experimental plan includes seventeen binders. The materials used are specific for Romania.

In addition, steady shear viscosity values of all binder blends were estimated with two different approaches from values of $\eta_0(T)$ of the base constituents. Correlation plots between the experimental and estimated results (with both approaches) were analysed in order to verify if these two estimation approaches are valid for these tested binders. Similar estimation methods were used in order to estimate the conventional properties of the same binder blends in [27].

2. Materials

Three base materials were used: one type of fresh binder (a 50/70 pen. grade binder), a RAP binder (extracted and recovered from a RAP material) and one type of rejuvenator (a mixture of vegetal oils).

The RAP material was classified and described by performing the tests required by EN 13108-8 [28]. Its measured binder content is 4.0%.

The rejuvenator (Rej) was used in four dosages from 0% to 15% by mass of RAP binder (with a 5% increment) corresponding to 0.0%, 0.2%, 0.4% and 0.6% by mass of the RAP material.

The experimental campaign considers 17 binders: 15 blends (12 blends of the three base materials and 3 blends between the base RAP binder and the rejuvenator) and the two base binders (Table 1). It must be mentioned that different properties of the same binder blends were analysed in Forton et. al [27, 29].

Proportions of these three base components (RAP binder, fresh binder and rejuvenator) were calculated in order to reproduce real ratios within corresponding bituminous mixtures (having a total binder content 5.6%) containing 25%, 50%, 75% and 100% RAP material and different dosages of Rej. A summary table regarding the proportions for all binders is reported in Table 1.

To simplify, binder blends were named according to the penetration grade of the fresh bitumen (50/70), the dosage of RAP material used for the production of bituminous mixture (25%, 50%, 75%) and the dosage of the rejuvenator by the mass of RAP bitumen (5%, 10%, 15%).

Table 1. Weight proportion of the three base materials (fresh and RAP binders and the rejuvenator) in tested binders [24]

Bitumens	weight proportion in percent (%)		
	50/70	RAP	Rej
50/70	100.0	-	-
RAP	-	100.0	-
RAP + 5% Rej	-	95.2	4.8
RAP + 10% Rej	-	90.9	9.1
RAP + 15% Rej	-	87.0	13.0
50/70 + 25% RAP	82.1	17.9	-
50/70 + 50% RAP	64.3	35.7	-
50/70 + 75% RAP	46.4	53.6	-
50/70 + 25% RAP + 5% Rej	81.4	17.7	0.9
50/70 + 50% RAP + 5% Rej	63.1	35.1	1.8
50/70 + 75% RAP + 5% Rej	45.22	52.17	2.61
50/70 + 25% RAP + 10% Rej	80.7	17.5	1.8
50/70 + 50% RAP + 10% Rej	62.1	34.5	3.4
50/70 + 75% RAP + 10% Rej	44.1	50.8	5.1
50/70 + 25% RAP + 15% Rej	80.0	17.4	2.6
50/70 + 50% RAP + 15% Rej	61.0	33.9	5.1
50/70 + 75% RAP + 15% Rej	43.0	49.6	7.4

The procedures used to produce the studied binder blends were chosen in order to reproduce in laboratory the actual production process of bituminous mixtures containing RAP material and rejuvenator.

Therefore, the fresh and RAP binders were heated at 160ºC in a thermostatic oven. The rejuvenator was not heated before blending. All binder blends were produced in two steps. First, the rejuvenator (at ambient temperature) was added to fresh binder (which was heated for 30 min) and this preliminary blend was manually mixed for 5 minutes. This blend was than heated for 20 min at

160ºC. Secondly, the RAP binder was added, and this final blend was manually mixed for 5 minutes in order to produce a homogenous blend. The 160ºC temperature was chosen with respect to the Romanian technical specifications for the production of bituminous mixtures.

3. Experimental campaign

3.1 Complex shear modulus test

A DSR apparatus with a 25 mm diameter plate-plate configuration with a 1 mm gap was used at temperatures ranging from 25ºC to 85ºC and at frequencies ranging from 0.1 Hz to 10 Hz.

As all the tests, for all considered binder blends, were performed at intermediate and high temperatures, a 5% shear strain amplitude, which is the Linear Visco-Elastic domain according to Airey, Rahimzadeh & Collop (2003) [30], was imposed.

Tests were performed at 5% targeted shear strain amplitude (γ), by imposing a sinusoidal shear strain signal and measuring the corresponding shear stress. However, the torque limit of the instrument was reached for strain amplitudes lower than the 5% targeted value during some tests at the lowest temperatures and highest frequencies [29]. Therefore, these tests were performed at strain amplitudes lower than 5%.

In order to highlight the influence of RAP binder and Rej content on the behaviour of the final blends, master curves of norm of complex shear modulus $|G^*|$ were built for all blends at a reference temperature of T_{ref} = 85ºC. The Time–Temperature Superposition Principle (TTSP) was applied and verified for all binders, temperature shift factors (a_T) were obtained and the master curves were plotted for all binders according to equation 1 [9], [27], [31], [32], [33].

$$|G^*(T,f)| = \left|G^*(T_{ref}, a_T \cdot f)\right| \quad (1)$$

where T is the test temperature, T_{ref} is the reference temperature and f is the frequency.

Master curves of $|G^*|$ and shift factors a_T at a reference temperature of 85ºC for the two base binders and RAP + Rej blends are shown in Figure 2 a and b, as an example. Data obtained at low temperature/high frequency during cycles performed at variable strain amplitude γ (lower than the targeted 5% value) are plotted with crossed (×).

The data presented in Black diagram (Figure 2 c) are located on a unique curve for each of the considered blends. It means that the time temperature superposition principle (TTSP) is valid for all tested binders. Then they are thermorheologically simple even when containing the rejuvenator.

It is observed that with increasing Rej content in the blends, the master curves of RAP + Rej blends progressively approach the one of the pure bitumen. The same tendency was observed for the a_T shift factors, with blends RAP + 10% Rej and RAP + 15% Rej having even lower a_T values than fresh 50/70 binder. Shift factor values a_T at a reference temperature of 85ºC for all binders are reported in Table A.1 (Appendix). Similar tendencies were observed in Forton et. al [27, 29] for the blends produced with fresh binder, 50% RAP and different amounts of rejuvenator at a reference temperature of 25ºC.

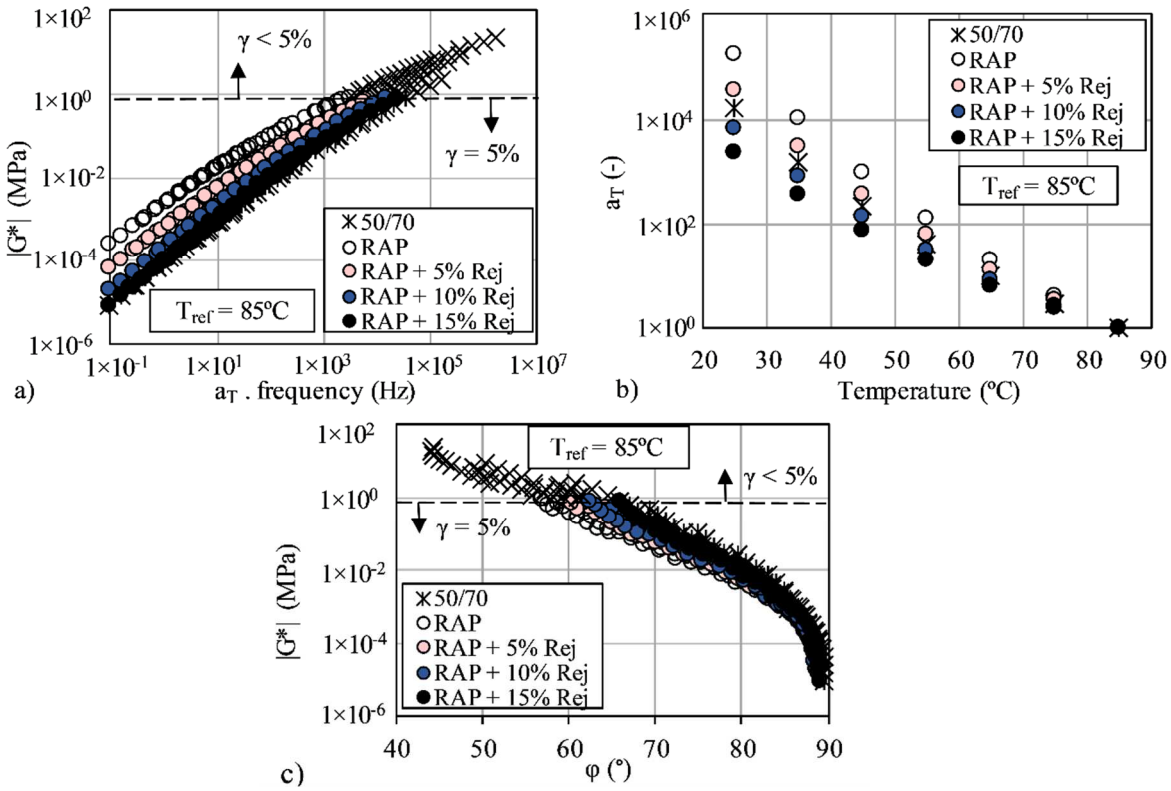

Figure 2. DSR complex modulus test results for 50/70 binder and RAP + Rej blends: (a) master curves of $|G^*|$ at 85ºC; (b) temperature shift factors at 85ºC; (c) Black diagram.

3.2 Determination of steady shear viscosity at 85ºC from DSR test results

Steady shear viscosity (η_0) at a given temperature (85°C) corresponds to the limit of the norm of the complex viscosity $|\eta^*|$ when the angular frequency ω tends towards zero (equation 2) [27].

$$\eta_0 = |\eta^*| = \frac{|G^*|}{\omega}, \omega \to 0 \quad (2)$$

$$log|G^*| = log\,\omega + log|\eta^*| - logarithmic\ form\ of\ equation\ (2) \quad (3)$$

As an example, Figure 3 ($|G^*|$ vs. ω, in a log-log scale) shows how η_0 values were obtained, by highlighting the Newtonian behaviour by analysing the high temperature/low frequency part of the curves [27], for fresh binder, RAP binder and their blends. The obtained η_0 values for all binders are shown in Table A.1 (Appendix).

As it can be observed in Figure 4, η_0 values at 85ºC increase with the increase of RAP binder content in the blends. Linear regressions (in logarithmic scale) could be performed on the obtained η_0 values at different temperatures with good approximation. Moreover, η_0 values decrease with the increase of rejuvenator content in the blends. These results were expected.

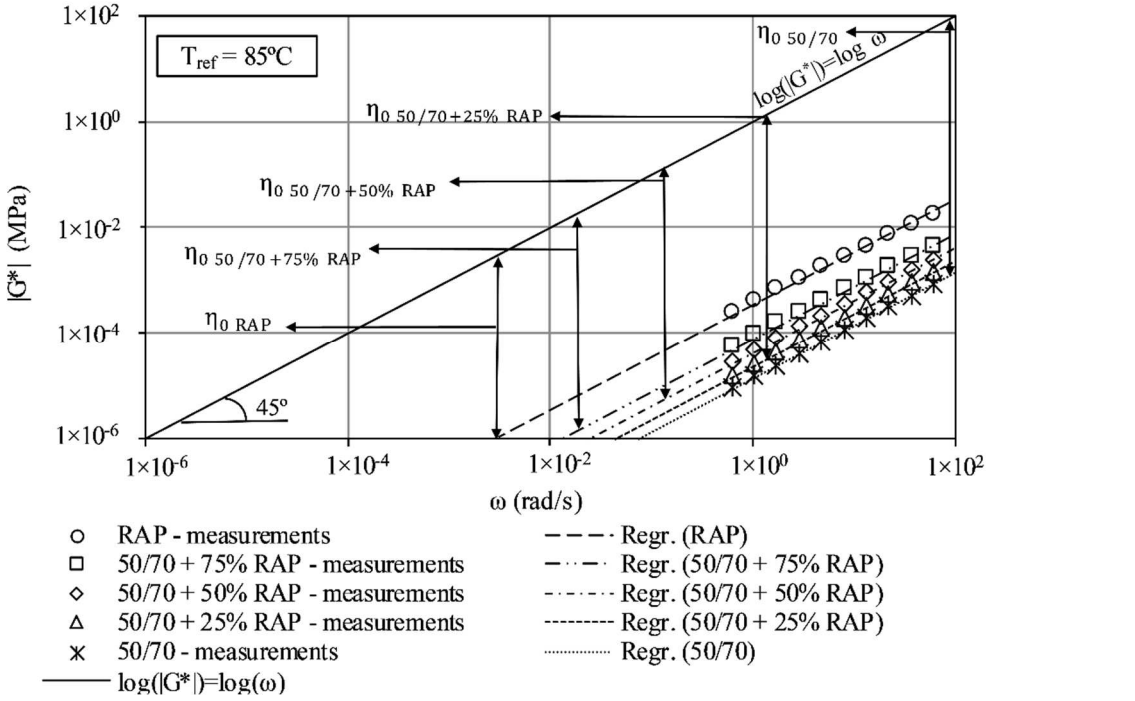

Figure 3. Steady shear viscosity (η_0) at 85ºC of 50/70 fresh and RAP binders and their blends.

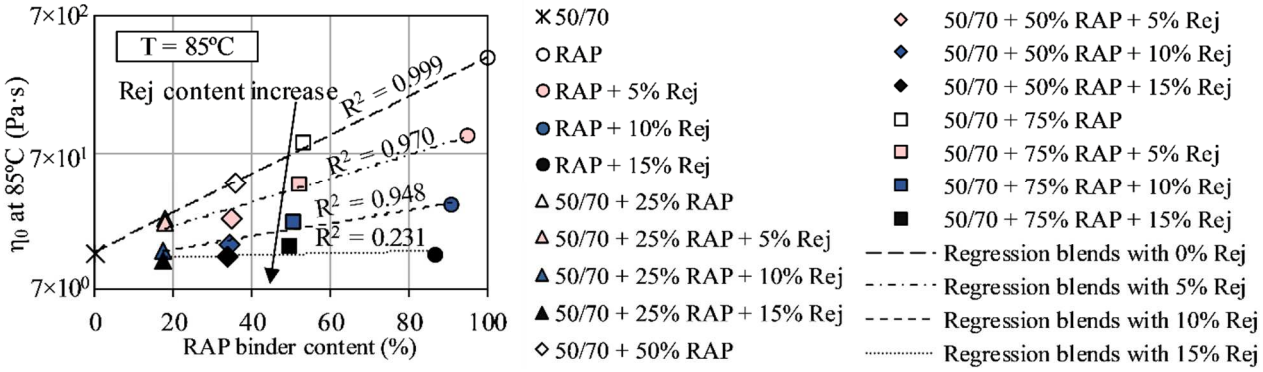

Figure 4. Steady shear viscosity at 85ºC for all binders.

3.3 Determination of steady shear viscosity at different temperatures

In order to calculate η_0 values for all binders at different temperatures equation (4) was used. In this equation, the value of the steady shear viscosity at a temperature *T*, $(\eta_0(T))$ is calculated from the values of the steady shear viscosity at the reference temperature of 85°C, $\eta_0(T_{ref} = 85°C)$, multiplied by the temperature shift factor at temperature *T*, a_T. The same shift factors used to build $|G^*|$ master curves are used.

$$\eta_0(T) = a_T \cdot \eta_0(T_{ref}) \quad (4)$$

The steady shear viscosity was calculated with equation (4) for all binders at temperatures from 25ºC to 75ºC. Results are reported in Table A.1 (Appendix) and in Figure 5.

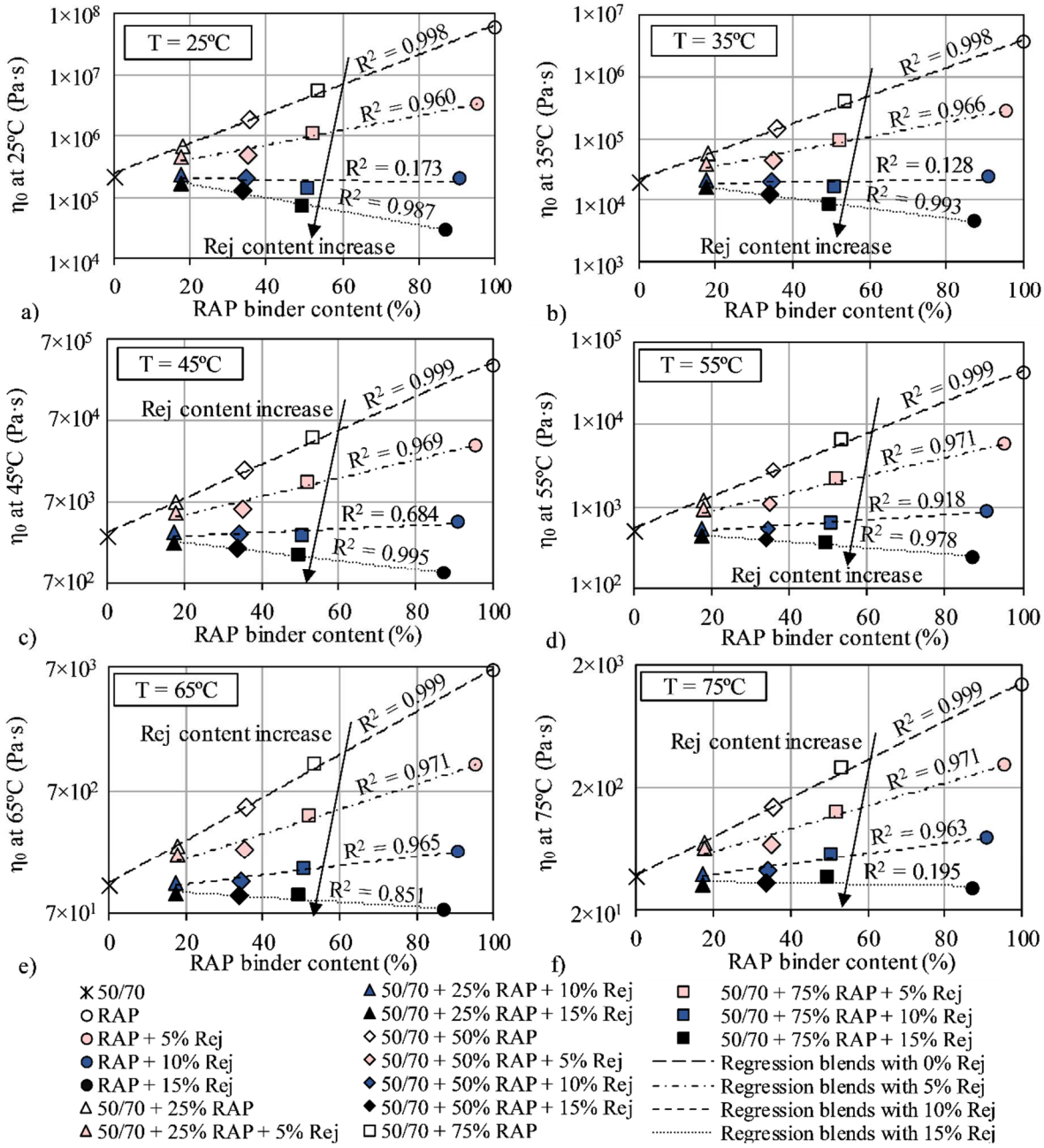

Figure 5. Results of steady shear viscosity at different temperatures for all binders: (a) T = 25ºC; (b) T = 35ºC; (c) T = 45ºC; (d) T = 55ºC; (e) T = 65ºC; (f) T = 75ºC.

As expected, values of $\eta_0(T)$ decrease with the increase of temperature. Also, $\eta_0(T)$ increase with increasing RAP binder content in the blends and decrease with the increase of Rej content within blends. Linear regressions in logarithmic scale as a function of RAP binder content were performed with rather good approximation for all binders, at all considered temperatures. As it can be observed in Figure 5 a and b and Table A.1 (Appendix), the values of $\eta_0(T)$ at low temperatures (25ºC and 35ºC) of the blends containing 10% Rej (independently of the RAP binder content) are close to the results obtained for the base fresh binder. This observation is not valid at higher temperatures (where $\eta_0(T)$ increases with the increasing RAP bitumen content).

4. Estimation of steady shear viscosity

Two approaches were proposed in order to determine the estimated values of $\eta_0(T)$ at different temperatures (from 25ºC to 85ºC) of all produced binder blends. The obtained results were then compared with the experimental values determined in Section 3.3. Similar estimation approaches were used in the case of the conventional properties of same binder blends and both approaches were considered valid (good correspondences were found between estimated and experimental values of the European conventional parameters) [27].

4.1 1st approach: two-way blending rule

The 1st approach considers the classical blending rule expressed in equation (5), which supposes that $\eta_0(T)$ values for fresh binder, RAP binder and blends of RAP + Rej (at the three different dosages used in the study) are used as input values. For this approach, $\eta_0(T)$ values for RAP + Rej blends must be known from experimental tests, which is a drawback as these blends should be tested for each of the three considered Rej contents (5%, 10% and 15%).

In the equation (5), known as log-log rule, [34], the estimated value of η_0 of any of the 12 blends at a given temperature ($\eta_{blend\ est.\ 1\ (T)}$) is determined from the experimental results of fresh binder $\eta_0(T)_{(50/70)}$, and RAP + Rej blends, $\eta_0(T)_{(RAP+Rej)}$, as a function of the relative mass concentration a of fresh binder in the blend.

$$log\ \eta_{blend\ est.\ 1}(T) = a \cdot log\ \eta_0(T)_{(50/70)} + (1-a) \cdot log\ \eta_0(T)_{(RAP+Rej)} \quad (5)$$

4.2 2nd approach: three-way blending rule

The 2nd approach consists in the three-way blending rule expressed in equation (6), which requires as input data only the values of $\eta_0(T)$ for the three base materials used in this study.

The estimated values of steady shear viscosity at a given temperature for any of the 15 blends ($\eta_{blend\ est.\ 2\ (T)}$) were calculated from the experimental results of fresh binder ($\eta_0(T)_{(50/70)}$), RAP binder ($\eta_0(T)_{(RAP)}$) and from equivalent values of the rejuvenator ($\eta_0(T)_{(Rej)}$).

$$log\ \eta_{blend\ est.\ 2}(T) = a \cdot log\ \eta_0(T)_{(50/70)} + b \cdot log\ \eta_0(T)_{(RAP)} + c \cdot log\ \eta_0(T)_{(Rej)} \quad (6)$$

where a, b and c are the relative mass concentrations of the three base materials, respectively ($a + b + c = 1$).

Equation (6) could be rewritten as equation (7), considering that a and c could be calculated as functions of b and of the percentage of Rej by the mass of RAP binder, r ($c = r \cdot b$).

$$log\ \eta_{blend\ est.\ 2}(T) = [1 - b \cdot (1+r)] \cdot log\ \eta_0(T)_{(50/70)} + b \cdot log\ \eta_0(T)_{(RAP)} + b \cdot r \cdot log\ \eta_0(T)_{(Rej)} \quad (7)$$

In order to obtain the equivalent values for the rejuvenator of ($\eta_0(T)_{(Rej)}$) at a given temperature, it was necessary to optimize the correlation between experimental results and estimated values of blends ($\eta_{blend\ est.\ 2\ (T)}$). The least square method was used by maximizing the R^2 value of the estimated vs. experimental correlation in order to obtain $\eta_0(T)_{(Rej)}$. It should be mentioned that these equivalent $\eta_0(T)_{(Rej)}$ values were used only for this second estimation approach, which is valid only for rather small Rej content (up to 15%). This equivalent viscosity is not equal to the viscosity of the rejuvenator used for this study.

In Figure 6, the experimental results of η_0 at different temperatures for RAP + Rej blends are plotted as a function of the rejuvenator content, together with the equivalent values of $\eta_0(T)_{(Rej)}$ determined for the rejuvenator. Linear regressions could be performed with excellent approximation at all considered temperatures. It was observed that all the regression lines can be obtained with the same R^2 (influence only on the 4th decimal) when considering that all lines intersect a unique point: 35% Rej content and 0.038 Pa·s. Figure 6 gives an overview of these results.

These results led to the idea of a "temperature-independent constant content-viscosity couple" for the rejuvenator which is expressed in Equations (8) and (9), where viscosity is expressed in Pa.s. Equation (8) is in fact equation (6) in which the amount of the fresh binder is equal to zero and $\eta_{blend\ est.\ 2}(T) = \eta_{RAP+35\%\ Rej} = 0.038\ Pa \cdot s$. Equation (7) can then be rewritten as in equation (10), consisting in the final form of the 2nd approach when viscosity is expressed in Pa.s.

$$log\ 0.038 = 0.65\ log\ \eta_0(T)_{(RAP)} + 0.35\ log\ \eta_0(T)_{(Rej)} \tag{8}$$

$$log\ \eta_0(T)_{(Rej)} = \frac{log\ 0.038}{0.35} - \frac{0.65}{0.35} log\ \eta_0(T)_{(RAP)} \tag{9}$$

$$log\ \eta_{blend\ est.2}(T) = [1 - b(1+r)]\ log\ \eta_0(T)_{(50/70)} + b\left(1 - \frac{0.65}{0.35}r\right) log\ \eta_0(T)_{(RAP)} + \frac{b \cdot r}{0.35} log\ 0.038 \tag{10}$$

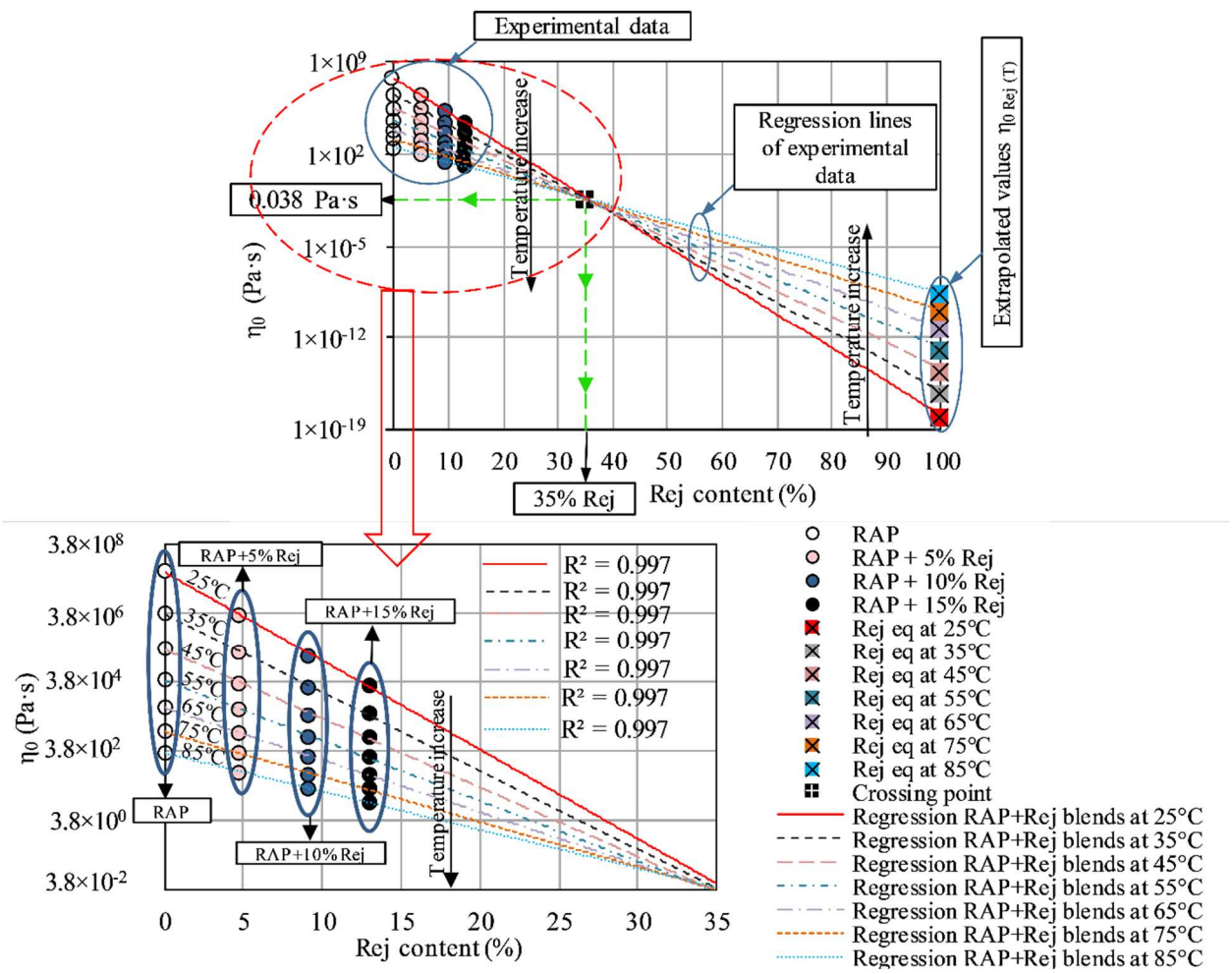

Figure 6. Experimental results of $\eta_0(T)$ for RAP + Rej blends, equivalent values for rejuvenator $\eta_0(T)_{(Rej)}$, plotted as a function of Rej content in the blends, at all considered temperatures.

4.3 Analysis of results

Plots of the estimated results obtained from the 1st approach and the 2nd approach versus the experimental results are and shown in Figure 7. Estimated results of $\eta_0(T)$ of all blends are reported in Table A.2 and Table A.3 (Appendix).

The coefficient of determination (R^2) was calculated for each plot with respect to the equality line.

In order to calculate R^2 for the 1st approach, steady shear viscosity values of the base constituents (fresh 50/70 binder, RAP binder and the three RAP + Rej blends, for a total of five binders) were not taken into account. Regarding the 2nd approach, R^2 was calculated without considering the steady shear viscosity values of the base constituents: fresh 50/70 binder, RAP binder and the 'temperature-independent constant content-viscosity couple' for the rejuvenator. These values are not considered because they correspond to input data, which are perfectly estimated.

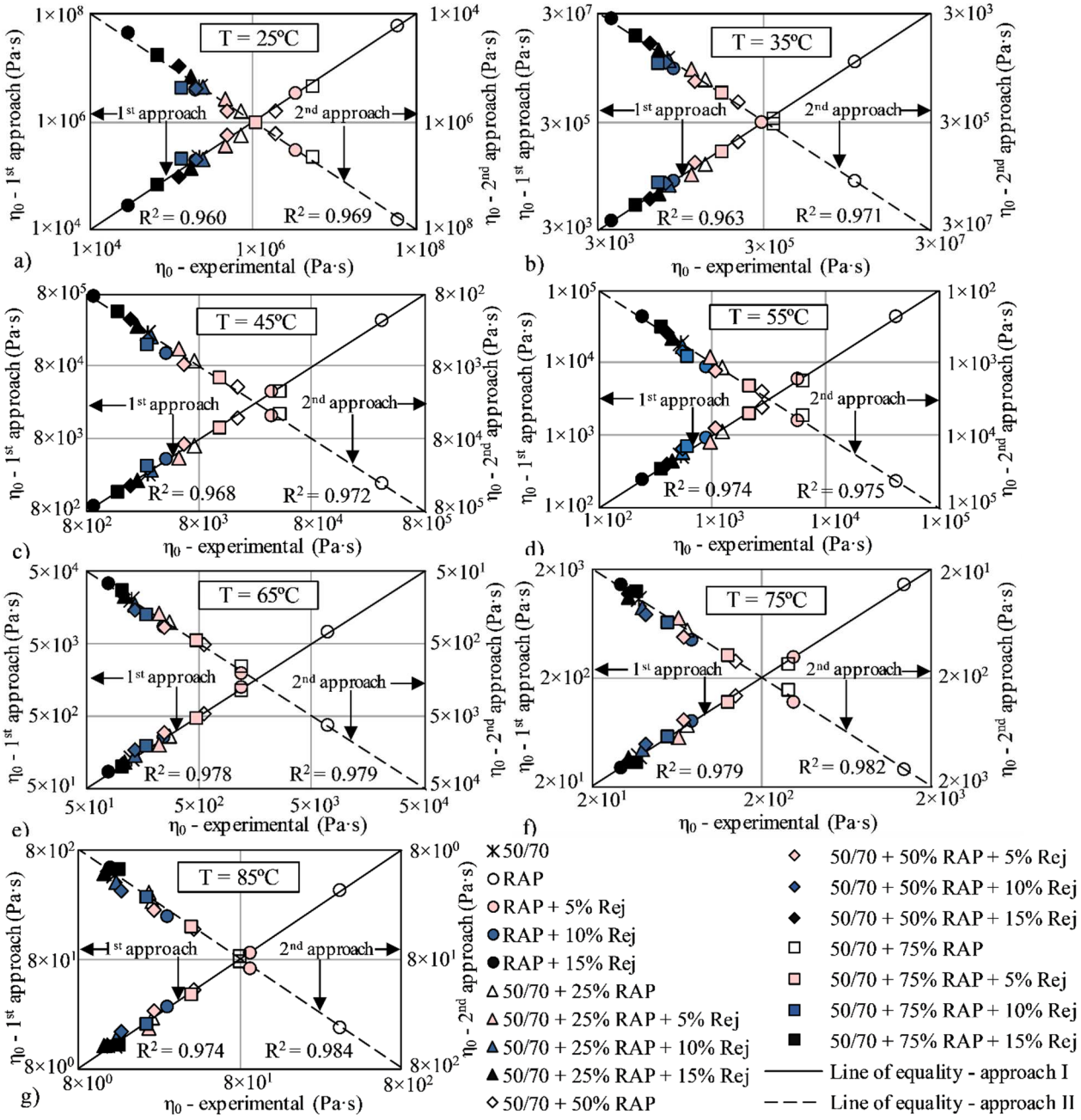

Figure 7. Plots of estimated vs. experimental results of steady shear viscosity for all binder blends: (a) T = 25ºC; (b) T = 35ºC; (c) T = 45ºC; (d) T = 55ºC; (e) T = 65ºC; (f) T = 75ºC; (g) T = 85ºC.

As it can be observed in Figure 7, the estimated results ($\eta_{blend\ est.\ 1}(T)$, $\eta_{blend\ est.\ 2}(T)$) of all binder blends are close to the corresponding experimental results. It can be noticed that with the decrease of temperature (from 85ºC to 25ºC) R^2 values decrease but they are still satisfactory (always higher than 0.960).

R^2 values obtained in the case of the 2nd approach are always higher than 0.969 and greater than the values obtained with the 1st approach. Considering the goodness of the correlation with experimental points and the reduced number of input data necessary, the 2nd approach can be considered more advantageous than the 1st approach.

As a general comment, with the 2nd approach a total of 105 η_0 values were estimated, at seven different temperatures for 15 blends, using as input data the experimental results of η_0 obtained at a reference temperature of 85ºC, $\eta_0(T_{ref} = 85°C)$, for fresh and RAP binders and the 'temperature-independent constant couple' for the rejuvenator. A global correlation plot between all these estimated values obtained by applying the 2nd approach and the experimental values of the 15 blends is shown in Figure 8. A satisfactory global R^2 was found (0.977).

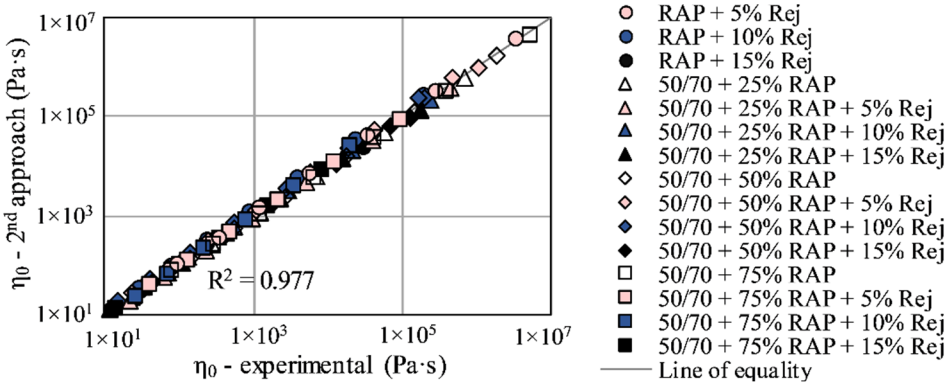

Figure 8. Global correlation plot of estimated (2nd approach) vs. experimental results of $\eta_0(T)$ at temperatures from 85ºC to 25ºC for the 15 blends of fresh 50/70, RAP binders and rejuvenator (Rej).

5. Conclusions

The objectives of the presented work were to study the influence of the addition of a rejuvenator of vegetal origin on the steady shear viscosity of binder blends of fresh and RAP binders and to propose two approaches in order to estimate η_0 of all blends from experimental results obtained for the base constituents.

Three base materials were used in this study: one type of pure bitumen (50/70), a RAP bitumen and a rejuvenator, which were blended in different proportions, producing 17 binders (including the two base bitumens).

Complex shear modulus tests were performed on all binders at temperatures from 25ºC to 85ºC and at frequencies from 0.1 Hz to 10 Hz. The Time-Temperature Superposition Principle was validated for all tested binders. Steady shear viscosity (η_0) at 85ºC was obtained as the norm of complex viscosity at high temperature/low frequency in the domain of Newtonian behaviour of binders. η_0 values at temperatures from 75ºC to 25ºC were calculated from the experimental values of η_0 at the reference temperature of 85°C, ($\eta_0(T_{ref} = 85°C)$), multiplied by the shift factors. Two different estimation approaches were proposed and η_0 values were estimated for all produced binder blends at all temperatures from 25ºC to 85ºC, from η_0 values of base constituents.

From the obtained results it can be concluded that, for all temperatures, η_0 values are increasing with the increase of RAP binder content and with the decrease of Rej content in the blends. The addition of the rejuvenator was observed to counterbalance the stiffening effect of the RAP binder in the blends. These effects that were expected are clearly quantified and well estimated by the two proposed approaches.

Slightly better correspondence was found between estimated η_0 values obtained with the 2nd approach, which is an original input of this work, and experimental values (R^2 values always higher than those found with the 1st approach, which is based on the classical log-log rule). Moreover, the

2nd approach has also the great advantage to need only one data for each of the three base constituents when the dosage if fixed.

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Appendix

Table A.1. a_T shift factors values at a reference temperature of 85ºC and experimental results of steady shear viscosity, $\eta_0(T)$, at different temperatures for all tested binders.

Binders	a_T (-) at T_{ref} = 85ºC							$\eta_0(T)$, (Pa·s)						
	85ºC	75ºC	65ºC	55ºC	45ºC	35ºC	25ºC	85ºC	75ºC	65ºC	55ºC	45ºC	35ºC	25ºC
50/70	1	2.87×10^{0}	9.65×10^{0}	3.95×10^{1}	2.08×10^{2}	1.51×10^{3}	1.67×10^{4}	1.32×10^{1}	3.79×10^{1}	1.27×10^{2}	5.22×10^{2}	2.74×10^{3}	1.99×10^{4}	2.21×10^{5}
RAP	1	4.14×10^{0}	2.05×10^{1}	1.26×10^{2}	9.96×10^{2}	1.09×10^{4}	1.77×10^{5}	3.39×10^{2}	1.41×10^{3}	6.96×10^{3}	4.26×10^{4}	3.38×10^{5}	3.69×10^{6}	6.01×10^{7}
RAP + 5% Rej	1	3.33×10^{0}	1.30×10^{1}	6.17×10^{1}	3.72×10^{2}	3.02×10^{3}	3.59×10^{4}	9.36×10^{1}	3.12×10^{2}	1.22×10^{3}	5.78×10^{3}	3.48×10^{4}	2.83×10^{5}	3.36×10^{6}
RAP + 10% Rej	1	2.70×10^{0}	8.40×10^{0}	3.09×10^{1}	1.41×10^{2}	8.33×10^{2}	6.97×10^{3}	2.90×10^{1}	7.84×10^{1}	2.44×10^{2}	8.97×10^{2}	4.08×10^{3}	2.42×10^{4}	2.02×10^{5}
RAP + 15% Rej	1	2.35×10^{0}	6.24×10^{0}	1.94×10^{1}	7.30×10^{1}	3.52×10^{2}	2.35×10^{3}	1.27×10^{1}	2.99×10^{1}	7.96×10^{1}	2.47×10^{2}	9.30×10^{2}	4.49×10^{3}	3.02×10^{4}
50/70 + 25% RAP	1	3.14×10^{0}	1.16×10^{1}	5.28×10^{1}	3.08×10^{2}	2.47×10^{3}	3.01×10^{4}	2.31×10^{1}	7.27×10^{1}	2.69×10^{2}	1.22×10^{3}	7.11×10^{3}	5.71×10^{4}	6.95×10^{5}
50/70 + 25% RAP + 5% Rej	1	2.96×10^{0}	1.03×10^{1}	4.38×10^{1}	2.39×10^{2}	1.81×10^{3}	2.10×10^{4}	2.16×10^{1}	6.39×10^{1}	2.22×10^{2}	9.45×10^{2}	5.17×10^{3}	3.91×10^{4}	4.54×10^{5}
50/70 + 25% RAP + 10% Rej	1	2.90×10^{0}	9.83×10^{0}	4.07×10^{1}	2.16×10^{2}	1.58×10^{3}	1.76×10^{4}	1.36×10^{1}	3.93×10^{1}	1.34×10^{2}	5.52×10^{2}	2.93×10^{3}	2.14×10^{4}	2.39×10^{5}
50/70 + 25% RAP + 15% Rej	1	2.84×10^{0}	9.45×10^{0}	3.82×10^{1}	1.97×10^{2}	1.40×10^{3}	1.50×10^{4}	1.14×10^{1}	3.24×10^{1}	1.08×10^{2}	4.35×10^{2}	2.25×10^{3}	1.59×10^{4}	1.71×10^{5}
50/70 + 50% RAP	1	3.37×10^{0}	1.34×10^{1}	6.54×10^{1}	4.09×10^{2}	3.51×10^{3}	4.51×10^{4}	4.17×10^{1}	1.40×10^{2}	5.59×10^{2}	2.72×10^{3}	1.71×10^{4}	1.46×10^{5}	1.88×10^{6}
50/70 + 50% RAP + 5% Rej	1	3.01×10^{0}	1.06×10^{1}	4.55×10^{1}	2.48×10^{2}	1.84×10^{3}	2.04×10^{4}	2.32×10^{1}	7.00×10^{1}	2.47×10^{2}	1.06×10^{3}	5.76×10^{3}	4.28×10^{4}	4.74×10^{5}
50/70 + 50% RAP + 10% Rej	1	2.82×10^{0}	9.28×10^{0}	3.70×10^{1}	1.88×10^{2}	1.31×10^{3}	1.37×10^{4}	1.47×10^{1}	4.15×10^{1}	1.37×10^{2}	5.46×10^{2}	2.77×10^{3}	1.93×10^{4}	2.03×10^{5}
50/70 + 50% RAP + 15% Rej	1	2.72×10^{0}	8.62×10^{0}	3.29×10^{1}	1.59×10^{2}	1.05×10^{3}	1.03×10^{4}	1.21×10^{1}	3.31×10^{1}	1.05×10^{2}	4.00×10^{2}	1.94×10^{3}	1.27×10^{4}	1.25×10^{5}
50/70 + 75% RAP	1	3.57×10^{0}	1.51×10^{1}	7.87×10^{1}	5.28×10^{2}	4.86×10^{3}	6.69×10^{4}	8.05×10^{1}	2.88×10^{2}	1.22×10^{3}	6.34×10^{3}	4.25×10^{4}	3.91×10^{5}	5.39×10^{6}
50/70 + 75% RAP + 5% Rej	1	3.17×10^{0}	1.18×10^{1}	5.32×10^{1}	3.04×10^{2}	2.35×10^{3}	2.66×10^{4}	4.01×10^{1}	1.27×10^{2}	4.74×10^{2}	2.13×10^{3}	1.22×10^{4}	9.42×10^{4}	1.07×10^{6}
50/70 + 75% RAP + 10% Rej	1	2.64×10^{0}	8.02×10^{0}	2.88×10^{1}	1.28×10^{2}	7.50×10^{2}	6.22×10^{3}	2.13×10^{1}	5.63×10^{1}	1.71×10^{2}	6.15×10^{2}	2.74×10^{3}	1.60×10^{4}	1.67×10^{5}
50/70 + 75% RAP + 15% Rej	1	2.53×10^{0}	7.31×10^{0}	2.51×10^{1}	1.06×10^{2}	5.93×10^{2}	4.74×10^{3}	1.44×10^{1}	3.64×10^{1}	1.05×10^{2}	3.61×10^{2}	1.53×10^{3}	8.54×10^{3}	6.82×10^{4}

Table A.2. Estimated values of steady shear viscosity at different temperatures from the 1st approach for all tested binder blends.

Blends	1st approach						
	η_0 - Steady shear viscosity (Pa·s)						
	T = 25ºC	T = 35ºC	T = 45ºC	T = 55ºC	T = 65ºC	T = 75ºC	T = 85ºC
50/70 + 25% RAP	6.01×10^{5}	5.06×10^{4}	6.48×10^{3}	1.15×10^{3}	2.60×10^{2}	7.23×10^{1}	2.36×10^{1}
50/70 + 25% RAP + 5% Rej	3.66×10^{5}	3.26×10^{4}	4.40×10^{3}	8.16×10^{2}	1.94×10^{2}	5.60×10^{1}	1.90×10^{1}
50/70 + 25% RAP + 10% Rej	2.17×10^{5}	2.07×10^{4}	2.96×10^{3}	5.79×10^{2}	1.44×10^{2}	4.36×10^{1}	1.54×10^{1}
50/70 + 25% RAP + 15% Rej	1.48×10^{5}	1.48×10^{4}	2.21×10^{3}	4.49×10^{2}	1.16×10^{2}	3.61×10^{1}	1.31×10^{1}
50/70 + 50% RAP	1.63×10^{6}	1.28×10^{5}	1.53×10^{4}	2.51×10^{3}	5.32×10^{2}	1.38×10^{2}	4.21×10^{1}
50/70 + 50% RAP + 5% Rej	6.02×10^{5}	5.29×10^{4}	6.99×10^{3}	1.27×10^{3}	2.93×10^{2}	8.23×10^{1}	2.72×10^{1}
50/70 + 50% RAP + 10% Rej	2.13×10^{5}	2.14×10^{4}	3.19×10^{3}	6.41×10^{2}	1.63×10^{2}	4.99×10^{1}	1.78×10^{1}
50/70 + 50% RAP + 15% Rej	1.01×10^{5}	1.11×10^{4}	1.80×10^{3}	3.90×10^{2}	1.06×10^{2}	3.46×10^{1}	1.30×10^{1}
50/70 + 75% RAP	4.45×10^{6}	3.27×10^{5}	3.62×10^{4}	5.52×10^{3}	1.09×10^{3}	2.63×10^{2}	7.52×10^{1}
50/70 + 75% RAP + 5% Rej	9.80×10^{5}	8.51×10^{4}	1.10×10^{4}	1.95×10^{3}	4.39×10^{2}	1.20×10^{2}	3.86×10^{1}
50/70 + 75% RAP + 10% Rej	2.10×10^{5}	2.22×10^{4}	3.42×10^{3}	7.06×10^{2}	1.83×10^{2}	5.69×10^{1}	2.05×10^{1}
50/70 + 75% RAP + 15% Rej	7.07×10^{4}	8.15×10^{3}	1.48×10^{3}	3.41×10^{2}	9.74×10^{1}	3.31×10^{1}	1.29×10^{1}

Table A.3. Estimated values of steady shear viscosity at different temperatures from 2nd approach for all tested binder blends.

Blends	2nd approach						
	η_0 – Steady shear viscosity (Pa·s)						
	T = 25ºC	T = 35ºC	T = 45ºC	T = 55ºC	T = 65ºC	T = 75ºC	T = 85ºC
RAP + 5% Rej	3.37×10^{6}	3.03×10^{5}	3.84×10^{4}	6.41×10^{3}	1.34×10^{3}	3.36×10^{2}	9.85×10^{1}
RAP + 10% Rej	2.45×10^{5}	3.11×10^{4}	5.30×10^{3}	1.14×10^{3}	2.99×10^{2}	9.15×10^{1}	3.20×10^{1}
RAP + 15% Rej	2.25×10^{4}	3.90×10^{3}	8.71×10^{2}	2.37×10^{2}	7.62×10^{1}	2.79×10^{1}	1.14×10^{1}
50/70 + 25% RAP	6.01×10^{5}	5.06×10^{4}	6.48×10^{3}	1.15×10^{3}	2.60×10^{2}	7.23×10^{1}	2.36×10^{1}
50/70 + 25% RAP + 5% Rej	3.67×10^{5}	3.31×10^{4}	4.49×10^{3}	8.33×10^{2}	1.98×10^{2}	5.69×10^{1}	1.92×10^{1}
50/70 + 25% RAP + 10% Rej	2.24×10^{5}	2.16×10^{4}	3.11×10^{3}	6.06×10^{2}	1.50×10^{2}	4.48×10^{1}	1.56×10^{1}
50/70 + 25% RAP + 15% Rej	1.40×10^{5}	1.43×10^{4}	2.18×10^{3}	4.46×10^{2}	1.15×10^{2}	3.56×10^{1}	1.28×10^{1}
50/70 + 50% RAP	1.63×10^{6}	1.28×10^{5}	1.53×10^{4}	2.51×10^{3}	5.32×10^{2}	1.38×10^{2}	4.21×10^{1}
50/70 + 50% RAP + 5% Rej	6.04×10^{5}	5.43×10^{4}	7.26×10^{3}	1.32×10^{3}	3.03×10^{2}	8.48×10^{1}	2.77×10^{1}
50/70 + 50% RAP + 10% Rej	2.29×10^{5}	2.35×10^{4}	3.52×10^{3}	7.02×10^{2}	1.76×10^{2}	5.29×10^{1}	1.85×10^{1}
50/70 + 50% RAP + 15% Rej	9.07×10^{4}	1.06×10^{4}	1.76×10^{3}	3.84×10^{2}	1.04×10^{2}	3.37×10^{1}	1.25×10^{1}
50/70 + 75% RAP	4.45×10^{6}	3.27×10^{5}	3.62×10^{4}	5.52×10^{3}	1.09×10^{3}	2.63×10^{2}	7.52×10^{1}
50/70 + 75% RAP + 5% Rej	9.81×10^{5}	8.83×10^{4}	1.16×10^{4}	2.06×10^{3}	4.62×10^{2}	1.25×10^{2}	3.97×10^{1}
50/70 + 75% RAP + 10% Rej	2.35×10^{5}	2.56×10^{4}	3.97×10^{3}	8.11×10^{2}	2.06×10^{2}	6.21×10^{1}	2.17×10^{1}
50/70 + 75% RAP + 15% Rej	5.98×10^{4}	7.84×10^{3}	1.42×10^{3}	3.33×10^{2}	9.49×10^{1}	3.18×10^{1}	1.22×10^{1}