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Properties of blends of fresh and RAP binders with rejuvenator: experimental and estimated results

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Abstract

The properties of various blends of a fresh binder (50/70 penetration grade) and a RAP-extracted binder, with and without a rejuvenator, were studied. A mixture of vegetal oils was used as rejuvenator in different dosages. A total of 17 binders were tested, including pure fresh and RAP binders. Conventional tests were performed in order to determine penetration at 25°C, softening point ($T_{R\&B}$), Fraass breaking point (T_{Fraass}), ductility (elongation at 25°C) and density at 25°C. The steady-shear viscosity (η_0) of all binders was calculated from complex modulus test results. Two different approaches were proposed in order to estimate values of penetration, $T_{R\&B}$, T_{Fraass} and η_0 of blends from properties of base constituents. Excellent correspondences with experimental results were observed.

Keywords: RAP extracted binder; rejuvenator; binder blending; steady-shear viscosity; estimations.

Highlights

- Properties of blends of two binders with and without rejuvenator were studied.
- Steady-shear viscosity was calculated from complex modulus test results.
- Strong correlations were found between penetration and other properties.
- Properties of all blends were estimated from base constituents with two approaches.
- Good correspondences were found between estimated and experimental results.

1. Introduction

Using a high percentage of Reclaimed Asphalt Pavement (RAP) in the production of a new Hot Mix Asphalt (HMA) is considered a challenging issue because of the potential interaction between RAP material and fresh binder [1], [2].

When high amounts of RAP (30% or more) are introduced in the production of a new HMA, specific rejuvenators are often used to achieve adequate workability and mechanical performance [3], [4], [5], [6].

Nowadays, many products including vegetal oils or recycled waste oils have been used as regenerating agents in order to mobilise the RAP bitumen with a double benefit of increasing RAP content and achieving good performances of the new mix [7], [8], [9].

When renewable materials are used for binders and bituminous mixtures, they must fulfil certain essential requirements related to the health and safety of the users and as well of the environment, their use must be an economically solution which should give some performance benefits and as well they must be recyclable and available in large quantities without suffering changes during the transport, storage and mixing process [10].

Several studies show the potential of the bio-oils (vegetal oils) to be used as rejuvenators in bituminous mixtures containing RAP or RAS by diminishing the effect of the increase in stiffness due to the presence of the aged materials [11], [12], [13], and also in blends with aged binders by restoring to a significant extend the properties of the aged binder [14].

The conclusions of some studies focusing on conventional properties (penetration, ductility, softening point), rheological properties (complex modulus) and fatigue resistance show the capability of vegetal oils to rejuvenate hard aged binders and to provide a final product with similar properties to fresh binders [1], [15], [16], [17], [18], [19], [20], [21].

The objective of this paper is to study the effect of a rejuvenator (consisting of a mixture of vegetal oils) in different dosages by evaluating the properties of different blends produced by mixing a fresh binder and a RAP-extracted binder with or without rejuvenator. Seventeen different binders, including pure fresh and RAP binders were tested. We used the term 'rejuvenator' for this mixture of vegetal oils based on the studied literature and on the obtained results which are showing the capability of this mixture of vegetal oils to rejuvenate (in terms of mechanical characteristics) the aged RAP binder and finally to provide a blend with similar mechanical properties as for a fresh binder.

Penetration at 25°C, softening point, Fraass breaking point, elongation and density at 25°C tests were experimentally determined for all binders. Complex modulus and temperature shift factors were determined at frequencies ranging from 0.1 to 10 Hz and temperatures ranging from 25°C to 85°C.

The viscosity of a binder plays a critical role regarding the mixing and compaction process of bituminous mixes and it can be determined by several methods [22].

In this paper the steady-shear viscosity of all binders was calculated from complex modulus test results.

Values of penetration, softening point, Fraass breaking point and steady-shear viscosity of blends were estimated from values of base constituents using two different approaches and compared with experimental results.

2. Experimental investigation

2.1 Materials

A straight-run 50/70 penetration grade bitumen was used as fresh binder.

The RAP binder was extracted from a well-known RAP material meeting the requirements of EN 13108-8:2016, [23]. Its binder content is 4.0% (measured through extraction and recovery). RAP binder was recovered from the RAP material using an extractor called ‘asphaltanalysator’ according to the European Standard EN 12697-1:2012, [24]. Trichloroethylene was used as solvent. The solution of bitumen and trichloroethylene from prior extraction was distilled with a rotary evaporator, according to EN 12697-3:2013, [25].

A mixture of vegetal oils was used as rejuvenator (Rej) in different dosages (0%, 5%, 10% and 15% by mass of RAP binder).

The experimental plan includes a total of 17 binders (Table 1): 12 blends of the 50/70 fresh binder with the RAP-extracted binder with and without rejuvenator, 3 blends of RAP binder with the rejuvenator and pure fresh and RAP binders.

Blending proportions between RAP-extracted, fresh base binder and rejuvenator were chosen in order to reproduce real ratios between these components within corresponding asphalt mixtures (with a 5.6% total binder content) containing 25%, 50%, 75% and 100% of RAP material (according to its binder content 4.0%) and 0.00 %, 0.20 %, 0.40 % and 0.60 % of rejuvenator by mass of RAP material (corresponding to 0%, 5%, 10% and 15% of rejuvenator by mass of the RAP binder).

The actual blending percentages of the different components for all blends are reported in Table 1. For simplicity, the blends were named after the percentage of RAP material added for the corresponding mixture and the percentage of the rejuvenator (Rej) by the mass of RAP binder (example: 50/70 + 25% RAP + 10% Rej).

Table 1. Proportion of different components in tested binders: pure bitumen (50/70), RAP-extracted binder (RAP) and Rejuvenator (Rej).

Binders	% by weight		
	50/70	RAP	Rej
50/70	100.00	0.00	0.00
RAP	0.00	100.00	0.00
RAP + 5% Rej	0.00	95.24	4.76
RAP + 10% Rej	0.00	90.91	9.09
RAP + 15% Rej	0.00	86.96	13.04
50/70 + 25% RAP	82.14	17.86	0.00
50/70 + 25% RAP + 5% Rej	81.42	17.70	0.88
50/70 + 25% RAP + 10% Rej	80.70	17.54	1.76
50/70 + 25% RAP + 15% Rej	80.00	17.39	2.61
50/70 + 50% RAP	64.29	35.71	0.00
50/70 + 50% RAP + 5% Rej	63.16	35.09	1.75
50/70 + 50% RAP + 10% Rej	62.07	34.48	3.45
50/70 + 50% RAP + 15% Rej	61.02	33.90	5.08
50/70 + 75% RAP	46.43	53.57	0.00
50/70 + 75% RAP + 5% Rej	45.22	52.17	2.61

50/70 + 75% RAP + 10% Rej	44.07	50.85	5.08
50/70 + 75% RAP + 15% Rej	42.97	49.59	7.44

In order to produce blends, fresh and RAP binders were heated at 160°C in a thermostatic oven. The rejuvenator (at ambient temperature) was added to pure fresh binder and this blend was manually mixed for 5 minutes. This preliminary blend was then heated for 20 min at 160°C. RAP binder was added and this final blend was manually mixed for 5 minutes in order to produce a homogenous blend.

The rejuvenator was first blended with the fresh binder in order to reproduce the real industrial process of the production of bituminous mixtures in which the rejuvenator is added to the fresh binder tank when all the components (fresh aggregates, RAP material and fresh binder) are heated before mixing.

2.2 Conventional tests

Conventional tests were performed on all binders in order to determine penetration at 25°C (EN 1426:2015, [26]), softening point ($T_{R\&B}$, EN 1427:2015, [27]), ductility at 25°C (elongation, SR 61, [28]), Fraass breaking point (T_{Fraass} , EN 12593:2015, [29]), and density at 25°C (EN 15326+A1:2009, [30]). Ductility at 25°C was determined by performing elongation test, as prescribed in the Romanian Standard SR 61 [28], bitumen samples were pulled apart at a constant speed of 50 mm/min in a water bath at 25°C until rupture. The elongation at rupture (in cm) was used as an indication of ductility. The results are reported in Table A.1 (Appendix). The Penetration Index (PI) was calculated according to EN 12591:2009, [31] and the results are also reported in Table A.1 (Appendix).

Penetration (in logarithmic scale) and softening point of all binders are plotted as functions of RAP binder content in Figure 1 a) and b).

The results obtained for the RAP binder are coherent with the expected results for an aged binder [32].

As expected, results in Table A.1 (Appendix) and Figure 1 a) and b) show a decrease in penetration and an increase in softening point as RAP binder content increases for the blends produced without rejuvenator. Increasing penetration values and decreasing ring and ball temperatures were observed when increasing the dosage of the rejuvenator in blends.

Fraass breaking point temperature and PI of all binders are plotted as functions of RAP binder content in Figure 1 c) and d), respectively.

An increase in both T_{Fraass} and PI values of blends without rejuvenator is observed as RAP binder content increases. On the contrary, values of both parameters decrease when the percentage of Rej in blends increases.

Similar tendencies to those observed for the T_{Fraass} and PI values were found for the values of density at 25°C. Regarding the results obtained for the elongation, it was not possible to observe the effect of increasing the percentage of rejuvenator on ductility results since measure span of the test machine is limited to 150 cm.

In Figure 1, linear regressions were performed for values of properties of blends having the same rejuvenator content (0%, 5%, 10% and 15%).

As a general comment, it can be observed that with increasing RAP binder content properties of blends without rejuvenator tend towards those of pure RAP binder, as expected. The effect of the rejuvenator counterbalances this tendency, as it can be observed from the change of slope of regressions in Figure 1 for different rejuvenator contents.

As it can be observed in Figure 1 and Table A.1 (Appendix), the results obtained (for penetration, $T_{R\&B}$, T_{Fraass} , PI and density) for the blends produced with 5% rejuvenator by mass of the RAP binder, show the same tendencies as those obtained for the blends produced without rejuvenator.

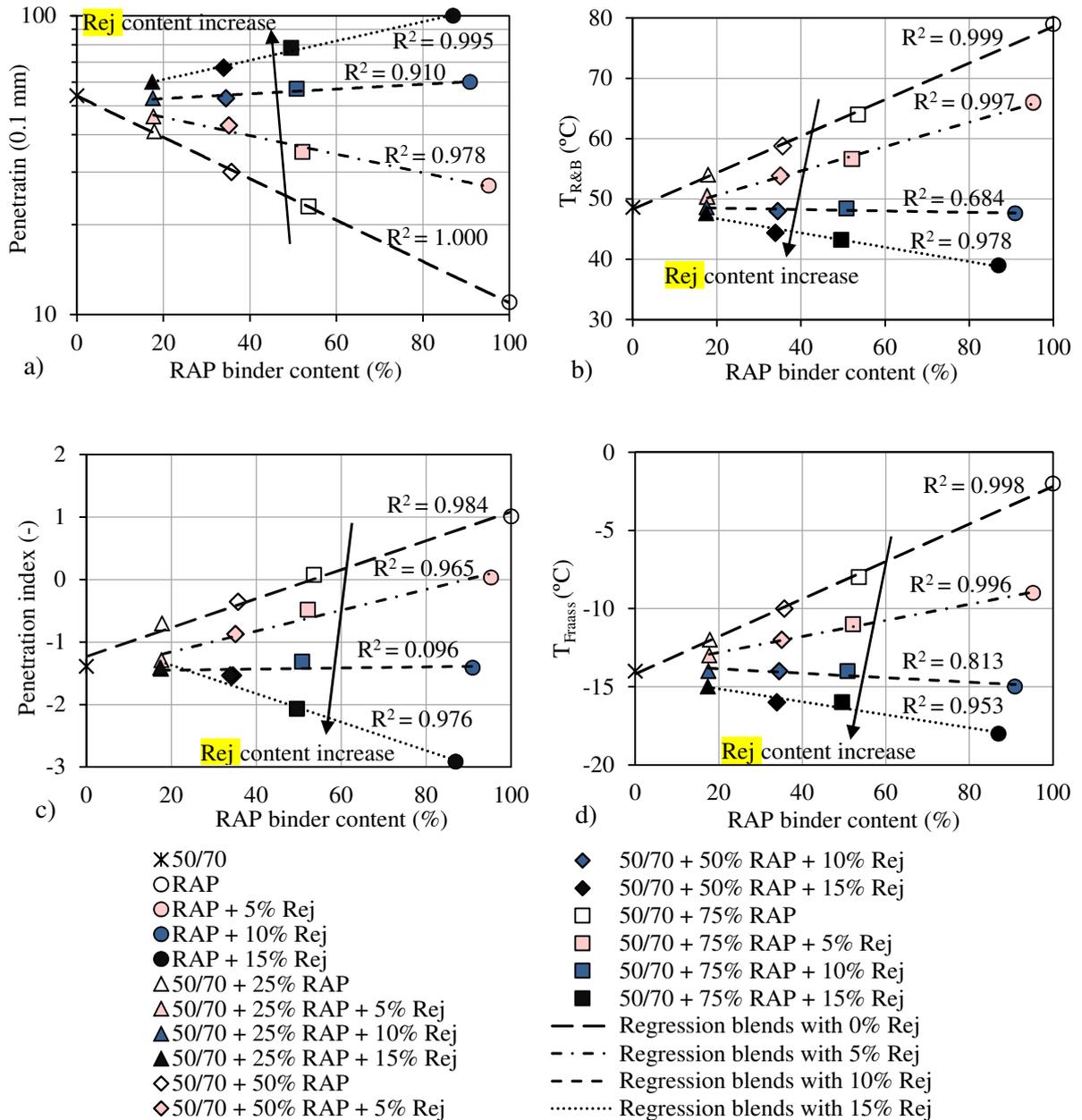


Figure 1. (a) Penetration of all binders as a function of RAP bitumen content; (b) Softening point of all binders as a function of RAP bitumen content; (c) Penetration Index values of all binders as a function of RAP bitumen content; (d) Fraass breaking point of all binders as a function of RAP bitumen content.

Moreover, the results obtained for the blends produced with 10% rejuvenator by mass of the RAP binder are similar to those obtained for fresh binder 50/70, independently of the RAP binder content. This indicates the capability of the rejuvenator (in terms of mechanical characteristics) to rejuvenate the hard aged RAP binder and finally to provide a final product with similar properties of fresh binder.

From our results, the dosage of 10% rejuvenator by mass of the RAP binder, seems to counterbalance the effect of the RAP binder within the blends (in terms of mechanical characteristics). This effect can be observed in Figure 1, where the regression lines for the blends produced with 10% rejuvenator are close to the horizontal line.

On the other side, for the blends produced with 15% rejuvenator by mass of the RAP binder, an inverse effect can be observed. It is interesting to notice that blends with 15% rejuvenator appear to become softer with increasing RAP binder content. This trend can be explained by the fact that the rejuvenator content is calculated with respect to RAP binder content and also by the fact that the 10% rejuvenator amount seems to be the ‘optimal dosage’ in order to obtain a blend with similar mechanical characteristics as a fresh 50/70 pen. grade binder.

2.3 Steady shear viscosity

Complex viscosity η^* of a binder is defined as its complex shear modulus G^* divided by the angular frequency ω multiplied by the imaginary unit i ($i^2=-1$):

$$\eta^* = \frac{G^*}{i\omega} \quad (1)$$

Steady shear viscosity η_0 can be obtained at a given temperature from the norm of complex viscosity at this temperature when angular frequency tends towards zero, as shown in equation (2).

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

In a logarithmic form equation (2) can be written, as follows:

$$\log|G^*| = \log \omega + \log|\eta^*| \quad (3)$$

where $|G^*|$ is the norm of complex shear modulus (in MPa), ω is the angular frequency (in rad/s) and $|\eta^*|$ is the norm of complex viscosity (in MPa·s).

In order to determine steady shear viscosity, complex modulus tests were performed on all binders using a DSR apparatus, at 7 temperatures ranging from 25°C to 85°C (10°C increment) and at frequencies ranging from 0.1 Hz to 10 Hz. A 25 mm diameter plate-plate configuration with a 1 mm gap was used.

The norm of complex shear modulus $|G^*|$ and its phase angle φ were calculated from DSR test results.

The time–temperature superposition principle was applied to obtain temperature shift factors a_T and plot master curves for all binders according to equations (4) and (5) [33], [34], [35].

$$|G^*(T, f)| = |G^*(T_{ref}, a_T \cdot f)| \quad (4)$$

$$\varphi(T, f) = \varphi(T_{ref}, a_T \cdot f) \quad (5)$$

where T and T_{ref} are, respectively, the test temperature and the reference temperature, and f is the frequency, related to angular frequency as in equation (6).

$$\omega = 2\pi f \quad (6)$$

In order to determine the steady shear viscosity, for all tested binders, $|G^*|$ was plotted as a function of ω in a log-log scale, at a reference temperature of 25°C. The high temperature/low frequency part of the curve (corresponding to the isotherm obtained at 85°C, shifted to 25°C using a_T , shown in Figure 2) was analysed in order to highlight the Newtonian behaviour of the binders in this loading domain. A linear regression was performed on this part of the curve (with an imposed 45° slope line), in order to determine η_0 .

Figure 3 shows an example for the blends produced without rejuvenator. The same analysis was performed for all the produced blends. The results obtained are reported in Table A.1 (Appendix).

Values of η_0 at 25°C of all the binders are plotted as function of RAP binder content in Figure 4.

The values of steady shear viscosity, for the blends produced without rejuvenator and the blends produced with 5% rejuvenator, increase with increasing RAP binder and rejuvenator contents within blends.

Moreover, it can be observed that values of steady shear viscosity of the blends produced with 10% rejuvenator by mass of RAP binder are close to the ones obtained for the fresh 50/70 binder, independently of the RAP binder content. For the blends produced with 15% rejuvenator, an inverse effect can be observed as η_0 values are decreasing with the increase of the RAP binder and rejuvenator contents. These results are coherent with what is observed from conventional tests (Section 2.2).

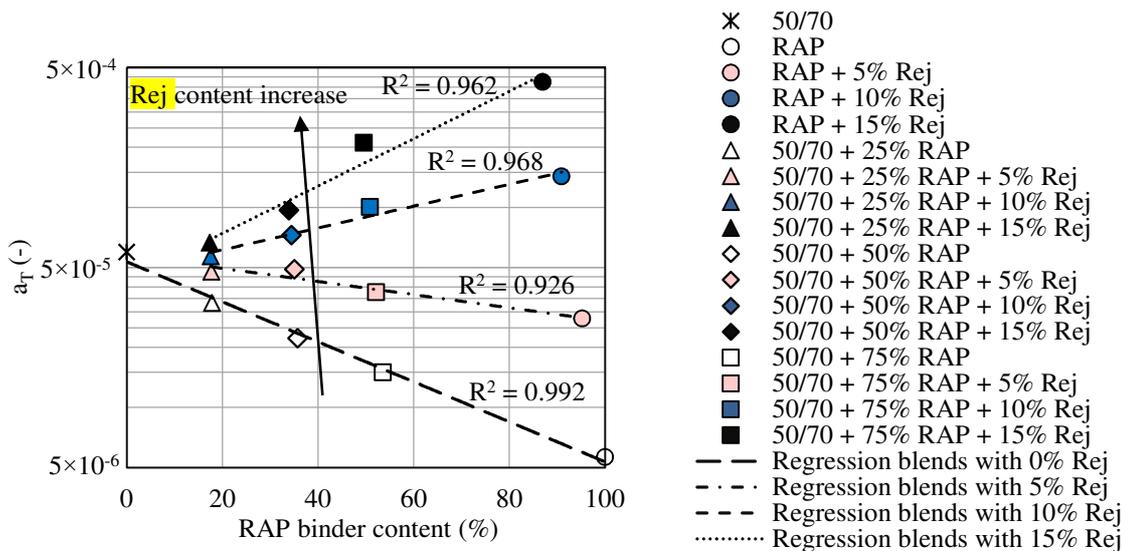


Figure 2. a_T at 85°C ($T_{ref} = 25^\circ\text{C}$) as functions of RAP binder content.

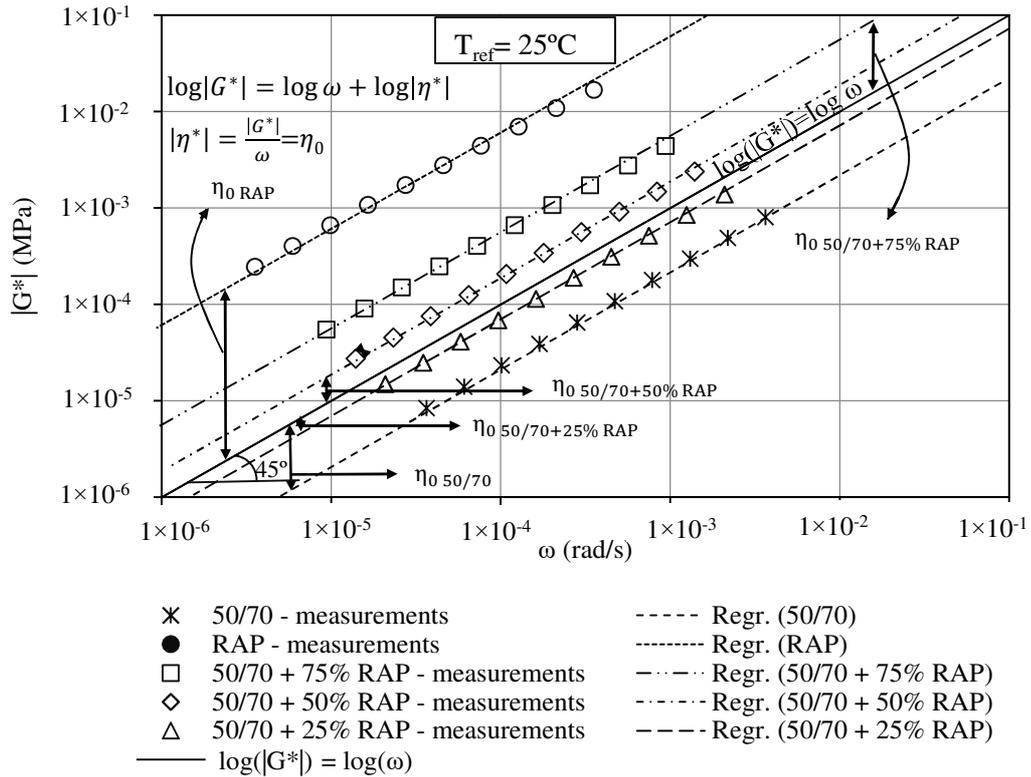


Figure 3. Example of determination of steady shear viscosity (norm of complex viscosity at 25°C for $\omega \rightarrow 0$) for fresh and RAP binders and the blends produced without **rejuvenator**.

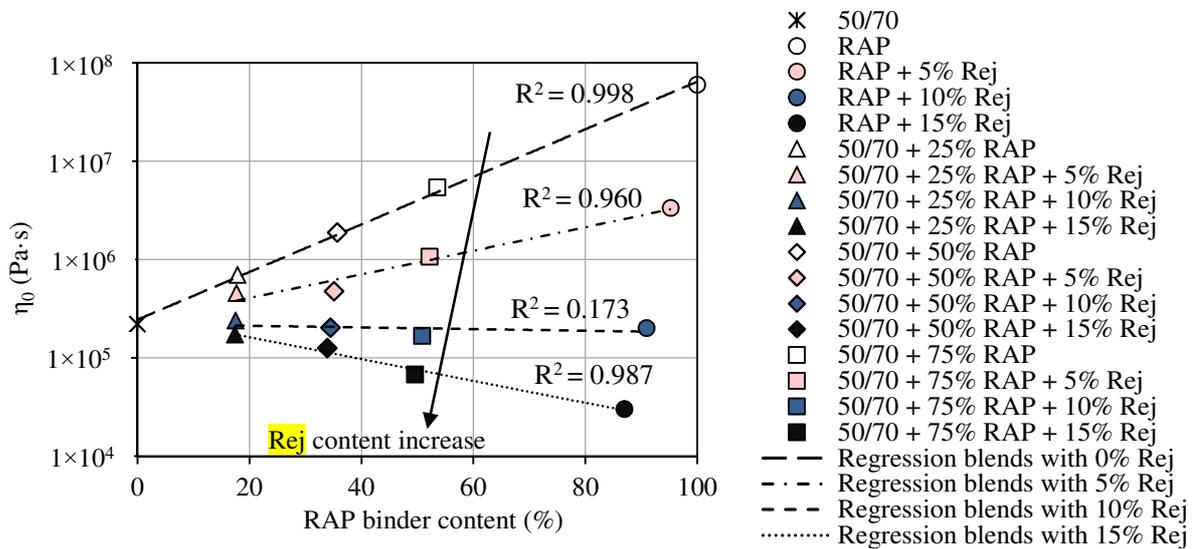


Figure 4. Steady shear viscosity (norm of complex viscosity at 25°C) for all binders, as a function of RAP binder content.

3. Relations between penetration, ring and ball temperature ($T_{R\&B}$), Fraass temperature (T_{Fraass}) and steady shear viscosity (η_0)

In order to find possible relations between penetration and ring and ball temperature ($T_{R\&B}$), Fraass breaking point temperature (T_{Fraass}) and steady shear viscosity at 25°C (η_0 , in logarithmic scale). Experimental values of penetration at 25°C (pen, in logarithmic scale) were plotted against experimental values of these parameters (Figure 5).

The graph of penetration against ring and ball temperature ($T_{R\&B}$), reported in Figure 5 a), shows the location of limits defined in standard EN 12591:2009, [31] for traditional binders (20/30, 35/50, 50/70 and 70/100).

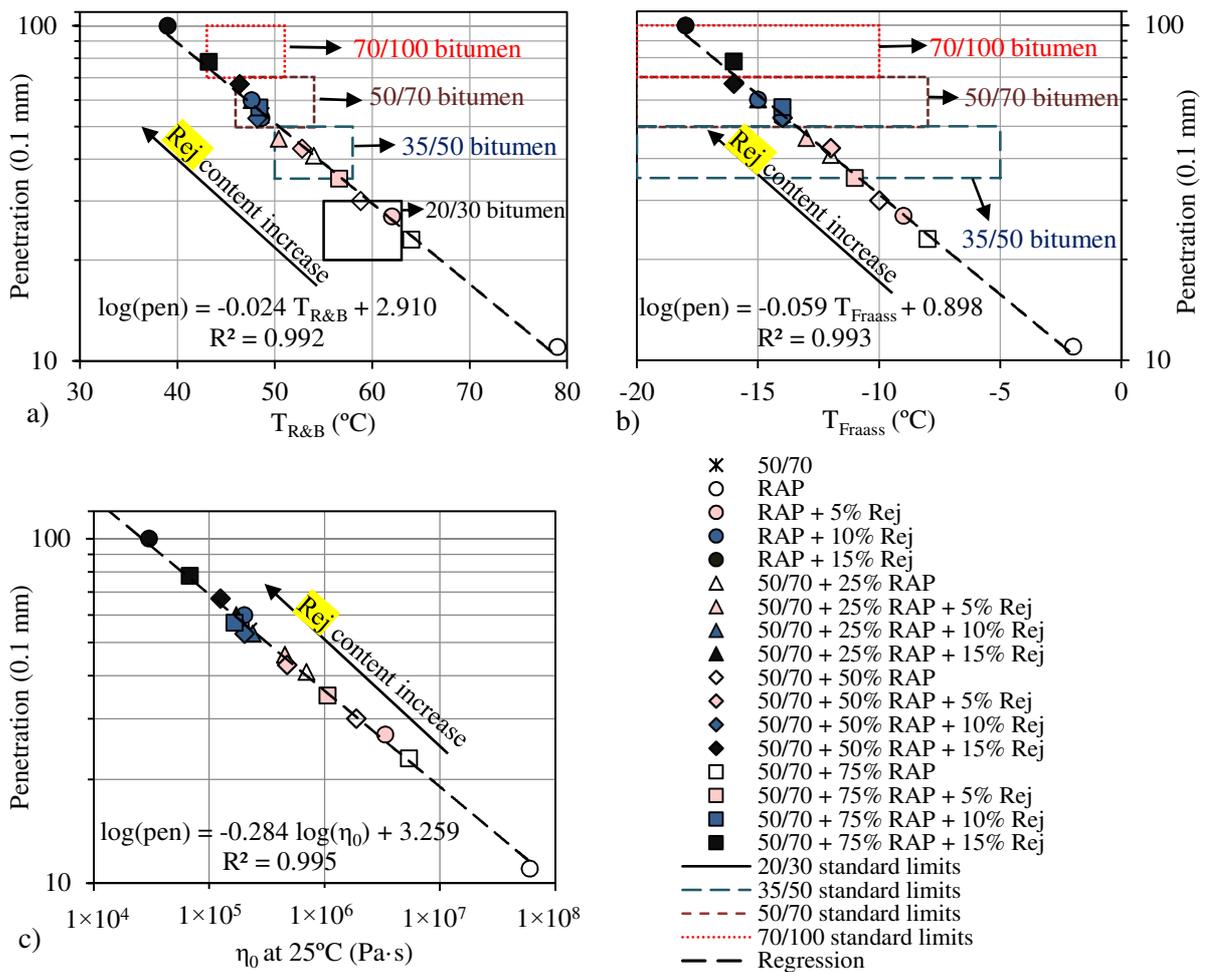


Figure 5. (a) Relation between ring and ball temperature and penetration for all tested blends and traditional binders limits; (b) Relation between Fraass breaking point temperature and penetration for all tested blends and traditional binders limits; (c) Relation between steady shear viscosity (norm of complex viscosity at 25°C) and penetration for all the tested blends.

As it can be observed, the blends of RAP and fresh binders produced with 5% rejuvenator by mass of RAP binder are within the limits of a 35/50 penetration grade bitumen. Similar, the blends produced with 10% rejuvenator by mass of RAP bitumen are within the

limits of a 50/70 penetration grade bitumen. As expected, $T_{R\&B}$ values of the tested binders increase with the decrease of penetration.

Similar observations can be made regarding penetration as a function of Fraass breaking point temperature (T_{Fraass}), as it can be observed in Figure 5 b).

As expected, the steady shear viscosity at 25°C of all tested binders increases with the decrease of penetration (Figure 5 c).

Strong correlations were found for all the linear regressions performed for the mentioned parameters.

In particular, R^2 values equal to 0.992, 0.993 and 0.995 were obtained for the linear regressions between, respectively, $\log pen$ and $T_{R\&B}$, $\log pen$ and T_{Fraass} and $\log pen$ and $\log \eta_0$.

4. Determination of parameters for blends from measurements on base constituents

Values of penetration at 25°C, $T_{R\&B}$, T_{Fraass} and η_0 at 25°C of the blends of pure fresh binder, RAP binder and rejuvenator were estimated using two different approaches and compared with experimental values.

4.1 First approach

The first approach supposes that values for fresh binders and values for blends of RAP and rejuvenator (RAP + Rej) are known from experimental tests. The blending rule expressed in equations (7) and (8) is considered.

Equation (7) was used to estimate ring and ball temperature ($T_{R\&B}$) and Fraass temperature (T_{Fraass}), while equation (8) (which is identical to Equation 7 in log-log axes) was used in order to estimate penetration and steady shear viscosity (η_0) at 25°C. Equation (8) is usually referred to as log-log rule, [36]. As values for fresh and RAP + Rej binders are known, only values of 12 produced blends have to be determined.

In the equations, estimated parameters of the 12 blends ($X_{blend\ est.\ 1}$ and $Y_{blend\ est.\ 1}$ for equations (7) and (8), respectively) are calculated from experimental values obtained for pure fresh binder ($X_{50/70}$ and $Y_{50/70}$ for equations (7) and (8), respectively) and for blends of RAP binder and rejuvenator ($X_{RAP+Rej}$ and $Y_{RAP+Rej}$ for equations (7) and (8), respectively), as a function of the relative mass concentration of fresh binder in the final blend, a .

$$X_{blend\ est.\ 1} = a \cdot X_{50/70} + (1 - a) \cdot X_{RAP+Rej} \quad (7)$$

$$\log Y_{blend\ est.\ 1} = a \cdot \log Y_{50/70} + (1 - a) \cdot \log Y_{RAP+Rej} \quad (8)$$

4.2 Second approach

The second approach requires only values of concentration and parameters of the three base components (fresh binder, RAP and rejuvenator). The blending rule expressed in equations (9) and (10) is considered.

Equation (9) was used to estimate values of $T_{R\&B}$ and T_{Fraass} , while equation (10) was used for values of penetration and η_0 at 25°C, for the 15 blends.

Estimated values of the blends ($X_{blend\ est.\ 2}$ and $Y_{blend\ est.\ 2}$ for equations (9) and (10), respectively) were calculated from experimental values obtained for pure fresh binder ($X_{50/70}$ and $Y_{50/70}$ for equations (9) and (10), respectively) and RAP binder (X_{RAP} and Y_{RAP} for equations (9) and (10), respectively) and from equivalent values for the rejuvenator (X_{Rej} and Y_{Rej} for equations (9) and (10), respectively) that are reported in Table A.2 (Appendix). In the equations, a , b and c are the relative mass concentrations of fresh binder, RAP binder and rejuvenator, respectively ($a + b + c = 1$).

$$X_{blend\ est.\ 2} = a \cdot X_{50/70} + b \cdot X_{RAP} + c \cdot X_{Rej} \quad (9)$$

$$\log Y_{blend\ est.\ 2} = a \cdot \log Y_{50/70} + b \cdot \log Y_{RAP} + c \cdot \log Y_{Rej} \quad (10)$$

In the equations (9) and (10), a and c could be calculated as functions of the relative mass concentration of RAP binder in the final blend, b , and the dosage of the rejuvenator by the mass of RAP binder, r ($c = r \cdot b$). Equations (9) and (10) could then be rewritten as equations (11) and (12).

$$X_{blend\ est.\ 2} = [1 - b \cdot (1 + r)] \cdot X_{50/70} + b \cdot X_{RAP} + b \cdot r \cdot X_{Rej} \quad (11)$$

$$\log Y_{blend\ est.\ 2} = [1 - b \cdot (1 + r)] \cdot \log Y_{50/70} + b \cdot \log Y_{RAP} + b \cdot r \cdot \log Y_{Rej} \quad (12)$$

Equivalent values for the rejuvenator (X_{Rej} and Y_{Rej}) were obtained by optimizing the correlation between estimated values of blends ($X_{blend\ est.\ 2}$ and $Y_{blend\ est.\ 2}$) and experimental results. More details are given in Section 4.3.

4.3 Analysis of results

Correlation plots of estimated (by applying both first and second approaches) vs. experimental results are reported in Table A.2 (Appendix) and Figure 6, for penetration at 25°C, $T_{R\&B}$, T_{Fraass} and η_0 , respectively.

In each plot, coefficients of determination (R^2) of both correlations (1st and 2nd approach vs. experimental results) were calculated with respect to the equality line. In the calculation of R^2 , values of base constituents were not taken into account: $X_{50/70}$, $Y_{50/70}$, $X_{RAP+Rej}$ and $Y_{RAP+Rej}$ (5 binders) for the first approach, $X_{50/70}$, $Y_{50/70}$, X_{RAP} , Y_{RAP} , X_{Rej} and Y_{Rej} (2 binders and the rejuvenator) for the second approach.

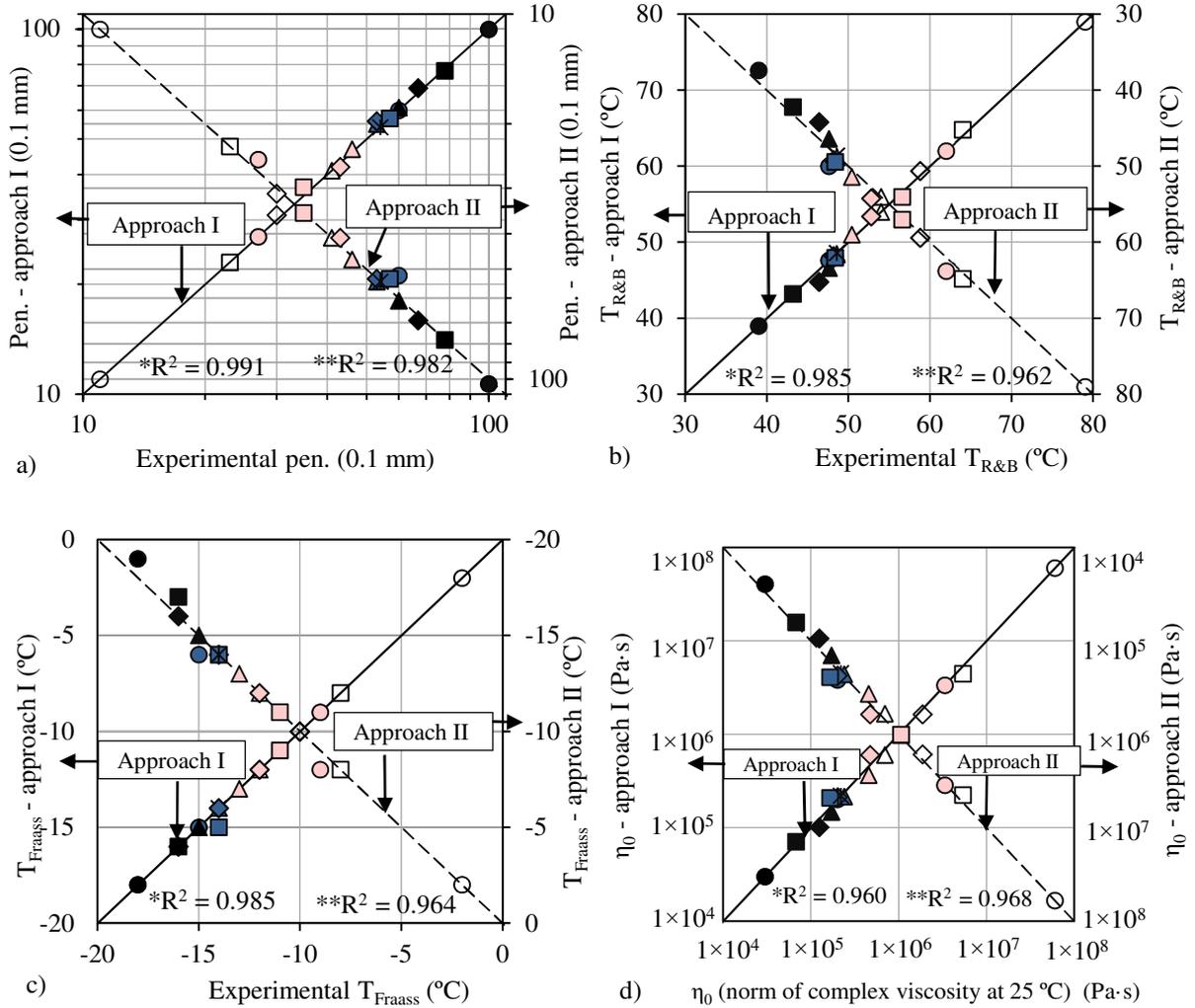
Regarding the second approach, as mentioned in Section 4.2, equivalent values of the rejuvenator (X_{Rej} and Y_{Rej}) were obtained by optimizing the correlations between estimated and experimental parameters of the final blends. Values of X_{Rej} and Y_{Rej} were obtained by maximizing the R^2 value using the least square method. They are reported in Table A.2 (Appendix).

It should be highlighted that they were used only in the context of the blending law, therefore they are not intended to reflect actual properties of the rejuvenator.

The estimated values determined with respect to these two proposed approaches were then rounded as follows:

- penetration values were expressed in tenths of mm rounded to the nearest integer;
- ring and ball temperature were expressed to the nearest 0.2 °C;

– Fraass breaking point temperature were rounded to the nearest integer.



* R^2 was calculated without taking into account penetration, $T_{R\&B}$, T_{Fraass} , η_0 values of pure fresh 50/70 binder, RAP binder and RAP + Rej blends (5 values) that are input data.
 ** R^2 was calculated without taking into account penetration, $T_{R\&B}$, T_{Fraass} , η_0 values of pure fresh 50/70 binder, RAP binder and Rej (3 values) that are input data.

- × 50/70
- RAP
- RAP + 5% Rej
- RAP + 10% Rej
- RAP + 15% Rej
- △ 50/70 + 25% RAP
- △ 50/70 + 25% RAP + 5% Rej
- ▲ 50/70 + 25% RAP + 10% Rej
- ▲ 50/70 + 25% RAP + 15% Rej
- ◇ 50/70 + 50% RAP
- ◇ 50/70 + 50% RAP + 5% Rej
- ◆ 50/70 + 50% RAP + 10% Rej
- ◆ 50/70 + 50% RAP + 15% Rej
- 50/70 + 75% RAP
- 50/70 + 75% RAP + 5% Rej
- 50/70 + 75% RAP + 10% Rej
- 50/70 + 75% RAP + 15% Rej
- Line of equality - approach I
- - - Line of equality - approach II

Figure 6. (a) Plot of estimated vs. experimental values of penetration for all the blends; (b) Plot of estimated vs. experimental values of ring and ball temperature for all the blends; (c) Plot of estimated vs. experimental values of Fraass breaking point temperature for all the blends; (d) Plot of estimated vs. experimental values of steady shear viscosity (norm of complex viscosity at 25°C) for all the blends.

Greater values of R^2 were found with the first approach than the second approach, except for η_0 at 25°C.

The advantage of the second approach is that the required input data are measured parameters for pure fresh and RAP binder. It is not necessary to produce and test blends of RAP binders and rejuvenator, as for the first approach.

The estimated values obtained by applying these two approaches are close to the measured values of penetration, $T_{R\&B}$, T_{Fraass} and η_0 for all the blends.

The satisfactory values of R^2 found (always higher than 0.96) show that both **estimation** methods can be considered valid for the tested blends.

5. Conclusions

The objective of the study was to investigate the effects of a mixture of vegetal oils set as rejuvenator (**Rej**) on mechanical properties of binder blends.

Conventional (penetration at 25°C, softening point, Fraass breaking point, elongation and density at 25°C) and rheological (DSR) tests were performed on various blends of a pure fresh 50/70 bitumen, a RAP-extracted binder and rejuvenator, in different proportions. In total, 17 different binders (including pure fresh and RAP binders) were produced and tested.

RAP binder was extracted from a well-known RAP material. The RAP binder content used for blends was calculated in order to reproduce the exact amount of RAP binder within a mixture containing 25%, 50%, 75% and 100% of RAP material, according to its binder content.

Different dosages of the rejuvenator (0%, 5%, 10% and 15% by mass of RAP binder) were used.

The results show a decrease in penetration and an increase in softening point (ring and ball temperature $T_{R\&B}$), Fraass breaking point temperature (T_{Fraass}) and penetration index (PI) for increasing RAP binder content and decreasing **rejuvenator** content in blends.

DSR complex modulus tests were performed from 25°C to 85°C and frequencies from 0.1 Hz to 10 Hz.

Steady shear viscosity η_0 at 25°C was calculated from DSR complex modulus tests by applying the time-temperature superposition principle, as the norm of complex viscosity at very low frequencies, in the domain of Newtonian behaviour of binders. Values of steady shear viscosity increase for increasing RAP binder content and decreasing **rejuvenator** content within blends.

From a thermo-mechanical point of view (**conventional tests, steady shear viscosity**), the rejuvenating effect of **the rejuvenator** was observed to counterbalance the effect of the aged RAP binder within binder blends.

Strong correlations were observed between penetration and $T_{R\&B}$, T_{Fraass} and steady shear viscosity at 25°C (η_0).

Two different approaches were used in order to **estimate** the values of penetration, $T_{R\&B}$, T_{Fraass} and η_0 at 25°C of all blends.

With both approaches, good correspondences were found between estimated and experimental values of all blends. Both methods can be considered valid for these tested blends.

6. References

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Appendix

Table A.1. Experimental results for tested binders presented in Table 1 and rejuvenator (Rej).

Materials	Penetration (0.1 mm)	T _{R&B} (°C)	T _{Fraass} (°C)	η_0 at 25°C (Pa·s)	Elongation at 25°C (cm)	Density at 25°C (kg/m ³)	Penetration Index (-)
50/70	54	48.60	-14	2.21E+05	> 150	1016	-1.39
RAP	11	79.00	-2	6.01E+07	52	1060	1.01
Rej	N/E*	N/E*	N/E*	N/E*	N/E*	930	N/E*
RAP + 5% Rej	27	62.00	-9	3.36E+06	99	1054	0.03
RAP + 10% Rej	60	47.60	-15	2.02E+05	> 150	1048	-1.41
RAP + 15% Rej	100	39.00	-18	3.02E+04	> 150	1043	-2.92
50/70 + 25% RAP	41	54.00	-12	6.95E+05	138	1024	-0.70
50/70 + 25% RAP + 5% Rej	46	50.40	-13	4.54E+05	> 150	1023	-1.29
50/70 + 25% RAP + 10% Rej	53	48.60	-14	2.39E+05	> 150	1022	-1.43
50/70 + 25% RAP + 15% Rej	60	47.60	-15	1.71E+05	> 150	1021	-1.41
50/70 + 50% RAP	30	58.80	-10	1.88E+06	98	1032	-0.36
50/70 + 50% RAP + 5% Rej	43	52.80	-12	4.74E+05	> 150	1030	-0.87
50/70 + 50% RAP + 10% Rej	53	48.20	-14	2.03E+05	> 150	1028	-1.54
50/70 + 50% RAP + 15% Rej	67	46.40	-16	1.25E+05	> 150	1026	-1.53
50/70 + 75% RAP	23	64.00	-8	5.39E+06	77	1041	0.08
50/70 + 75% RAP + 5% Rej	35	56.60	-11	1.07E+06	> 150	1037	-0.48
50/70 + 75% RAP + 10% Rej	57	48.40	-14	1.67E+05	> 150	1034	-1.32
50/70 + 75% RAP + 15% Rej	78	43.20	-16	6.82E+04	> 150	1032	-2.07

* N/E - no experimental test performed

Table A.2. Estimated values of penetration, ring and ball temperature, Fraass breaking point temperature and steady shear viscosity ($T_{ref} = 25^{\circ}C$) for binders presented in Table 1.

Materials	1 st approach				2 nd approach			
	Penetration (0.1 mm)	$T_{R\&B}$ ($^{\circ}C$)	T_{Fraass} ($^{\circ}C$)	η_0 at 25 $^{\circ}C$ (Pa·s)	Penetration (0.1 mm)	$T_{R\&B}$ ($^{\circ}C$)	T_{Fraass} ($^{\circ}C$)	η_0 at 25 $^{\circ}C$ (Pa·s)
50/70	N/E*	N/E*	N/E*	N/E*	N/E*	N/E*	N/E*	N/E*
RAP	N/E*	N/E*	N/E*	N/E*	N/E*	N/E*	N/E*	N/E*
Rej equivalent	N/E*	N/E*	N/E*	N/E*	3.07E+08	-240.24	-131.5	6.61E-19
RAP + 5% Rej	N/E*	N/E*	N/E*	N/E*	25	63.80	-8	3.49E+06
RAP + 10% Rej	N/E*	N/E*	N/E*	N/E*	52	50.00	-14	2.63E+05
RAP + 15% Rej	N/E*	N/E*	N/E*	N/E*	103	37.40	-19	2.48E+04
50/70 + 25% RAP	41	54.00	-12	6.01E+05	41	54.00	-12	6.01E+05
50/70 + 25% RAP + 5% Rej	47	51.00	-13	3.66E+05	47	51.40	-13	3.70E+05
50/70 + 25% RAP + 10% Rej	55	48.40	-14	2.17E+05	54	48.80	-14	2.27E+05
50/70 + 25% RAP + 15% Rej	61	46.60	-15	1.48E+05	61	46.40	-15	1.42E+05
50/70 + 50% RAP	31	59.40	-10	1.63E+06	31	59.40	-10	1.63E+06
50/70 + 50% RAP + 5% Rej	42	53.40	-12	6.02E+05	41	54.20	-12	6.12E+05
50/70 + 50% RAP + 10% Rej	56	48.20	-14	2.13E+05	53	49.20	-14	2.35E+05
50/70 + 50% RAP + 15% Rej	69	44.80	-16	1.02E+05	69	44.20	-16	9.43E+04
50/70 + 75% RAP	23	64.80	-8	4.45E+06	23	64.80	-8	4.45E+06
50/70 + 75% RAP + 5% Rej	37	56.00	-11	9.80E+05	35	57.00	-11	1.00E+06
50/70 + 75% RAP + 10% Rej	57	48.00	-15	2.10E+05	53	49.40	-14	2.44E+05
50/70 + 75% RAP + 15% Rej	77	43.20	-16	7.09E+04	78	42.20	-17	6.33E+04

* N/E - Not Estimated, experimental values taken as input for estimation