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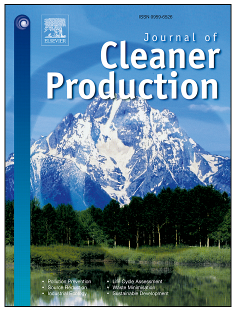

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Towards 100 % recycling of reclaimed asphalt in road surface courses: binder design methodology and case studies

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Abstract

Reclaimed Asphalt (RA) has shown great potential to be reused in new asphalt mixtures, however its incorporation in top asphalt pavement layers is still very limited (10-30%). In fact, despite the advantages that its use implies, RA content in road pavement surface courses is still restricted in most countries due to mainly legislation limitations, but also some technical issues. This paper aims at being a step further to improve the latter by providing a methodology that allows producing fundamental inputs for confidently performing mix design of asphalt mixtures incorporating up to 100% RA. The methodology consists in an advanced preliminary binder's blend design that can be used with any type of RA and also in presence of rejuvenators. This procedure includes in the production of blending charts and laws that considers the uncertainties on accounting the extent of final binder content, Degree of Blending and Replaced Virgin Binder. The description of the methodology is accompanied with results of two extreme case studies consisting in the preliminary design of binders for asphalt mixtures with high content of two types of RA corresponding to extreme cases: the short-term aged RA (STA-RA), having a very soft residual binder (Pen> 20dmm) and the long-term aged RA, having a much harder residual binder (Pen <10dmm). As a result, the proposed methodology allowed assessing the feasibility of using up to 90% of RA and determining whether the use of rejuvenating agents was needed.

Keywords: Reclaimed Asphalt, Rejuvenator, Binder design, Blending chart, Replaced Virgin Binder, Recycling

1. Introduction

Current concerns about the scarcity of raw materials for the construction and maintenance of roads (and the increase in price that it implies), together with the great potential shown by Reclaimed Asphalt (RA) to be successfully recycled in asphalt mixtures, are encouraging the increase of the use of this material to produce high RA content mixtures (Stimili et al. 2016). For this purpose, great efforts are being made to understand how to recycle RA directly within surface courses so to avoid its downgrading (Re-Road.fehrl.org, 2013). However, in general, the share of recycling of RA in new asphalt courses remains rather lower than it could be technically, being wearing courses the most challenging ones due to the required high performance such as resisting distresses and skid resistance (West et al. 2016). In fact, despite the advantages that its use implies, RA content in road pavement surface courses is still restricted in most countries due to mainly legislation limitations, but also technical issues such as: variability of RA properties, the often-unknown nature, uncertainties on mixture's performance and the lack of fundamental understanding of some of the mechanisms involved during its mixing with other components of asphalt mixes.

Generally, high RA content mixtures for wearing courses are considered those that have more than 20-30% in weight, depending on the countries and type of RA (Austroads 2015). Different studies have been carried out to shed lights on whether the increase of RA percentages in wearing courses is actually feasible or not. (Sabouri et al, 2015a; Sabouri et al, 2015b; Doyle and Howard 2010; Maupin et al. 2008). Beginning with low increases, Maupin et al. (2008) reported the results of testing plant-produced mixes for wearing courses including 21-30% of RA. They showed that there were no significant differences between the higher RA mixes and the control mixes for fatigue, rutting and susceptibility to moisture. Binder testing showed that the addition of RA raised the high temperature grading one to two grades, which should be assumed in mix design, and care has to be taken at low temperatures. In addition, there were no construction problems attributed to the use of the mix with higher RA percentages. The same mixes were later studied by Apeagyei et al. (2013) to check the influence of the high RA content in mix stiffness, finding that 30% RA did not produce a considerable effect on it.

Several studies showed that the key to increase the amount of RA in asphalt is a balanced mix design (Canon Falla et al. 2016, Bueche et al. 2016). On this regard, Zhou et al. (2011) developed a balanced RA mix design for high RA content mixtures for surface layers based on changing the binder content of the mix to optimise the maximum density. To validate the design, Zhou et al. (2011) built two field sections with 35% RA content mixes designed with their methodology in different locations. The overall conclusion from the study was that high RA mixes can have better or similar performance to virgin mixes, but they must be well designed following appropriate mix design methods.

Going further in the increase of RA content, Doyle and Howard (2010) studied mixes for wearing courses including 25 and 50% and considering the use of additives to produce warm technologies. Durability, cracking and rut resistance and moisture damage of the mixes were examined and results indicated that the use of high RA in surface mixtures would be feasible without adversely affecting mix performance. Celauro et al. (2010) conducted another investigation of mixtures with 50% RA content for surface layers concluding that, undertaking a tailored design with such a high percentage of RA, mixtures with "high-performance" could be obtained.

NCHRP Report 752 (West et al. 2013) showed that in mixtures with 55% RA content, stiffness could increase up to 25-60% compared to virgin ones, thus leading to cracking problems. On the other hand, rutting and moisture resistance are likely to be better or similar to those of conventional mixtures as the percentage of RA increases (McDaniel et al. 2002; Silva et al. 2012; Tran et al. 2012; Mogawer et al. 2012).

Results of the Austroads report (2015), as well as Sabouri et al. (2015a; 2015b) reinforce the previously published general trends that an increase in RA content leads to an increase in stiffness of the asphalt, a reduction in fatigue life, and an increase in permanent deformation resistance. The results do not suggest the RA content has an appreciable impact on moisture sensitivity of the asphalt specimen. Furthermore, It was observed that for mixes with hard RA, here called "long-term aged", incorporating content below 30%, the performance properties are very similar, but differ significantly from mixes with 60% of RA and those containing only virgin binder (0% RA) (Austroads, 2015). Instead, when RA mixtures were manufactured with even 40% of soft RA, here called "short-term aged", results of performance-related tests provided evidence of a little impact of the RA. This is justified from the little differences between RA and virgin materials stiffnesses (Sabouri et al, 2015a; Sabouri et al, 2015b).

In summary, these studies all agree that obtaining good performance of high RA content asphalt concretes strongly depends on RA properties and mixture design. Special attention has to be paid to the mixture design due to the presence of the aged stiff binder. In fact the aged binder could represent an advantage in terms of rut resistance at high service temperature (30 – 60C) but it usually favours cracking phenomenon at lower temperatures (+30C to below 0C). Furthermore, these studies considered 50-60% RA content as almost a limit for asphalt mixes, especially for surface courses. This is partially related to the final performance of the asphalt concrete that will strongly depend on the properties of the RA, on the RA handling procedures (Bressi et al., 2016) and also to the final grading curve of the targeted mixture that usually needs fixing with additional virgin aggregates. Nevertheless, regardless of the final performance of the asphalt, so far the main technical reason playing against 100% RA asphalt mixtures has been technological and it is due to limitations of the majority of existing asphalt plants that, due to equipment design issues (such as fumes produced by over-heated RA), are not able to incorporate more than 50-60% in new asphalt mixtures (Zaumanis & Mallick, 2015). Current aspirations are to achieve greater RA rates (aiming at 100%) in order to maximise the advantages of RA usage, however technological change of the asphalt plants is needed and it's sporadically happening (Rowe et al., 2015; Zaumanis et al., 2014)), but also material characterisation and binder and mixtures design should be adapted to consider RA as the main ingredient, while ensuring the usual desired performance (Canon Falla et al., 2015; Lo Presti et al. 2014).

In this regard, investigating technologies and procedures to take advantage of the binder already contained in the Reclaimed Asphalt binders (RA binders) play a critical role (Hassan et al. 2015, Zaumanis et al. 2014; Zhao et al. 2016). Therefore, developing a proper binder blend's design between RA binders and virgin materials is the first step for designing feasible 100% RA content mixtures. Currently, different approaches are being followed to carry out this task in different countries. In Europe, the standard EN 13108-8:2005 for reclaimed asphalt establishes that if RA content is higher than 10% for surface layers and than 20% for base layers, a logarithmic blending law for penetration and a linear blending law for softening point should be applied to select the proper virgin binder to use. On the other hand, in the United States of America, for high RA contents (>20%), NCHRP Report 452 (2001) described a particular procedure to obtain blending charts assessing high, intermediate and low critical temperatures of the blend of RA and virgin binder. After building blending charts, next step in both specifications is to use the final RA percentage in the mix to obtain the value that the property under assessment (i.e. penetration, softening point, etc.) would have after the manufacture of the mixture. Nevertheless, RA percentage is not the percentage of RA binder that will be blended with the virgin binder. The real percentage of RA binder that will blend is known as Replaced Virgin Binder (RVB) and depends on several factors such as RA binder content, binder content in the final mixture and the degree of blending (DOB) between virgin and aged binders. NCHRP Report 752 (West et al. 2013) already suggested using what they called "RAP binder ratio" but only taking into account binder content in the mixture. Regarding the DOB, recent researches have argued that for high RA contents (>20%) high blending rates take place (Soleymani et al., 2000; Shirodkar et al. 2011; McDaniel et al. 2012).

Other aspect to take into account while developing blend design is that when RA content is wanted to be higher than a certain percentage (limitations depends on RA properties and local specifications), or when RA contains particularly hard aged binder, it could be necessary to introduce another component in the mix (in addition to the virgin binder). This component is commonly known as rejuvenator or rejuvenating/recycling agent and is responsible for restoring some of the properties that the reclaimed material had before its service life (Shen and Ohen, 2002; Karlsson and Isacsson 2006; Romera et al. 2006; Tran et al. 2012). The effect of rejuvenators on RA mixes has already been studied and applied in full-scale by some authors (Mallick et al. 2010; Silva et al. 2012; Zaumanis et al. 2013) showing that these materials could allow the use of 100% RA mixes for wearing courses. However, traditional binder blend's design still only considers RA and virgin binders without taking into account the use of rejuvenators.

Within this framework, this paper proposes a methodology that allows predicting the binder's properties of the asphalt mixtures containing up to 100% RA. This methodology consists in the construction of blending charts for conventional and performance-related binder properties, including the use of RVB and DOB concepts, it allows including the use of rejuvenators and it is independent of the RA source. In order to prove the flexibility of the methodology with regards to the RA source, this investigation shows also the results of the application of this methodology with two case studies corresponding to extreme conditions of RA sources: the short-term aged RA (STA-RA), having a very soft residual binder (Pen> 20dmm) and the long-term aged RA, having a much harder residual binder (Pen <10dmm). Results are presented and discussed together with recommendations for an immediate implementation from contractors, researchers, asphalt professionals and road engineers.

2. Preliminary Binder's design methodology

Most countries have developed their own blending models for the use of RA binder and rejuvenators in new asphalt mixtures. Thereby, European countries use conventional properties to design blends, while USA use performance-related properties. The proposed methodology includes a combination of the two (Figure 1). In this study, only the results of the binder design for both case studies are shown. More details on each of the undertaken step are published elsewhere (Jiménez del Barco Carrion et al. 2015). Furthermore, the procedure will include the flexibility of using rejuvenators, as well as the other key concepts: RVB and DOB concepts. Final procedure and testing plan followed by the authors are summarized in Figure 1.

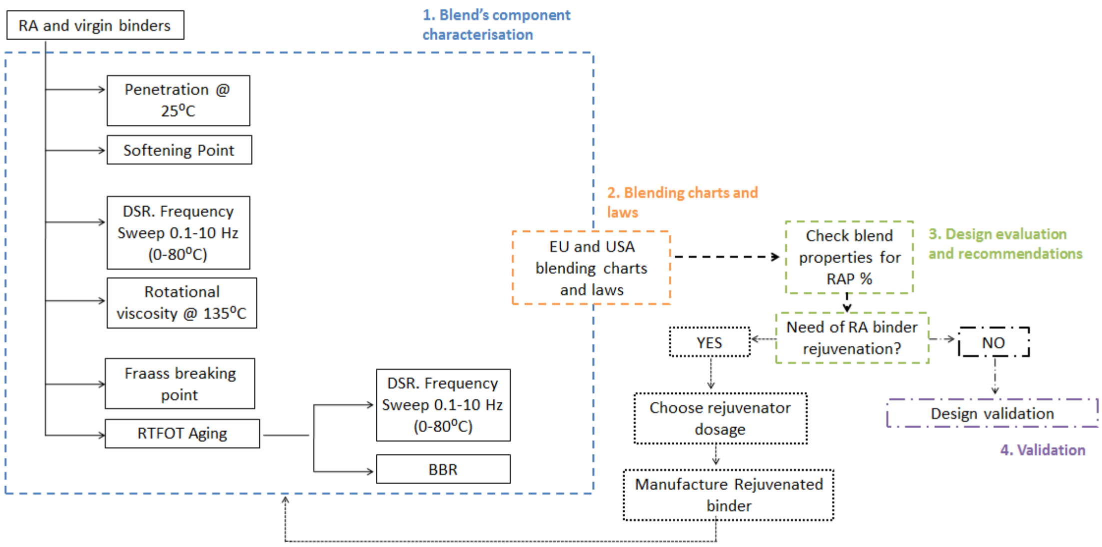

Figure 1. Preliminary binder design methodology for high-content RA asphalt mixture

As depicted in Figure 1, the proposed methodology includes four stages as follows:

1. <u>Blend's component characterisation (in blue in Figure 1)</u>

In this step, RA and virgin binders are tested to be conventionally and rheologically characterised according to the plan showed in Figure 1

2. Building blending charts and laws (in orange in Figure 1)

Once each of the final blend component have been characterised, blending charts are built on the basis of the selected blending laws between RAb and usually fresh bitumen. Blending laws are the models internationally used to assess the property of the final blend depending on the dosage of each component (EN 13108-8:2005; NCHRP Report 452 2001). 'Blending charts' are graphs in which the x-axis usually represents the percentage of RA in the asphalt mix from 0% to 100%, while the y-axis represents the property of the binder that we want to target in the design procedure (i.e. Pen). In this sense, the 0% RA represents the value of the property of the rejuvenator (i.e. neat bitumen) and the 100% is usually the property of the RA binder that will be blended with the virgin binder.

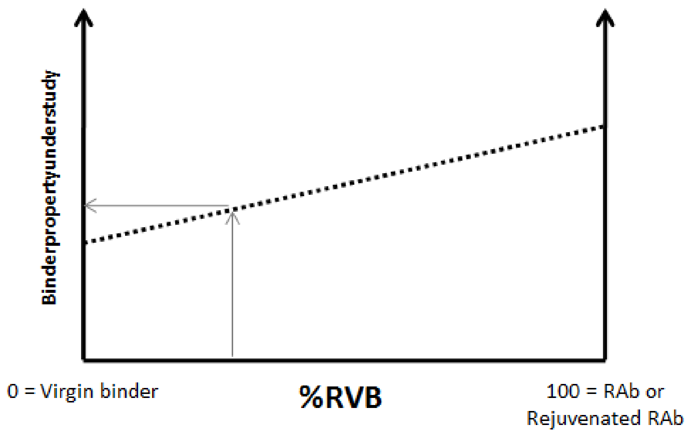

Figure 2. Example of proposed blending chart

Figure 2 shows the blending chart of the proposed methodology which is based on a linear blending law and that includes the possibility of incorporating rejuvenating agent for the RA. For this reason the x-axis represent the Replaced Virgin Binder (RVB), while the 100% y-axis represent the properties of Rejuvenated RAb. Using the RVB% in place of the RA% is a key fact affecting also the blending laws where RA percentages are not the in weight in the mix but the real percentage of virgin binder that will be replaced by RA. As mentioned earlier, this value is called the Replaced Virgin Binder (RVB) and is calculated following Equation 1 with all the parameters expressed in decimals.

$$RVB\ (\%) = 100 \cdot \frac{RA\ content\ in\ the\ mixture \cdot DOB \cdot RA\ binder\ content}{binder\ content\ in\ the\ mixture} \quad (1)$$

Where,

- *RA content in the mixture*: is the total RA percentage to add in the mixture by weight,
- *RA binder content*: is the binder content in the RA
- *binder content in the mixture*: is the designed final binder content in the mixture, which is considered having Variability of the final binder content in the mixture (± 0.5%)
- *DOB*: is the assumed degree of blending between RA and virgin binders. In fact, given that the real percentage of blending that will occur on the mix is unknown, the possibility of 100 and 60% of blending was considered. This initial hypothesis was based on previous research of other authors who found that for high RA percentages high blending is achieved (Soleymani et al. 2000; Shirodkar et al. 2011; McDaniel et al. 2012). These authors experimentally obtained the DOB through different procedures such as comparing the performance of mixes with different RAP content (Soleymani et al. 2000), manufacturing mixes only with fine RAP and virgin coarse aggregates and observing the effect (Shirodkar et al. 2011) or using Hirsch model to predict full blending and then comparing with experimental results (McDaniel et al. 2012).

3. Design evaluation and Recommendations (in green in Figure 1)

Having the blending charts, the desired RA percentages are replaced in them and the value of each property of the final binder blend is predicted and compared to the target. In the case studies shown in this paper, the two fresh binders represented the target. From this comparison, then it will be possible to predict whether incorporating the selected RA% will provide an asphalt mixture with acceptable properties, or if rejuvenating agents are needed, only depending on the binder properties. This final recipe will provide confirmation on the quantity and quality of the chosen blend components and will represents the desired inputs for a further mix design.

4. Design validation (in purple in Figure 1)

Once an acceptable binder recipe is found, with or without rejuvenators, validation is performed by means of blending the binders in the laboratory in the previously determined proportions and subjecting them to further testing that will be compared with binder recovered from the resulting high-content RA mixture. The results of this comparison will provide information on the accuracy of the preliminary design and potentially also the actual occurred DOB.

3. Case Studies: binder design with Short (RA-STA) and Long Term Aged RA (RA-LTA)

RA coming from two different sources were specifically selected and identified as: short term aged RA (RA-STA) and long term aged RA (RA-LTA). It was known that RA-STA was manufactured with a polymer modified binder denominated as PMB 25/55-25, meaning that its needle penetration at 25^{o}C is within the range 25-55 dmm (according to EN 1426:2007) and its ring & ball softening point is equal or higher than 55^{o}C (according to EN 1427:2007). On the other hand, RA-LTA was manufactured with a conventional 50/70 penetration grade bitumen (penetration within the range 50-70 and softening point within the range 46-54^{o}C according to

EN 12591:2009). In order to characterise both RAs, binder contents were determined following the standard EN 12697-1:2012. At last, binders were recovered from the RA following EN 12697-4:2005.

The virgin bituminous binders to be added to RA to achieve the desired targeted properties of the final asphalt mixtures were selected to be the same than the one used in the manufacture of the RAs. These would be: a PMB 25/55-55 for the RA-STA mixtures the virgin binder and 50/70 penetration grade for the asphalt mixes incorporating RA-LTA .

Furthermore, as detailed by the binder blend's design, for some of the mixes also a rejuvenator (Rej) was needed. This was selected to be a special combination of regenerated oil and a Fischer-Tropsch wax that is specifically produced to allow manufacturing asphalt concrete with very high content of RA. In fact, the oil rejuvenates the bitumen of the RA to a predetermined degree of softness, while the Fischer-Tropsch wax improves the mixability and workability of the asphalt.

3.1. Blend's components characterisation

Table 1 shows the results of the conventional tests undertaken for RAb-STA, RAb-LTA and virgin binders (VB-STA and VB-LTA). It can be observed the effect of ageing over RA binders: penetration decreases due to hardening while softening point, rotational viscosity and Fraass breaking point increase.

Table 1. RAb and VB conventional properties

BITUMEN	Penetration @25°C (dmm)	Softening point (°C)	Rotational viscosity @ 135°C (mPa.s)	Fraass breaking point (°C)
RAb-STA	21.7	65.7	1518	-8
VB-STA	43	60.4	1195	-16
RAb-LTA	8.3	71.4	1827	+8.7
VB-LTA	68	47.6	273	-8

High, intermediate and low critical temperatures for both binders are shown in Table 2. BBR temperatures were selected based on previous DSR results. Critical temperatures in Table 2 are the final evidence of the effect of ageing in the binder. High and intermediate temperatures slightly increased for the short term aged RA case and in a more notable way for the long term aged RA case. In this sense, RA binders exhibit better resistance to rutting and fatigue. On the other hand, the increase of low critical temperature (i.e. warmer low temperature) in both cases would worsen thermal cracking behaviour. Differences between RAb-STA and VB-STA are not very significant, which confirms that RA-STA is a 'young' RA. On the contrary, differences between RAb-LTA and VB-LTA are more visible, meaning that RAb-LTA is an 'old' RAb.

Table 2. Critical temperatures for RAb and VB

Binder	High (^{o}C)	Intermediate (^{o}C)	Low (^{o}C)
VB-STA	79.4	19.1	-16
RAb-STA	80.1	22.5	-13.5
VB-LTA	66	19	-16
RAb-LTA	87	33	-6

3.2. Blending charts

Once the testing was finished, blending charts and laws were constructed for penetration, softening point and critical temperatures. Those charts are shown in Figure 3 and Figure 4.

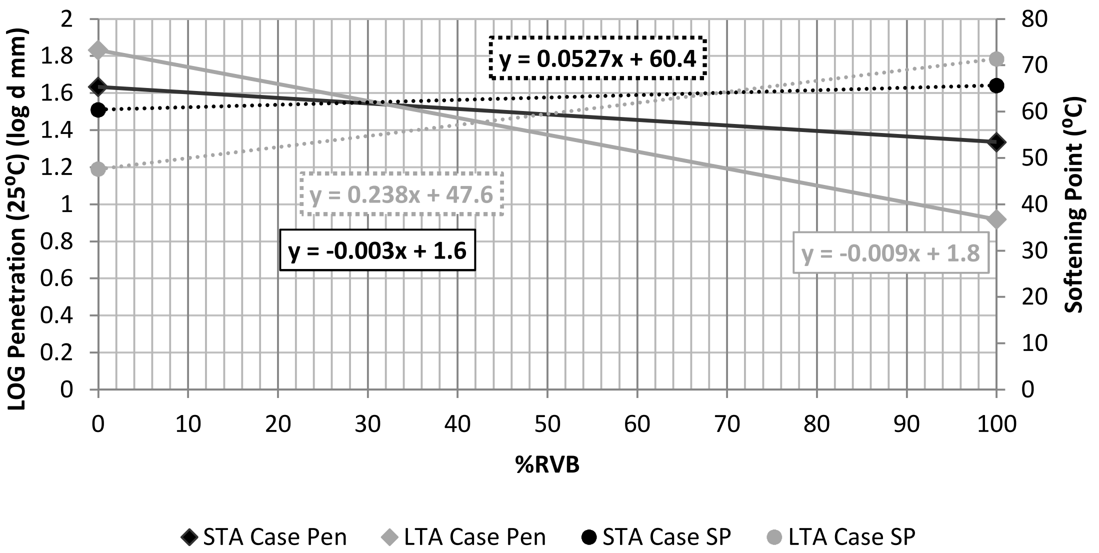

Figure 3. Penetration at 25ºC (Pen) and softening point (SP) blending chart and law between RA and virgin binders

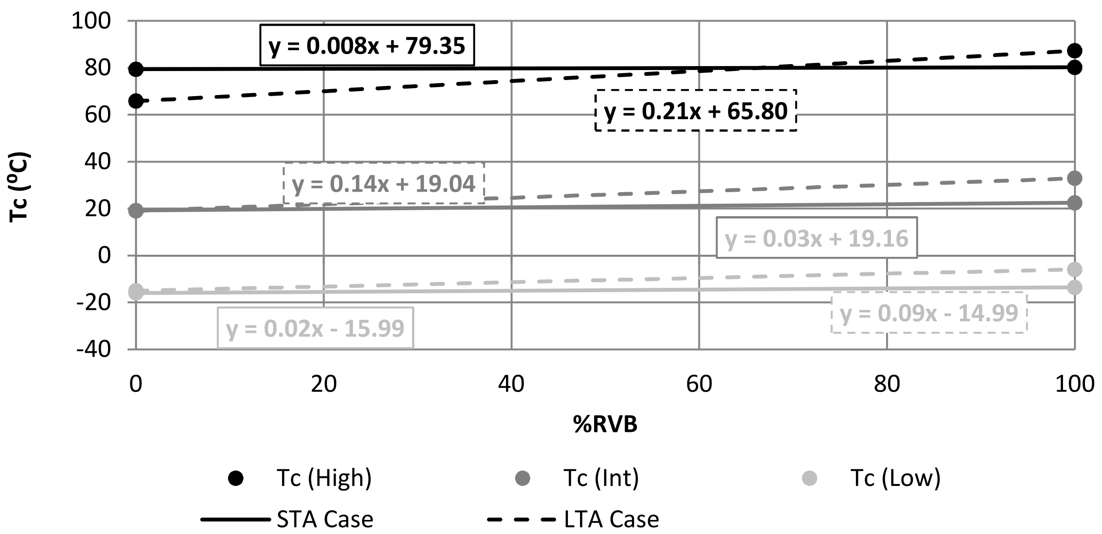

Figure 4. Critical temperature blending chart and law between RA and virgin binders

In the short term ageing case study, the aim was to assess the possibility of manufacturing mixtures with 30, 60 and 70% of RA-STA. The limitation to 70% was due to the differences between the RA-STA and the final grading curve of the targeted mixes. In other words, for issues related with the aggregate skeleton, it is not possible to manufacture the targeted asphalt mixes with 100% of the selected RA-STA. The binder content in the RA-STA was found to be 4.86% and final binder content in the mix was defined as 7.2%. Due to possible changes in the asphalt plant, to see the effect of the binder content in the mix and due to that different RA content changes the optimum binder content of the mix, a variability of ±0.5% was considered, so also 7.0 and 7.4% were considered.

On the other hand, in the long term aged RA case, 30, 60 and 90% of RA-LTA in weight of the mix were considered for the design. In this case, the selected RA-LTA was quite "compatible" with the targeted asphalt mixture, to the point that based on grading curves it is possible to recycle up to even 90% of the RA-LTA. The binder content of this RA was obtained for the fine and coarse fraction as 6.83% and 4.76% respectively, being each fraction 52.16 and 47.84% of the total RA-LTA. Binder content in the long-term aged RA mixtures would be 6.5% but also 6.0 and 7.0 % were considered in the calculations. Given these parameters, RVB percentages were calculated and are shown in Table 3 and Table 4 for each case. As explained above, in both cases the maximum amount of RA% was established, elsewhere, by checking how close the RA grading curves were from the targeted grading bands of the selected mixtures.

Table 3. Replaced Virgin Binder (RVB) percentages and blend results for the short term aged RA case study

Estimated Degree of Blending (DOB)	%RA	%Binder	%RVB	PEN (dmm)	SP (°C)	High Critical temp.	Int Critical temp.	Low Critical temp.
	0		*0*	*43*	*60.4*	*79.4*	*19.1*	*-16*
100%	30	6.7	21.76	37.0	61.5	79.5	19.9	-15.5
		7.2	20.25	37.4	61.5	79.5	19.8	-15.5
		7.7	18.93	37.8	61.4	79.5	19.8	-15.5

60%	30	6.7	13.06	39.3	61.1	79.5	19.6	-15.7
		7.2	12.15	39.6	61.0	79.5	19.6	-15.7
		7.7	11.36	39.8	61.0	79.4	19.5	-15.7
100%	60	6.7	43.53	31.9	62.7	79.7	20.6	-14.9
		7.2	40.50	32.6	62.5	79.7	20.5	-15.0
		7.7	37.87	33.2	62.4	79.7	20.4	-15.1
60%	60	6.7	26.11	36.0	61.8	79.6	20.0	-15.3
		7.2	24.30	36.4	61.7	79.5	20.0	-15.4
		7.7	22.72	36.8	61.6	79.5	19.9	-15.4
100%	70	6.7	50.78	30.4	63.1	79.8	20.8	-14.7
		7.2	47.25	31.1	62.9	79.7	20.7	-14.8
		7.7	44.18	31.8	62.7	79.7	20.6	-14.9
60%	70	6.7	30.47	34.9	62.0	79.6	20.2	-15.2
		7.2	28.35	35.4	61.9	79.6	20.1	-15.3
		7.7	26.22	35.9	61.8	79.6	20.0	-15.3
	100		*100*	*21.7*	*65.7*	*80.1*	*22.5*	*-13.5*

Table 4. Replaced Virgin Binder (RVB) percentages and blend results for the long term aged RA case study

Estimated Degree of Blending (DOB)	%RA	%Binder	%RVB	PEN (dmm)	SP (^oC)	High Critical temp.	Int Critical temp.	Low Critical temp.
	0		*0*	*68*	*47.6*	*66*	*19*	*-16*
100%	30	6.0	29.20	36.8	54.5	72.1	23.1	-12.3
		6.5	26.95	38.6	54.0	71.6	22.8	-12.6
		7.0	25.03	40.2	53.6	71.2	22.5	-12.7
60%	30	6.0	17.52	47.0	51.8	69.6	21.5	-13.4
		6.5	16.17	48.4	51.4	69.3	21.3	-13.5
		7.0	15.02	49.6	51.2	69.0	21.1	-13.6
100%	60	6.0	58.40	19.9	61.5	78.3	27.1	-9.7
		6.5	53.91	21.9	60.4	77.4	26.5	-10.1
		7.0	50.05	23.7	59.5	76.5	26.0	-10.5
60%	60	6.0	35.04	32.5	55.9	73.3	23.9	-11.8
		6.5	32.37	34.4	55.3	72.7	23.5	-12.1
		7.0	30.03	36.2	54.7	72.2	23.2	-12.3
100%	90	6.0	87.60	10.8	68.4	84.6	31.2	-7.1
		6.5	80.86	12.4	66.8	83.1	30.2	-7.7
		7.0	75.08	14.0	65.5	81.9	29.4	-8.2
60%	90	6.0	52.56	22.5	60.1	77.1	26.3	-10.2
		6.5	48.51	24.5	59.1	76.2	25.8	-10.6
		7.0	45.05	26.4	58.3	75.5	25.3	-10.9

100	*100*	*8.3*	*71.4*	*87*	*33*	*-6*

Having the blending laws and the RVB percentages, the theoretical values of the evaluated properties of the blend between RAb and VB at the desired percentages were obtained. These results are shown in Table 3 and Table 4. Table 3 and Table 4 also include the values of hypothetic 0% and 100% RA as a reference to see how property values change approaching each extreme.

At this point, both cases have to be independently analysed through answering the question: do we need a rejuvenator for using those RA binders blended with the virgin binders and achieve the target? Therefore, from now on both cases are independently presented.

3.3. Design evaluation and Recommendations

3.3.1. Short term aged RA case study (soft RA)

Short term aged RA target binder to achieve with the blend of RAb-STA and VB-STA is a PMB 55-25/55 (same than VB-STA). In this sense, if results from Table 3 are compared with the target binder:

- Penetration values are within the range 30.4 - 39.8 dmm for every RA percentage and blending assumption, and therefore within the limits of a PMB 55-25/55.
- Softening point is always higher or equal to 61ºC, thus is higher than 55ºC.
- High critical temperature is always higher than the VB-G ones, which could imply a better rutting resistance.
- Low and intermediate critical temperatures are higher than the VB-STA one, but being maximum 1.2ºC higher in the case of the low temperature, and 1.7ºC in the case of the

intermediate temperature, always for the assumption of 100% blending and 70% of RA.

Given these claims, the final recommendations for the mix design with RA-STA are: there is no need of rejuvenator in any of the RA and blending percentages considered. However, some issues could arise with low temperature cracking phenomenons.

3.3.2. Long term aged RA case study (hard RA)

Target binder for the RA-LTA mixtures was a 50/70 penetration grade bitumen (same than VB-LTA). Comparing the results of the blend design between RAb-LTA and VB-LTA from Table 4 and the target binder, it can be said that:

- Penetration values are not within the range 50-70 dmm in any of the RA-LTA percentages or blending assumptions considered but lower.
- Blend softening point is higher than 54ºC for all the RA-LTA and blending percentages considered. In this sense, none of the blends can be considered a 50/70 penetration grade bitumen.
- High critical temperature of the blends is higher than VB-LTA one which could be seen as an advantage.
- Low and intermediate critical temperatures of the blends are higher than the VB-IT ones which could lead to a lower fatigue and thermal cracking resistance.

Due to the RAb-LTA characteristics, the blend with the VB-LTA is not able to achieve an adequate binder to be used in high RA content mixtures. Therefore, a new blend design considering the use of the rejuvenator was carried out.

Blend design with rejuvenator: The first step in carrying out the blend design with a rejuvenator was to define the ratio between the rejuvenator and the RAb-LTA to obtain the Rejuvenated RAb- LA. In this case, this additive/RAb-LTA ratio was selected following the instructions of the provider of the additive: Rej/RAb-LTA = 0.2. This dosage recommendation was based on empirical experiences of the provider. Due to the introduction of a new component in the mixture, RVB (%) have to be calculated again taking into account each rejuvenator ratio following Equation (2):

$$RVB\ (\%) = 100 \cdot \frac{RA\ \ in\ the\ mixture \cdot DOB \cdot RAb\ content \cdot (1 + REJ\ ratio)}{binder\ content\ in\ the\ mixture} \qquad (2)$$

Where, RA in the mixture is the total RA percentage to add in the mixture by weight, DOB is the assumed degree of blending between RA and virgin binders, RAb content is the binder content in the RA, REJ ratio is the ratio Rej/RAb for each rejuvenator and binder content in the mixture is the designed final binder content in the mixture, being all the parameters expressed in decimals.

In this sense, %RVB were calculated for the different combinations (18 in total). These values, shown in Table 5, will then be replaced in the blending laws to obtain the property of the final blends. From Table 5, it can be observed that when the percentage of RA is 90%, full blending is considered (100%) and binder content in the mix is 6%, the RVB percentage is higher than 100%. This result leads to assess that when full blending is considered (100%), 6% binder content for the 90% RA mixture is not enough to achieve the desired rejuvenation effect for the selected RA. Therefore, if the mix design will identify 6% as the optimum binder content, other Rejuvenators with higher rejuvenating effect (lower amount) would need to be selected. However, increasing the binder content to 6.5%, or assuming that partial blending would take place, RVB percentages are again less than 100% and the mix manufacture would be feasible with the selected rejuvenator.

Table 5. Percentages of Replaced Virgin Binder (%RVB) for the blend design with rejuvenator

Estimated Degree of Blending (DOB)	%RA	%Binder	%RVB
100%	30	6.0	34.8
		6.5	32.1
		7.0	29.8
60%	30	6.0	20.9
		6.5	19.3
		7.0	17.9
100%	60	6.0	69.6
		6.5	64.2
		7.0	59.7
60%	60	6.0	41.8
		6.5	38.5
		7.0	35.8
100%	90	6.0	104.4
		6.5	96.4
		7.0	89.5
60%	90	6.0	62.6
		6.5	57.8
		7.0	53.7

Table 6 shows the results of the conventional characterisation of Rejuvenated RAb-LTA. From the results, the softening effect that both rejuvenators exert in the RAb-LTA can be seen as compared to the RAb-LTA initial properties showed in Table 1. The rejuvenator increased the penetration of the RAb-LTA. It has to be said that the penetration value of the Rejuvenated RAb-LTA is not completely reliable due to the nature of the additive, which after one hour in a test conditioning bath at 25°C showed signs of phase separation. However, it was taken as an approximation for the design. Softening point of the Rejuvenated RAb-LTA with rejuvenator decreased 3^{0}C. It is also worth noting the remarkable reduction that the rejuvenator produced in the viscosity of the RAb-LTA at 135°C, which would significantly enhance the workability of the bituminous mixture (due to the waxes).

Table 6. Conventional properties of Rejuvenated RAb-LTA

Binder	Additive/RAb-IT Ratio	Penetration @ 25°C (dmm)	Softening point (°C)	Rotational viscosity @ 135°C (mPa.s)
Rejuvenated RAb-LTA	0.2	92	68.4	372.5

Critical temperatures of the rejuvenated binder were obtained according to NCHRP Report 452 (2001). Table 7 displays these results. They highlight the effect of the rejuvenator in the RAb-LTA, which decreases the intermediate and low critical temperatures (i.e. colder critical temperatures) and maintains the high critical temperature. This effect implies that the rejuvenator improve fatigue and thermal cracking resistance without affecting plastic deformation resistance. These results are in accordance with those showed by others authors (Tran et al. 2012).

Table 7. Critical temperatures for Rejuvenated RAb-LTA

Binder	High (^{o}C)	Intermediate (^{o}C)	Low (^{o}C)
Rejuvenated RAb-LTA	71	11	-21

Blending charts and blending laws for the blend of Rejuvenated RAb-LTA with VB-LTA are shown in Figure 5 and Figure 6. Table 8 displays the result of using the blending laws with the %RVB from Table 5, which takes into account all the design parameters.

According to Table 8, final blends of Rejuvenated RAb-LTA and VB-LTA would be feasible for mixture production with every RA percentage, even 90%. Although penetration results seem a bit high, the rest of the studied properties show convenient binders for the manufacture of high RA content mixtures. This fact could be due to the nature of procedure used for penetration tests and the phase separation signs already commented. Critical temperatures reveal good binder performance in comparison to resist rutting. However, some attention should still be taken in terms of fatigue and thermal cracking.

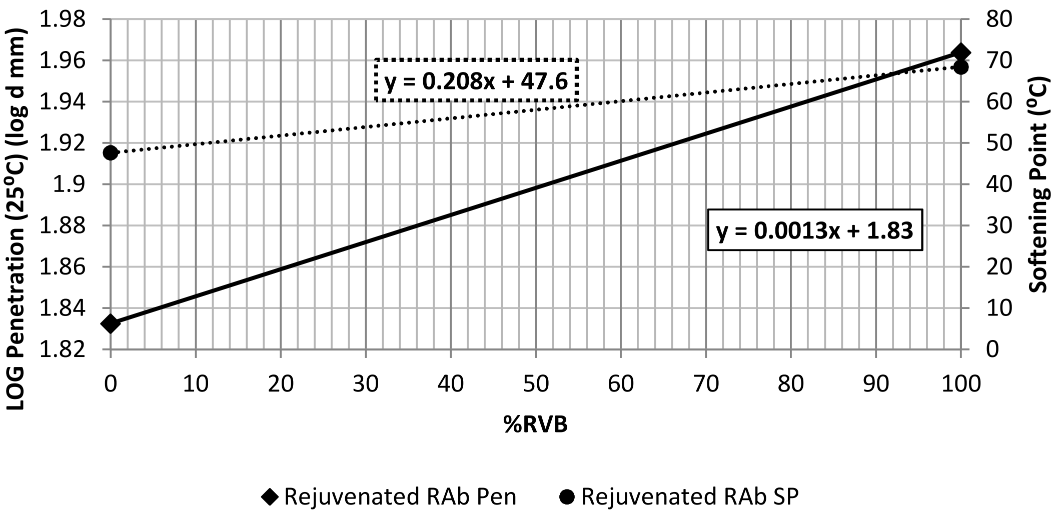

Figure 5. Penetration at 25ºC (Pen) and softening point (SP) blending chart and law between Rejuvenated RAb-LTA and VB-LTA

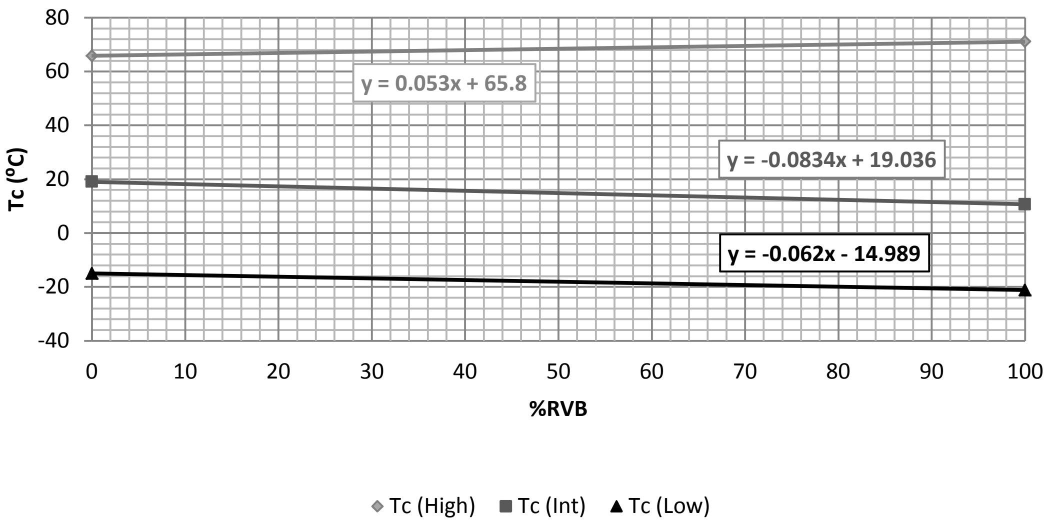

Figure 6. Critical temperature blending chart and law between Rejuvenated RAb-LTA and VB-LTA

Table 8. Replaced Virgin Binder (RVB) percentages and blend results for the long term aged RA case study with rejuvenators

Estimated Degree of Blending (DOB)	%RA	% Binder	% RVB	Pen 25ºC dmm	SP (ºC)	Tc High	Tc Int	Tc Low
100%	30%	6.0	34.8	75.5	54.8	67.6	16.1	-17.1
		6.5	32.1	74.9	54.3	67.5	16.4	-17.0
		7.0	29.8	74.4	53.8	67.4	16.6	-16.8
60%	30%	6.0	20.9	72.4	51.9	66.9	17.3	-16.3
		6.5	19.3	72.1	51.6	66.8	17.4	-16.2
		7.0	17.9	71.8	51.3	66.7	17.5	-16.1

100%	60%	6.0	69.6	83.9	62.1	69.5	13.2	-19.3
		6.5	64.2	82.6	61.0	69.2	13.7	-19.0
		7.0	59.7	81.4	60.0	69.0	14.1	-18.7
60%	60%	6.0	41.8	77.1	56.3	68.0	15.6	-17.6
		6.5	38.5	76.4	55.6	67.8	15.8	-17.4
		7.0	35.8	75.8	55.0	67.7	16.1	-17.2
100%	90%	6.0	104.4	-	-	-	-	-
		6.5	96.4	91.0	67.6	70.9	11.0	-21.0
		7.0	89.5	89.1	66.2	70.5	11.6	-20.5
60%	90%	6.0	62.6	82.2	60.6	69.1	13.8	-18.9
		6.5	57.8	81.0	59.6	68.9	14.2	-18.6
		7.0	53.7	80.0	58.8	68.6	14.6	-18.3

4. Summary of results

The proposed methodology was adopted with two extreme case studies aiming at providing inputs for mix design of asphalt up to 90% of Short Term and Long Term aged RA. The developed design includes the consideration of conventional and performance-related properties of binders through the production of blending charts and laws. The concept of Replaced Virgin Binder in the mixture was considered in the design, as well as the degree of Blending between RA and virgin binders that was assumed being between 100 and 60%. This design allowed predicting whether the chosen fresh binders, in combination with each of the RAs, lead to obtain a binder blend with the desired target properties, or determining whether the use of rejuvenators was needed.

In the short term aged RA case study, it was understood that the design could be performed without the need of rejuvenators for the mixes with 30, 60 and 70% RA mixtures.

On the other hand, in the long term aged RA case study, results of the recovered RA binder revealed that it was not possible to design a binder for the targeted asphalt mixtures, 30, 60 and 90% RA, without using rejuvenating oils. Thus, a new design was carried out considering Rejuvenated RA and virgin binders. The new design showed improvements in final blend behaviour and fundamental inputs to confidently manufacture well-performing asphalt mixtures.

The main reason of the different approach used for the preliminary design with STA-RA and LTA-RA, stands in the relative difference with the respective selected virgin binders (Table 2). In fact, STA-RA binder has very similar rheological and conventional properties when compared to the selected virgin binder, while the relative differences in the case of LTA-RA is much more significant.

Other important findings:

- Degree of Blending and Replaced Virgin Binder concepts are extremely important in order to carry out a realistic blend design. These concepts have great influence on obtaining blend properties from blending charts and laws.
- Before undertaking binder design with virgin and Rejuvenated RA binders, a right rejuvenator dosage has to be defined to obtain the desired rejuvenating effect on RA binder. Then, Replaced Virgin Binder percentages have to be calculated taking into account the percentage of RA into the mixture and the amount of rejuvenators. This point is important to ensure that the mix design is feasible with the selected rejuvenators' ratios.
- The two case studies have proved that every RA binder should be carefully studied before being used in the selected asphalt mixtures. Depending on RA binder properties, RA could be used in different ways, needing rejuvenating agents or not.
- Care has to be taken when testing RA binders with rejuvenator oils for needle penetration since phase separation issues could occur, making results meaningless.
- The use of the rejuvenator has improved RA binder behaviour up to the point of allowing the increase of RA content in the selected mixture up to 90%.

- Future work to improve the methodology should be focused on developing methods to obtain rejuvenator dosages to restore RA binder properties.
-

5. Discussion and Conclusions

The take-away fact of this research is that in order to conceive asphalt mixtures mainly made of RA (higher 50% RA), it is necessary to perform a detailed preliminary binder's blend design that can provide fundamental inputs for the mix design phase. This investigation provide such advanced methodology that allows tailoring binder blend's recipes to manufacture asphalt mixtures incorporating up to 100% RA. This procedure is based on adapted blending charts and laws allowing the use of rejuvenating agents and the possibility of varying the value of key concepts such as final binder content, Degree of Blending (DOB) and Replaced Virgin Binder (RVB). Authors are aware that in order to obtain such a drastic increase of RA in asphalt mixtures, a technological change is needed for most of the existing asphalt plant and other factors should play in favour such as local policies and improved RA handling to ensure that RA gradation and quality are not a limitation. However, sporadically these changes are happening already and considering that RA is the most recycled material in the planet, this trend is likely to grow exponentially. With this in mind, this research offers a validated methodology that can already be used from asphalt technologists to have better control when maximising the amount of RA in ordinary asphalt plants (up to 50-60%) and can represent a fundamental tool for those practitioners tailoring binder recipes in the few existing asphalt plant allowing producing mixture with 100%RA.

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Paper title:

TOWARDS 100 % RECYCLING OF RECLAIMED ASPHALT IN ROAD SURFACE COURSES: BINDER DESIGN METHODOLOGY AND CASE STUDIES

Highlights:

- Review of current practices, policies and limitations for using reclaimed asphalt (RA) in asphalt road surfaces
- Methodology to design binders for asphalt mixtures for road surfaces incorporating up to 100% RA
- Design, evaluation and recommendations for two case extreme studies differentiating for the type of RA source
- Adaptation of the design methodology with the use of rejuvenators