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# Analysis of the effect of rejuvenators on the performance of aged asphalt binders

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## Abstract

In the following years, the investment of developed countries in maintenance tasks will far overwhelm the construction of new infrastructures. One of the main activities will be the rehabilitation of pavements that generates large quantities of reclaimed asphalt pavements (RAP). The reuse of this material incorporated to the asphalt mixture in high percentages provide considerable economic and environmental benefits but it also could lead to a premature appearance of cracking or ravelling. To overcome these problems, the use of rejuvenators could play a key role. In this study, the effect of rejuvenators of different nature was determined through rheological analysis. For this purpose, aged binder extracted from RAP was blended with different types of rejuvenators at different dosages. According to the results, the type of rejuvenator used will have a great impact in the final performance of the aged bitumen.

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## 1. INTRODUCTION

Asphalt mixtures are the most widely employed material worldwide in paving tasks. When these materials reach the end of their useful life, they are removed by milling the layers in which they were resulting in large quantities of milled material known as RAP (Reclaimed Pavement Asphalt), which can be incorporated into new mixtures. This gives way to significant economic (the use of high-rate RAP can reduce construction costs by 50 to 70% [1]) and environmental (commodity savings and lower landfill use) benefits. However, the use of these materials in high percentages has certain limitations, the most important of which is linked to aged bitumen contained in RAP [2]. The oxidation processes to which the aged bitumen is subjected give rise to a stiffening of the same that is transmitted to the whole of the mixture, causing it to lose some of the viscoelastic properties that would otherwise bring cohesion to it [3]. In addition, the increase in the stiffness of the binder also results in mixtures more susceptible to cracking failure at low temperatures compromising their durability [4, 5, 6].

Thus, and to ensure the applicability of high rates of RAP in bituminous mixtures, it is necessary to be able to reverse this phenomenon through the restoration of the original properties of aged bitumen [7]. To achieve this goal, when the RAP content used is low (below 25-30%) the use of higher penetration binders can to some extent compensate for the effect of aging. However, for larger amounts the use of rejuvenating agents is essential [8]. This type of additives compensate for the effects of oxidative aging by adding aromatic components and resins to ensure that the binder reaches chemical and rheological characteristics similar to those of the original bitumen [9]. Along with this, the resulting bitumen should be able to provide sufficient adhesion and cohesion between aggregates to prevent damage to the mixture associated with water action and loss of particles [10].

This type of rejuvenating additives have traditionally been formulated from compounds based on the fractions of lower molecular weight of the bitumen (aromatic and saturated) and they are still used today. In recent years, however, new types of rejuvenators have emerged that use recycled oils and plant compounds to restore the properties of the binder. Depending on their nature, these additives interact in different ways with the aged bitumen present in the RAP, resulting in different behaviours of the mixture that incorporates them [11]. Thus, an assessment of basic parameters such as the reduction of penetration or the viscosity of the bitumens incorporating these additives can lead to misunderstandings showing similar variations for all of them (due to the oil-based composition of the same). Nevertheless, the rheological analysis of the properties of aged bitumens will show variations in the behaviour of these depending on their nature also conditioning the behaviour of the asphalt mixtures to which they are incorporated. Therefore, the main objective of this research is to determine the effect of the variation in the nature of the rejuvenators on the rheological properties of bitumen extracted from RAP by studying how dosage variations and chemical properties influence the behaviour of the material.

## 2. MATERIALS AND METHODOLOGY

This study examines the effect of four rejuvenators of different nature (Figure 1) on the rheological properties of aged bitumen: the first of them (R I) is mainly composed of oleyldiamine ethoxylate; the second (R II) consists mainly of non-recycled bio-oils while the additives R III and R IV are different compounds of ester resins of vegetal origin. These additives were mixed with an aged bitumen extracted from a milled material (RAP) (Figure 2).

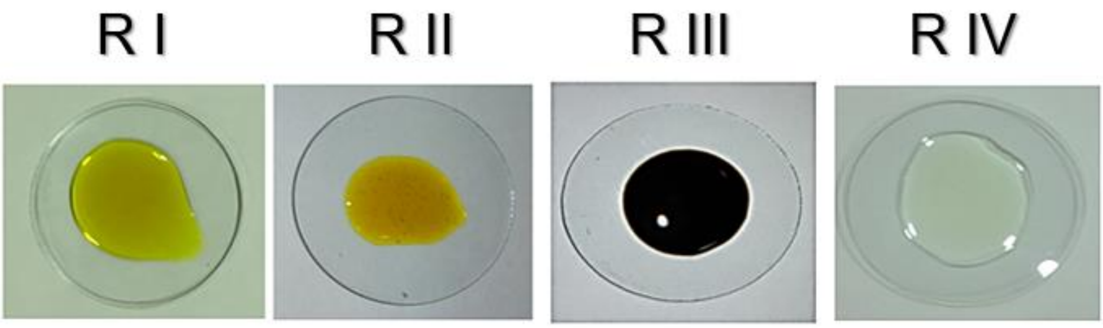


**Figure 1: Different rejuvenators additives employed in the study.**

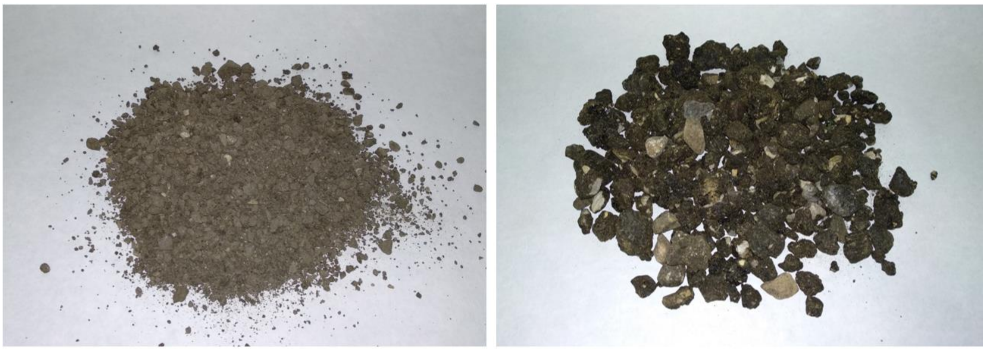

**Figure 2: Reclaimed Asphalt Pavement (RAP) employed in the study for bitumen extraction.**

Aged bitumen was extracted from RAP by centrifugal extractor and rotary evaporation equipment to remove the solvent used. This process was carried out at temperatures below that of bitumen mixing and for a reduced period so as not to contribute to extending the aging of the binder. After that, the rheological properties of the binder were compared with those obtained after the incorporation of different percentages of the rejuvenated additives chose: 3%, 6% and 9% for R I, R II and R III rejuvenators; 3%, 5% and 7% for the R IV additive. The dosage of the different additives was selected according to the recommendations of the different manufacturers. Similarly, to assess the degree of rejuvenation obtained with additives, the rheological properties of a B50/70 bitumen were also studied so to evaluate the performance of the original bitumen present in RAP prior to oxidation. For the mixing process, a temperature of 90 °C was selected which allows the application of these additives in warm-asphalt mixtures if desired. Throughout the process, the temperature was controlled by the use of an infrared thermal imaging camera.

For the rheological evaluation of the different bitumens, frequency sweeps (0-20 Hz) were carried out over a temperature range between 10 and 80 °C in order to characterize all possible service conditions of the same. Based on the results obtained, the evolution of the properties due to the effect of the rejuvenators was analysed by the representation of the complex stiffness module (G*) and phase angle for the 5 Hz isochrones. Along with that, parameters that evaluate the fragility of the aged binders were evaluated. First, the parameter "G* Sin (δ)" proposed by the Strategic Highway Research Program (SHRP) at different temperatures and for a frequency of 5 Hz. Then, parameters R-value and Crossover frequency [12] were obtained from the master curves at a reference temperature of 20 °C; and the Glove-Rowe parameter "G* (Cos (δ))$^2$/ Sin (δ)" at a temperature of 15 °C and an angular frequency of 0.005 rad/s was also evaluated. The latter allows by representing results in a Black space to establish limits that indicate the risk of cracking at low temperatures [13].

## 3. ANALYSIS OF THE RESULTS

Table 1 shows first the results of the fatigue parameter "G* Sin (δ)" for the different percentages of the rejuvenators tested, at three temperatures that simulate different service conditions of the material. Generally speaking, it can be seen how as the percentage of rejuvenator used increases, regardless of the nature of the same, values tend to move away from those of aged bitumen (RAP) and to approach those of the original binder (B 50/70). Similarly, it can also be seen how at low and medium temperatures the obtained values are closer to the original bitumen, while the difference grows as the temperatures are higher.

**Table 1. Evolution of the G* Sin (δ) parameter for different percentages of the rejuvenators.**

| Bitumen | G* x Sin (δ) (Pa) | | |
|---|---|---|---|
| | 10° C | 45° C | 80° C |
| **RAP** | 2,18E+07 | 6,99E+05 | 1,19E+04 |
| **3% R I** | 2,36E+07 | 5,76E+05 | 8,72E+03 |
| **6% R I** | 1,69E+07 | 4,71E+05 | 7,75E+03 |
| **9% R I** | 7,82E+06 | 2,56E+05 | 3,79E+03 |
| **3% R II** | 1,32E+07 | 3,85E+05 | 1,04E+04 |
| **6% R II** | 1,41E+07 | 2,71E+05 | 5,76E+03 |
| **9% R II** | 1,36E+07 | 2,43E+05 | 4,59E+03 |
| **3% R III** | 2,27E+07 | 5,18E+05 | 7,73E+03 |
| **6% R III** | 1,61E+07 | 3,16E+05 | 5,09E+03 |
| **9% R III** | 1,29E+07 | 2,38E+05 | 5,03E+03 |

| | | | |
|---|---|---|---|
| **3% R IV** | 1,53E+07 | 3,62E+05 | 8,32E+03 |
| **6% R IV** | 1,35E+07 | 3,02E+05 | 5,42E+03 |
| **9% R IV** | 9,33E+06 | 1,98E+05 | 3,47E+03 |
| **B50/70** | 1,64E+07 | 8,63E+04 | 1,13E+03 |

Although all additives are able to recover to some extent the original behaviour of bitumen, in Figure 3 it can be seen how the effect achieved for the highest doses of each of them varies depending on the nature of the rejuvenator used, which confirms their influence. Thus, in all cases there is a reduction of the complex module (G*) of the binder and an increase in the phase angle, which results in less rigid and elastic behaviour, closer to the original properties of the binder. In this way, we see how the additive R I is the closest to the behaviour of the original binder both in terms of complex module and phase angle. In either case, it is also appreciated here more clearly, how regardless of the nature of the rejuvenator, the effect of these on the rheological response tends to be less marked in high temperatures. This indicates that the action of the rejuvenator will be less effective in RAP materials intended to operate at high service temperatures.

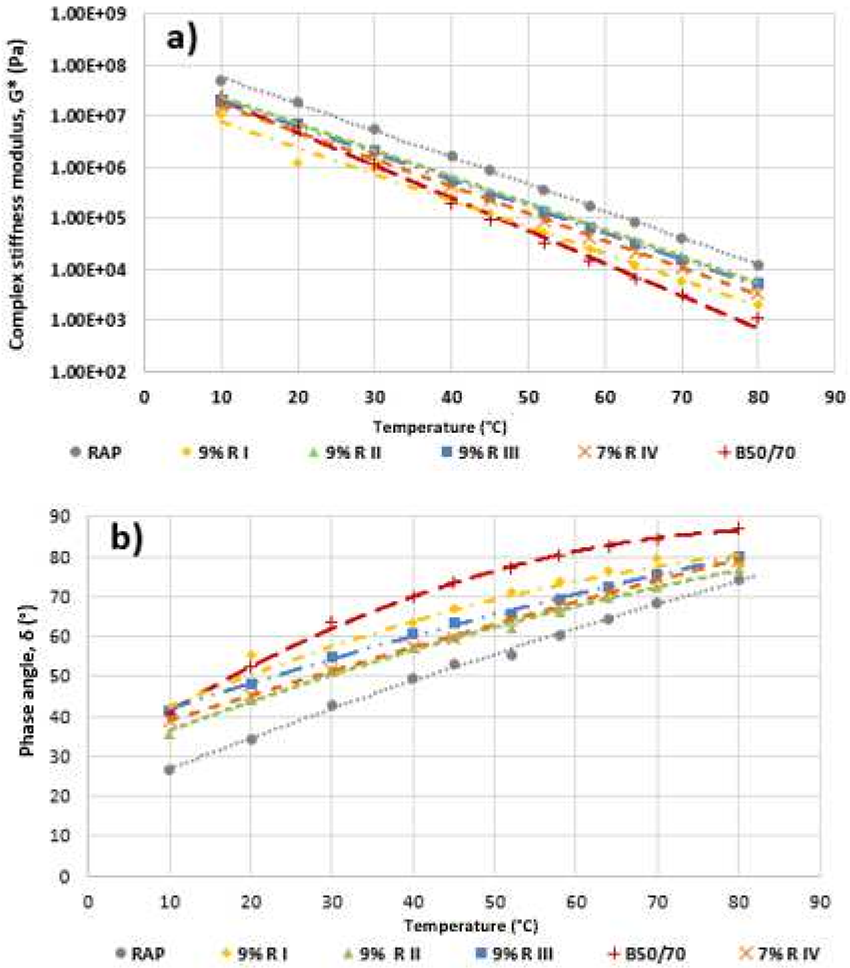


**Figure 3: Effect of optimal content of rejuvenators on the complex module G* (a) and phase angle (b) of aged bitumen.**

Figure 4 shows the average values of R-value and Crossover frequency obtained at a reference temperature of 20 °C for the different percentages of the different additives studied. These values are very useful when evaluating aged bitumens and how rejuvenating additives can reverse it. As the value of R-Value decreases and the Crossover frequency increases, the greater the degree of rejuvenation achieved. Based on these results, it can be seen how the additive R III (composed of esters resins of vegetal origin) is the one that manages, as its dosage increases, reach values closer to those of reference bitumen B 50/70.

If we analyse the evolution of the additive R I we can see how this is totally different from that of the additive R III which confirms the influence of the nature of the rejuvenator on the mechanism of action of the same and on the properties finally achieved. For the highest dosage of this additive, the R-value and Crossover frequency values obtained are higher than those of unaged bitumen (B 50/70). This implies that the material still remains rigid for a certain degree of viscoelastic response (the values of R-value has not decreased enough), the action of the rejuvenator means that this visco-elastic response can be reproduced at a higher level of frequencies without prolonging the stiffening process in them. Finally, the additives R II and R IV show a similar effect on the rheological properties of aged bitumen (RAPs), with an intermediate degree of performance between the other additives and less effective than these, since a high degree of discrepancy is maintained between the obtained for their higher dosages and the original bitumen B 50/70.

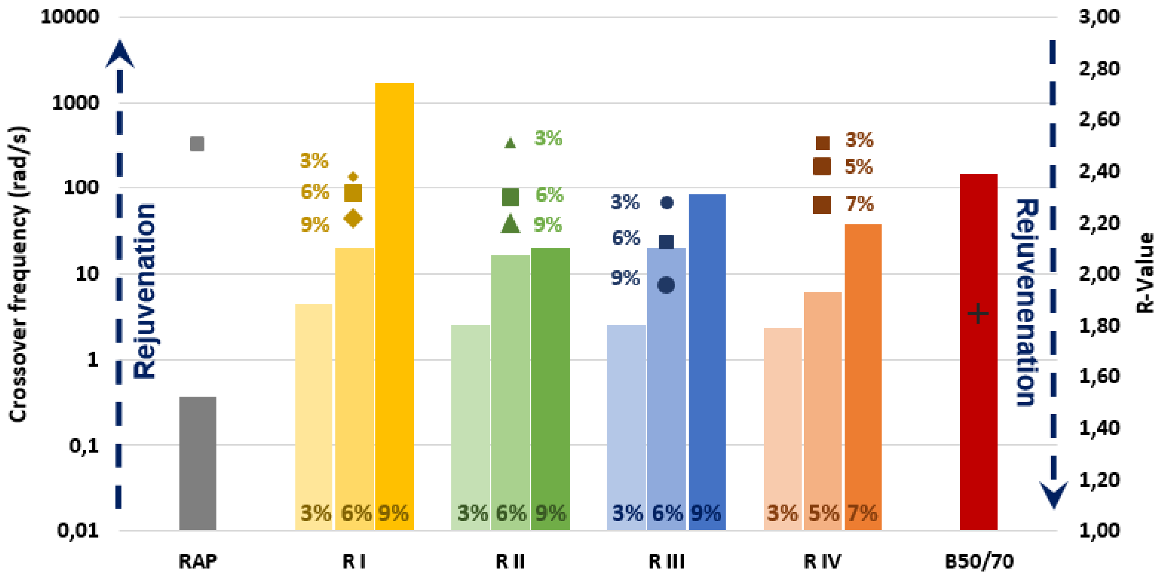


**Figure 4: Average values of R-value and Crossover frequency of the binders studied.**

Finally, Figure 5 shows the values of the Glove-Rowe parameter within a Black space (in terms of complex rigidity module and phase angle) for a reference temperature of 15 °C and an angular frequency of 0.005 rad/s. This parameter is related to the ductility of the binder at low temperatures and it can be correlated with BBR-type results to assess the risk of cracking of a binder. Thus two zones within Black's space are established for this parameter depending on the risk of cracking, one for which there is a risk of starting it (G-R x 180 kPa), and another from which the values above correspond to bitumens whose asphalt mixtures are at high risk of major cracking (G-R x 450 kPa). In this way, it can be observed that aged bitumen is between these two limits, i.e. it is likely to develop cracking. The aim of the rejuvenators is to move away from this area and get as close as possible to the state of the original bitumen.

As can be seen, the use of rejuvenating players clearly reduces the fragility of aged bitumens and with it the risk of cracking the asphalt mixtures, since even for the lower content all binders move away from the risk zone. However, the results show again how the degree of rejuvenation varies depending on the nature of the additive used. In this sense, it can be observed again how the effect obtained by the additives R II and R IV is very similar and much less effective than that obtained by the other two additives. The additives R I and R III, despite their differences in the mechanism of modification of the rheological properties of aged bitumen, are the most effective in restoring their original state, approaching to bitumen B 50/70 at their highest dosage. In either case, it is important to note that the choice of dosage plays an important role in the degree of rejuvenation obtained, since as can be seen, it is possible to obtain similar values of Glove-Rowe parameter by varying the dosage of rejuvenators of a different nature indicating that not all additives have the same optimal dosage.

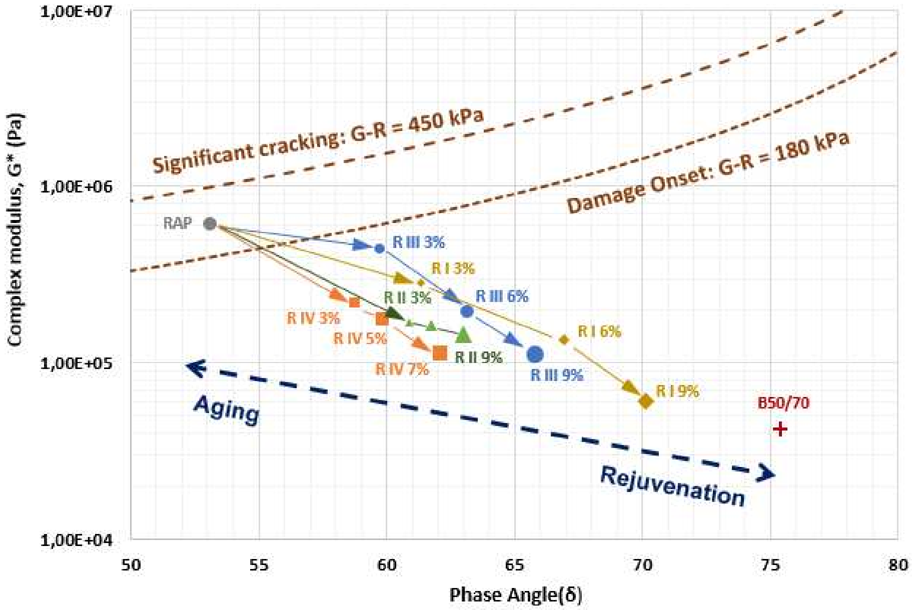


**Figure 5: Representation of the average value of Glove-Rowe parameter in terms of Black space for an angular frequency of 0.005 rad/s and a temperature of 15 °C.**

## 4. CONCLUSIONS

This study evaluates the effect produced by the use of rejuvenators of different nature on the rheological properties of aged bitumen extracted from milled material (RAP). In relation to the results obtained, the following conclusions can be drawn:

- The use of rejuvenating additives has been proved to reduce the fragility of aged bitumens, to reduce the risk of cracking and to partially restore the rheological properties lost during oxidation.

- In general terms, as the dosing of the rejuvenator increases, the aged bitumen contained in the RAP tends to achieve rheological properties (complex module, G* and phase angle) getting closer to those of the binder without aging. However, it has been shown that all additives neither have the same effect at their highest dosage or all have the same optimal content.

- As the temperature increases, the effect of rejuvenating additives (regardless of their nature) on the rheological behaviour of aged bitumen tends to become less marked, indicating that these additives will be less effective in RAP materials operating at high service temperatures.

- There are variations in the capacity of different bio-rejuvenators to restore the original properties of aged bitumen. Although the rejuvenator composed of oyldiamine ethoxylate (R I) is the most effective at restoring aged bitumen behaviour, similar behaviour can be achieved by using the R III additive composed of esters resins of vegetal origin.

## ACKNOWLEDGEMENTS

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