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Rheological investigation on the ageing performance of bio-recycled asphalt binders and mixtures

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ABSTRACT

The current need to move towards more sustainable technologies in the construction sector has promoted the investigation of using alternative materials in asphalt mixtures for pavements. Biomaterials, used as biobinders, have shown their potential as partial replacement of bitumen in asphalt mixtures as solution to decreasing the demand for fossil-fuel-based binders as well as CO_2 emissions. However, more research is needed to increase the replacement of bitumen in asphalt mixtures. In this investigation,biobinders are used as full replacement of virgin bitumen and as recycling agent within asphalt mixtures with high Reclaimed Asphalt (RA) content. Blends of biobinders and RA binders, and bio-recycled asphalt mixtures, were produced, subjected to ageing and rheologically characterised. The results show that the rheological properties of binders' blends seem adequate for their use, while the bio-recycled asphalt mixtures seem to have a faster ageing than conventional ones, hence their full-scale application still remains a concern.

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KEYWORDS
Asphalt; recycling; biomaterials; ageing; sustainability

1. Introduction

The current need to move towards the application of more sustainable technologies in the construction sector has promoted the investigation of the viability of using alternative materials in asphalt mixtures for pavements. In this regard, Reclaimed Asphalt (RA), crumb rubber from recycled tyres, construction and demolition wastes and recycled plastics are some of the most studied materials and its application in the field has already been undertaken even for decades in the case of RA and crumb rubber (Lo Presti, 2013; Tarsi et al., 2020). Most recently, the idea of introducing renewable materials in pavements to replace the traditionally used bitumen has been gaining attention (Ingrassia et al., 2019b; Zahoor et al., 2021) for two main reasons: (1) to decrease the demand for fossil fuel-based bituminous binders and (2) to reduce the carbon footprint of pavement construction. Renewable binders for asphalt mixtures, known as biobinders, can be produced from many different natural resources such as agricultural crops, municipal wastes, agricultural and forestry byproducts and natural tree and gum resins (Peralta et al., 2012), being of particular interest those materials obtained from wastes or byproducts from other industries (Mantalovas et al., 2020).

Nowadays, there have been different efforts to study the replacement of bitumen in asphalt mixtures in different ways. According to literature, biobinders can be utilised in three different ways to decrease the demand for fossil fuel-based bituminous binders: (1) as a bitumen modifier ($<$ 10%

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bitumen replacement), (2) as a bitumen extender (25–75% bitumen replacement) and (3) as a direct alternative binder (100% replacement) (Airey & Mohammed, 2008; Peralta et al., 2012; Raouf, 2010). According to the review conducted by Weir et al. (2022) on the use of biobinders for asphalt mixtures, most of the current studies focus on the first use mentioned, adding $< 10\%$ of biobinders in the mixture. These researchers established the need to go further and study the use of biobinders as extenders or total replacement of bitumen to maximise their potential in terms of sustainability.

In this sense, the combination of biobinders and RA in new asphalt mixtures is an interesting and challenging option to be investigated. Due to its nature, biobinders are usually soft or oily materials which could be use as rejuvenating agents for the old and stiff binder present in RA. Several studies have focused on this idea and shown that the bio-modification, in low percentages ($< 15\%$), could improve workability, rheology, fracture behaviour, rutting and fatigue performance of the aged binders (Fini et al., 2016; Gong et al., 2016; Gong et al., 2017; Hill et al., 2016; Mogawer et al., 2016; Nayak & Sahoo, 2017). Thereby, this rejuvenating effect could be used to increase the RA content in new asphalt mixtures and totally replace the additional virgin bitumen with biobinders. The limited studies that have analysed this approach have shown that biobinders, as a total replacement of virgin bitumen in asphalt mixtures containing RA, allow having similar rheological properties and can have an equivalent rutting and fatigue performance to conventional mixtures (Blanc, Chailleux, et al., 2019; Blanc, Hornych, et al., 2019; Jiménez del Barco Carrión et al., 2017).

However, the ageing of biobinders has been found to be the main drawback avoiding their further application in pavements (Weir et al., 2022). Biobinders have shown different evolution of their rheological properties and change of their performance compared to conventional binders depending on the feedstock used for their production (Camargo et al., 2018; Fakhri & Norouzi, 2022; Fini et al., 2017; Ingrassia et al., 2019a). Unfortunately, the literature on ageing characteristics of bio-asphalt mixtures is not very rich, hence before promoting their use in asphalt pavements, it is essential that any biomaterial is completely characterised before being used to ensure its adequate performance in terms of ageing.

Hence, this paper aims at enriching the knowledge in this field by studying the ageing of two biobinders, in place of virgin bitumen, used as recycling agent in bio-recycled asphalt mixtures containing very high content of RA (50%). For this purpose, biobinders blended with the RA binder and the related bio-recycled asphalt mixtures have been designed, manufactured and then rheologically characterised before and after ageing.

2. Materials

Two control binders, two biobinders and one source of Reclaimed Asphalt (RA) and virgin aggregates were used for this investigation as follows.

2.1. Binders and blends

Two biobinders were used as full replacement of the virgin binder added in very high-content RA mixtures. The biobinder (BB) was produced in the laboratory by mixing 20% of linseed oil and 80% of pine-modified rosin. It is worth mentioning that this biobinder is produced only for research purposes to be compared with conventional bitumen and is not commercially available or produced at larger scale. The biobinder 'BioPhalt®' (BP) was provided by a company (Patent No. de publication: 2 915 204, 2008). It is made from vegetal oil, residues of the paper industry and modified with SBS polymers; its exact composition cannot be disclosed here.

The RA binder (RAb) was extracted from two fractions of RA (0/8 and 8/12 mm) according to EN 12697-4 (2005) and using dichloromethane (DCM) as solvent. The two RA binders from the two fractions were blended in accordance to the mix design.

Two control binders were used in different ways to be compared with the biobinders. On the one hand, a 50/70 penetration grade bitumen (50/70) was used as target for the production of the blends

Table 1. Binders and blends' conventional properties.

Binders and blends	Name	Penetration @ 25°C [mm^{-1}] (EN 1426, 2015)	Softening Point [°C] (EN 1427, 2015)
50/70 penetration grade bitumen	50/70	68	48.0
Reclaimed asphalt binder	RAb	9	75.8
BioBinder (80% pine resin + 20% linseed oil)	BB	235	40.0
Biophalt®	BP	147	73.5
SBS modified binder	PMB	85	67.0
Reclaimed asphalt binder plus BioBinder	RAb + BB	69	45.0
Reclaimed asphalt binder plus Biophalt®	RAb + BP	63	62.0
Reclaimed asphalt binder plus SBS modified binder	RAb + PMB	37	70.0

of RA binder and biobinders, and further comparison with their rheological behaviour. On the other hand, an SBS-modified binder (PMB) commonly used for rejuvenating purposes with RA was selected to be blended with the RA binder and further compare such blend with the blends of RA binder and biobinders.

Blends of RAb, biobinders and the control PMB were produced. The percentage of blend between the RAb and each added binder was calculated according to the Replaced Virgin Binder (RVB) concept (Lo Presti et al., 2016) for RA mixtures assuming full blending, 50% RA in the final mixture and total binder content of 5%. The RVB calculation is shown in Equation (1).

$$RVB(\%) = 100 \cdot \frac{RA \cdot DOB \cdot RAbc}{bc} = 100 \cdot \frac{0.05 \cdot 1 \cdot 0.036}{0.05} = 36\% \quad (1)$$

where RA is the total RA percentage to be added in the mixture by mass, DOB is the assumed degree of blending between RA and virgin binders (100%), RAbc is the binder content in the RA and bc is the designed final binder content in the mixture, with all the parameters being expressed in decimals. Therefore, blends were composed of 36% RAb and 64% added binder by mass.

For the production of blends, RAb was heated at 160°C (due to its hardness) and the virgin binders were heated at 140°C. Then, materials were blended and introduced in an oven at 150°C for one hour. After that, blends were stirred for 15 min at 200 r.p.m. over a hot plate to ensure the homogeneity of the final product and remove air bubbles.

Table 1 shows the results of the conventional properties of the binders and blends (36% RAb + 64% binder). The low penetration value and high softening point of the RA binder is a first sign of the need for rejuvenation to use this material in high content in asphalt mixtures. In this regard, the blend with biobinders allow having similar penetration values to the 50/70 bitumen.

2.2. Asphalt mixtures

50% RA mixtures were manufactured and studied in the laboratory. Mix design was selected as GB5®, which stands for 'Graves Bitumes 5'. These types of mixtures were recently developed to optimise aggregates' packing by maximising their interlock and allowing for high complex modulus and improved fatigue and rutting resistance (Olard & Pouget, 2015). This mix design was chosen in order to provide a strong mineral skeleton to produce high-performance mixtures with high-RA content and biobinders.

Three mixtures were manufactured with 50% RA content by mass and using BB, BP and PMB as the only added binder respectively. Mixtures were termed 'Mix BB', 'Mix BP' and 'Mix PMB' depending on the added binder used. Total binder content in the three mixtures was 5% and the voids content was 3% for all of them. Figure 1 shows GB5® mixtures' gradation.

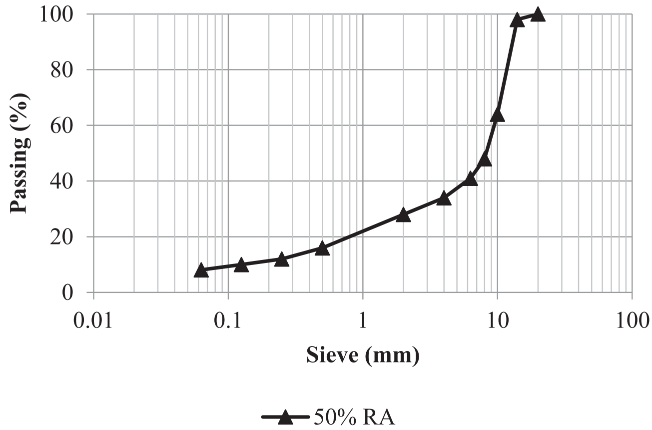

Figure 1. GB5® 50% RA mixtures' gradation.

3. Methods

Binders' blends and asphalt mixtures ageing was studied by means of the change in their linear viscoelastic (LVE) properties after ageing conditioning. In this regard, different ageing techniques and type of analysis were used for binders' blends and asphalt mixtures as follows.

3.1. Ageing of binder blends

For the study of the ageing properties of the binders' blends, they were subjected to short- and long-term ageing in the laboratory. Short-term ageing, which aims at simulating the ageing that the binders suffer during the manufacturing of the asphalt mixture in an asphalt plant, was performed by means of rolling thin-film oven test (RTFOT) (EN 12607-1 2014). Long-term ageing, which aims at simulating the ageing that the binders suffer after a number of years of service of the pavement, was carried out by means of RTFOT and consecutive pressure ageing vessel (PAV) test (EN 14769, 2012) for 20 h at 100°C and 2.1 MPa of pressure. In addition, the binders' blends were recovered after the manufacturing of the asphalt mixtures (EN 12697-4, 2005) in the laboratory to be analysed and compared with the artificial short-term ageing.

The LVE properties of the unaged and aged blends were tested by means of frequency and temperature sweeps using a Dynamic Shear Rheometer from 1 to 10 Hz and from 0°C to 80°C. Two repetitions were made for each blend. Two parallel-plate geometries were used to cover the range of temperatures: 8 mm diameter and 25 mm diameter. The tests at 30°C and 40°C were performed with the two geometries to then select the correct data according to Airey (2002). Next, the master curves of the norm of the complex modulus and phase angle were produced using the methodology specified in Chailleux et al. (2006) to obtain the shift factors at a reference temperature of 15°C.

In addition to master curves, the LVE properties of the binders were analysed by plotting the R-value versus cross-over frequencies (Rowe et al., 2015); and determining the Glover-Rowe parameter (G-R) for fatigue cracking (Rowe, 2011).

3.2. Ageing of asphalt mixtures

After manufacturing and compaction of slabs, trapezoidal specimens were obtained to allow two-point bending testing (EN 12697-26, 2012). The specimens were first tested in their unaged stage and then subjected to ageing in a water bath at 60°C and tested in two-point bending mode after 4 days, 8 days and 45 days of conditioning. The tests were performed from −10°C to 40°C from 40 Hz to 1 Hz according to EN 12697-26 (2012) Annex A.

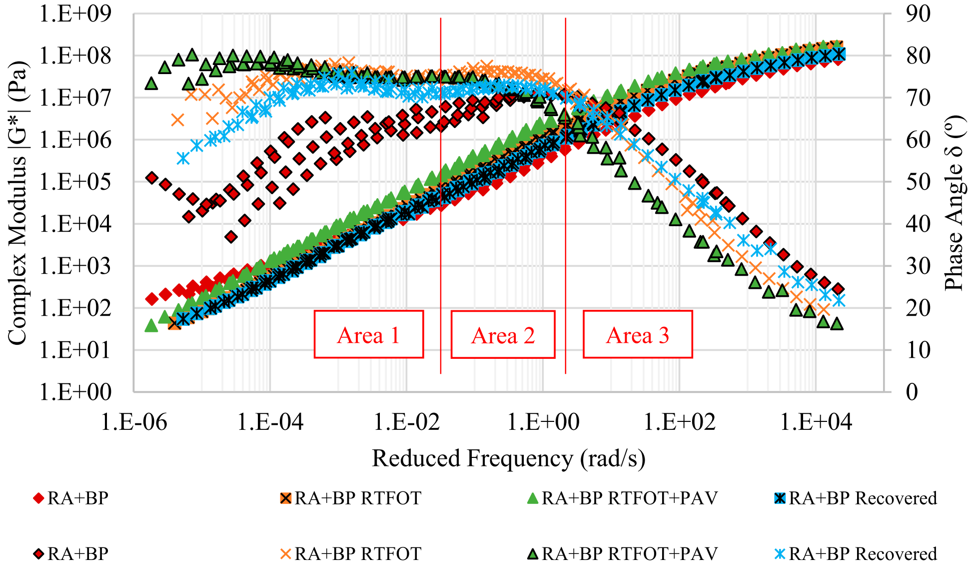

Figure 2. Master curves of the norm of the complex modulus and phase angle of unaged and aged RA + BP, RA and RA + BP recovered at $T_{ref} = 15$°C.

In order to analyse the results, Black diagrams and master curves of the norm of the complex modulus and phase angle were obtained after the different ageing conditioning times following the procedure described in Chailleux et al. (2006) at a reference temperature of 15°C.

Mensching et al. (2017) recently discussed the effect of the β and γ parameters (from the fitting of a sigmoidal function to asphalt mixtures' master curve) on the shape of master curves changing with ageing. To perform this analysis, the master curves of the asphalt mixtures were fitted with a standard sigmoidal function and the $(-\beta/\gamma)$ versus γ plot was produced to evaluate the relative position of the points after ageing.

4. Results and discussion

4.1. Binders' blends

Figures 2–4 show the master curves of the unaged and aged blends of the RA and different added binders together with the ones recovered from the asphalt mixtures after their manufacturing.

In the case of RA + BP, the change of its LVE properties with ageing depends on the range of frequency in the sense that the complex modulus and the phase angle either increase or decrease. Two threshold frequencies can be identified, one for the complex modulus and one for the phase angle. This provides three areas in Figure 2. Firstly, at lower frequencies than 0.01 rad/s (Area 1), RA + BP moves towards a more viscous response after ageing having lower complex modulus and higher phase angle. Next, between 0.01 and 1 rad/s (Area 2), the ageing produces an increase in both complex modulus and phase angle meaning that the binder is stiffer but has a more viscous response. Finally, at higher frequencies than 1 rad/s (Area 3), RA + BP exhibit higher modulus and lower phase angle. This complex behaviour after ageing may be due to the combination of BP, which is highly modified and the polymer would be degrading, and the RA binder, creating a gap in the change of phase angle and complex modulus with ageing. Finally, RA + BP after RTFOT and after its recovery from the asphalt mixture appear to have equivalent master curves meaning that RTFOT would effectively simulate the manufacturing of the asphalt mixture in the laboratory.

In Figure 3, RA + BB seems to be the blend most affected by ageing in comparison with Figures 2 and 4. Conversely to what happened to RA + BP, the recovered RA + BB from the asphalt mixture does

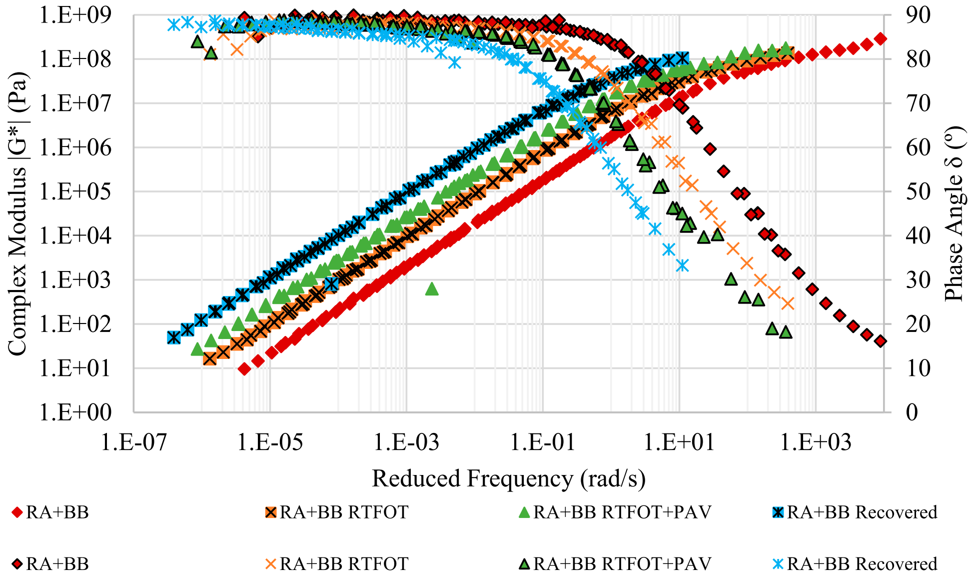

Figure 3. Master curves of the norm of the complex modulus and phase angle of unaged and aged RA + BB, RA and RA + BB recovered at $T_{ref} = 15$°C.

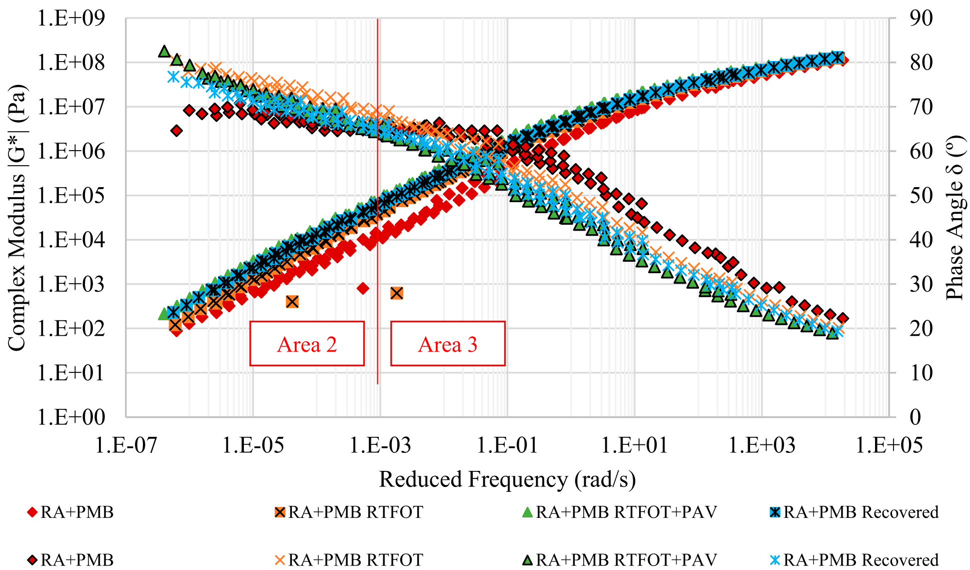

Figure 4. Master curves of the norm of the complex modulus and phase angle of unaged and aged RA + PMB, RA and RA + PMB recovered at $T_{ref} = 15$°C.

not match the RTFOT master curve and exhibits even greater ageing than RA + BB after RTFOT + PAV. This fact means that RA + BB may suffer significant ageing during the manufacture of the asphalt mixture which could be due to its composition (resin and oil) and could result in performance issues. The difference between the RA + BB recovered and the laboratory aged RA + BB could also be due to modifications suffered during the recovery process with the solvent affecting the binder. Therefore, its ageing in the laboratory and its recovery should be taken only as a reference for comparison with the rest of binders and the asphalt mixture has to be carefully studied separately. This fact stresses the importance of comparing the traditional ageing methods to the actual ageing during the asphalt

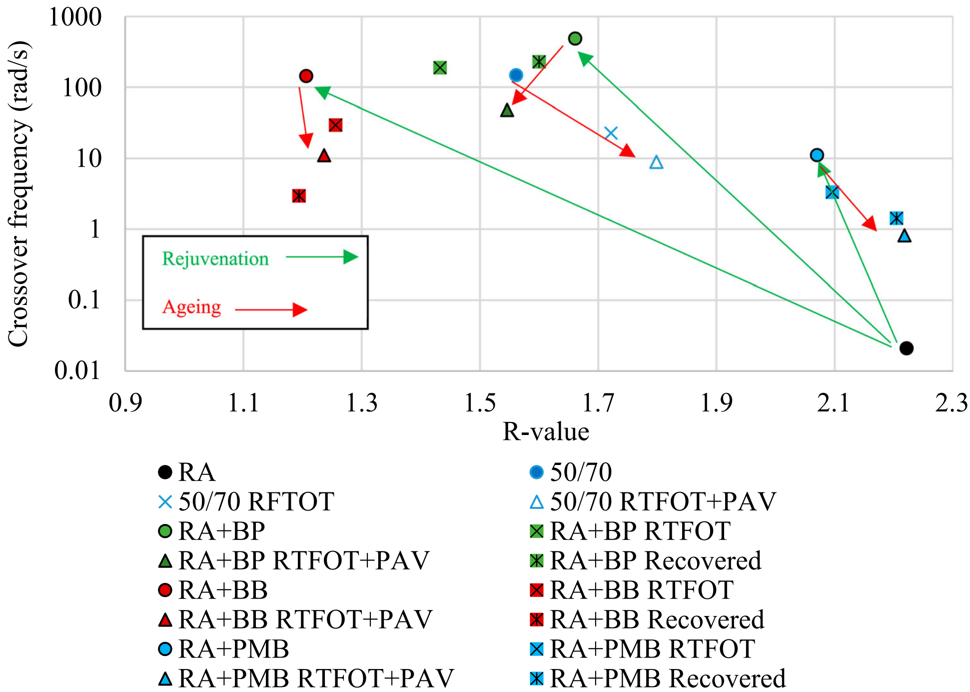

Figure 5. R-value versus crossover frequency of unaged and aged binders and blends.

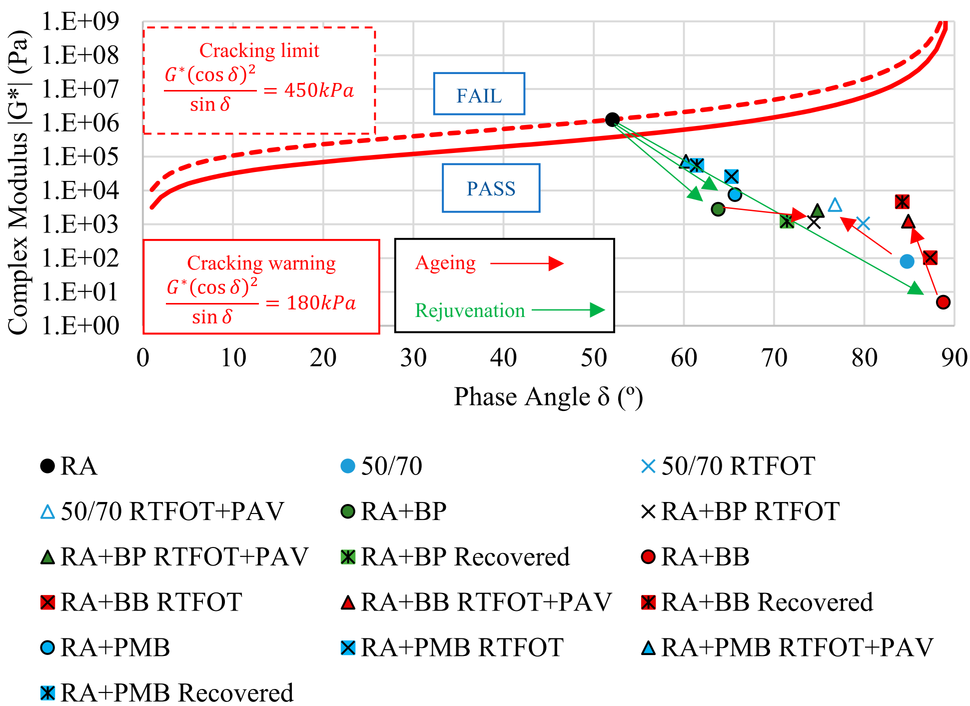

Figure 6. G-R parameter.

mixture manufacturing for new materials. The ageing study of binders by means of protocols that are not able to reproduce the actual ageing conditions in the field may lead to erroneous conclusions with important consequences such as the selection of the pavement layer in which to use these

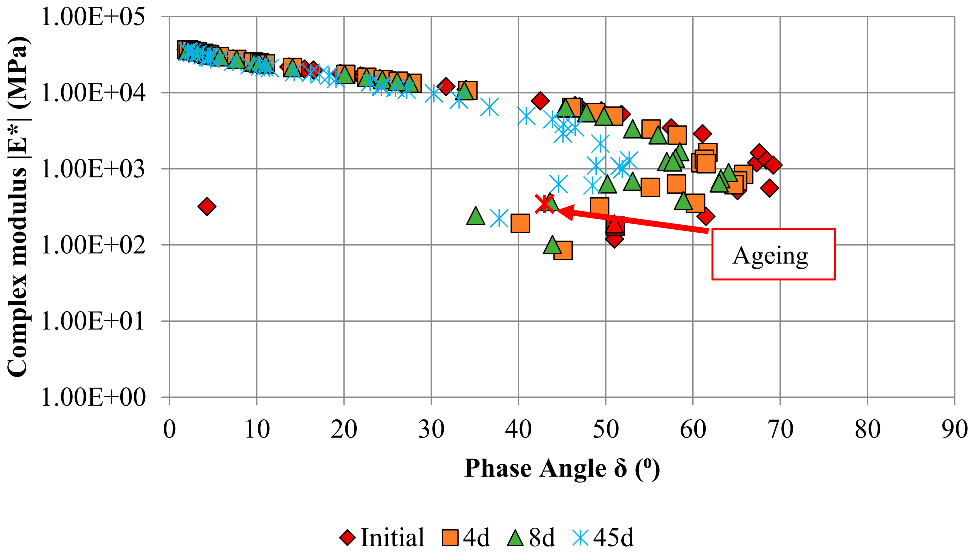

Figure 7. Black diagram of aged 50% RA Mix BB.

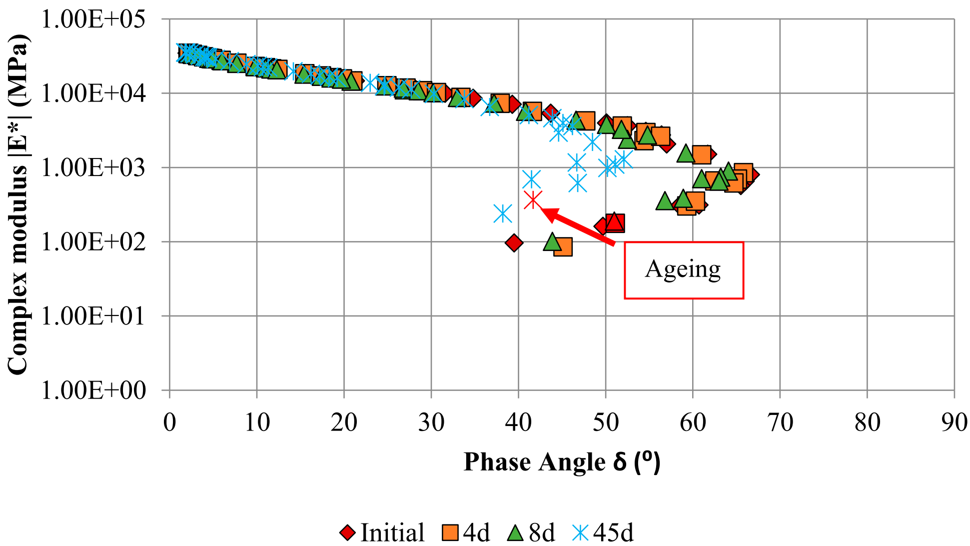

Figure 8. Black diagram of aged 50% RA Mix BP.

materials. It should be also highlighted that RA + BP contains a similar resin to RA + BB but the presence of SBS polymers seems to greatly improve its resistance to ageing, and the linseed oil in BB could be responsible for the ageing.

Figure 4 displays the ageing behaviour of RA + PMB showing that is comparable to RA + BP due to their similar SBS polymer modification, but only shows Areas 2 and 3 divided at 0.001 rad/s. In addition, the RTFOT curve and the recovered curve are equivalent revealing the equivalency of RTFOT ageing and the ageing after laboratory manufacture of asphalt mixtures with petroleum-based binders.

In order to put together the results of all the materials, their rheological data were simplified in terms of R-values and crossover frequencies to be plotted in one figure and visually used to assess the relative ageing.

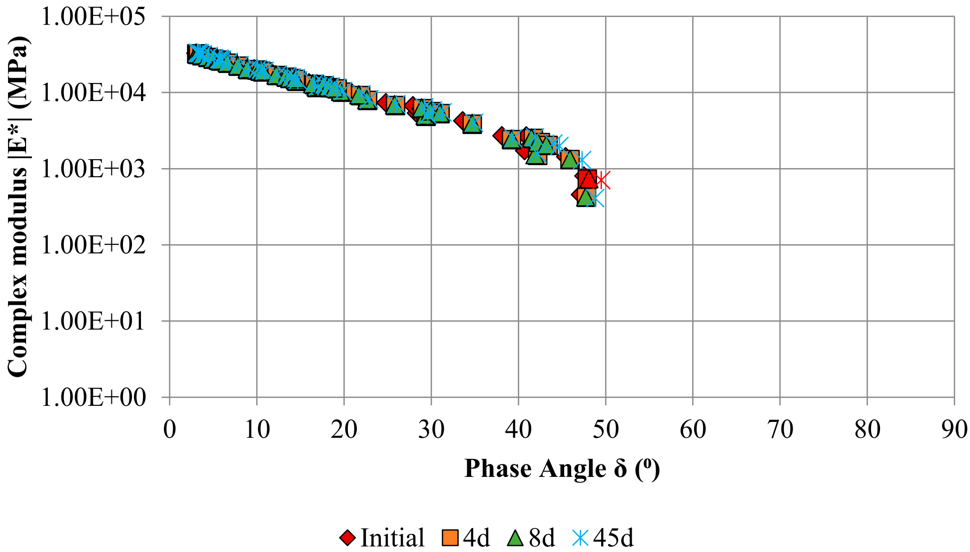

Figure 9. Black diagram of aged 50% RA Mix PMB.

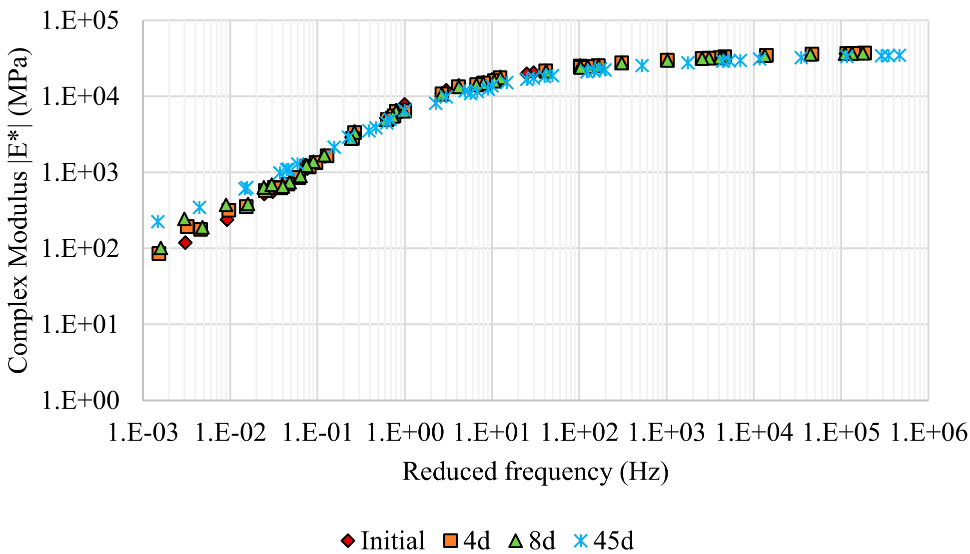

Figure 10. Master curve of the norm of the complex modulus of aged 50% RA Mix BB at $T_{ref} = 15°C$.

As described by Rowe et al. (2009), the ageing of binders produces a change in the shape of their master curves that can be translated into the change of their R-value and crossover frequency. The cross over frequency is the frequency in a master curve at which the phase angle is 45° (i.e. at which the storage and the loss modulus are equal). The R-value is the log distance between the glassy modulus and the modulus at the cross over frequency. For conventional binders, the crossover frequency moves to lower values and the master curve of the complex modulus becomes flatter. In this regard, ageing reduces crossover frequencies and increases R-values while rejuvenation should have the opposite effect. According to this, in Figure 5 the RA binder appears as the most aged binder being in the lowest and further right position. The effect of the blend of the RA binder with the biobinders and PMB can therefore be interpreted as rejuvenation. After the ageing of the blends, RA + BB and RA + PMB move

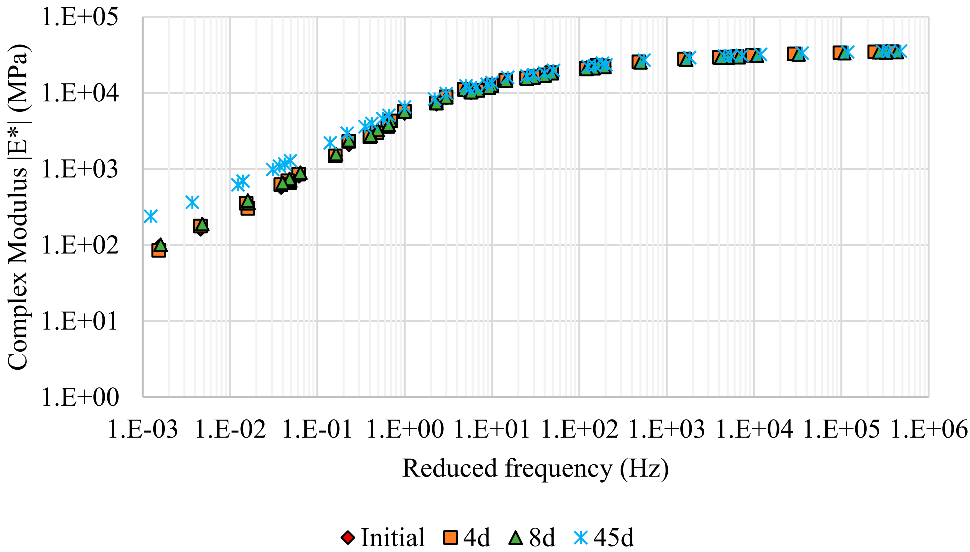

Figure 11. Master curve of the norm of the complex modulus of aged 50% RA Mix BP at $T_{ref} = 15°C$.

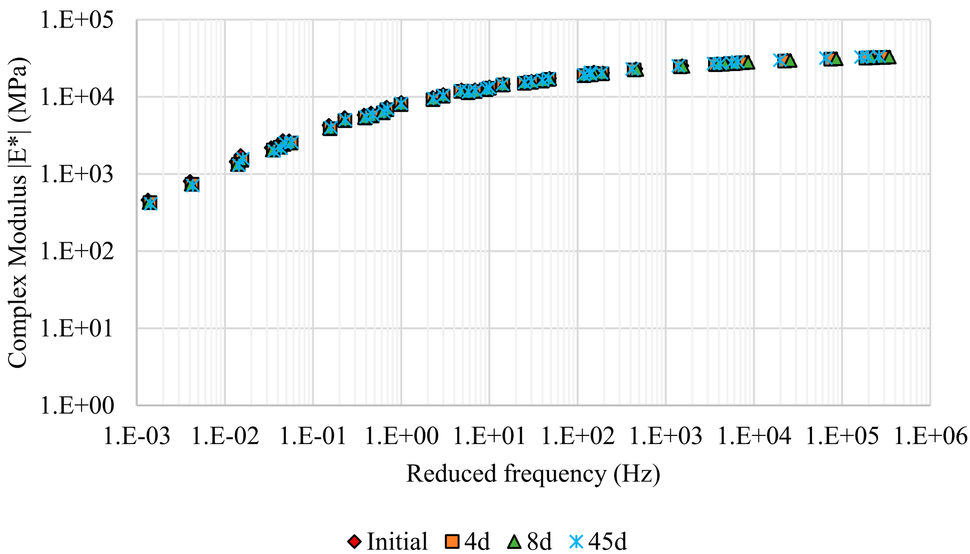

Figure 12. Master curve of the norm of the complex modulus of aged 50% RA Mix PMB at $T_{ref} = 15°C$.

down and to the right. However, all the aged RA + BP and the recovered RA + BB have a different relative movement with respect to the unaged binder in the plot, reducing their crossover frequencies but also decreasing the R-values. This may occur because the ageing of the blends is not only changing the shape of the master curves making them flatter, but also producing an upward displacement of the master curve of the complex modulus which may be changing the glassy modulus of these binders. In the case of RA + BP and RA + BB and recovered blends, this could also be due to a possible modification in the biobinders because of the solvent used in their recovery from asphalt mixtures. If this happens and the glassy modulus is not 1 GPa but higher, the calculation of the R-value should be different and the use of this plot is not directly applicable with the blends of RA and biobinders.

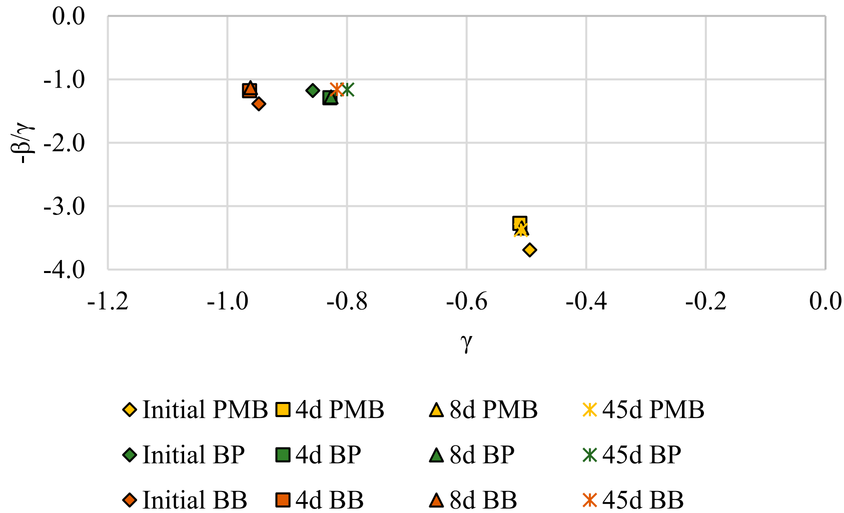

Figure 13. Ageing parameter of mixtures.

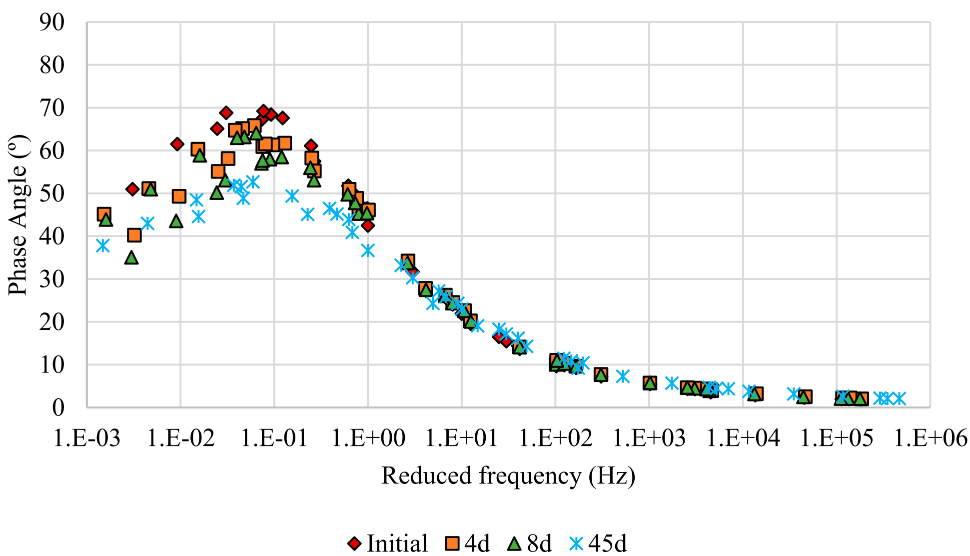

Figure 14. Master curve of the phase angle of aged 50% RA Mix BB at $T_{ref} = 15°C$.

Finally, the cracking potential of the materials was analysed using the G-R parameter to further understand the influence that ageing could have in their performance-related properties. G-R parameters comprise the complex modulus and phase angle at 0.005 rad/s and 15°C and are compared to the crack warning and limit values. In this regard, different researchers (Mensching et al., 2016; Rahbar-Rastegar et al., 2017) have shown that the ageing of binders should produce a movement of the initial point towards the cracking warning and limit boundary. In the same way, rejuvenation should produce the opposite effect. These movements are displayed with red and green arrows respectively in Figure 6. The RA binder is the only material in the Fail area and its blend with the other binders clearly move it to the Pass area improving therefore the expected cracking performance. The ageing of the materials, with the exception of those containing BP, produced their translation towards the cracking criteria but do not exceed them. In the case of RA + BP, the movement of the points is different

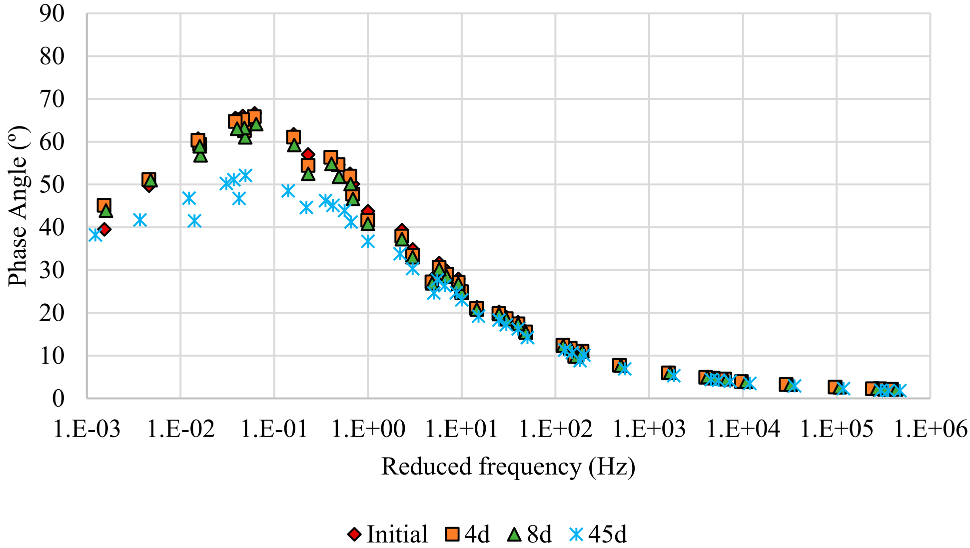

Figure 15. Master curve of the phase angle of aged 50% RA Mix BP at $T_{ref} = 15°C$.

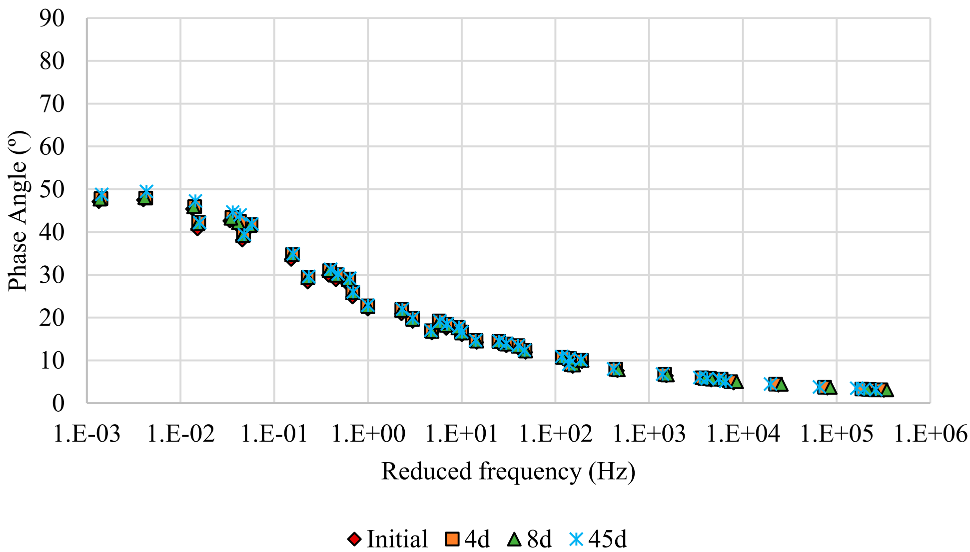

Figure 16. Master curve of the phase angle of aged 50% RA Mix PMB at $T_{ref} = 15°C$.

because of its different ageing behaviour. The frequency at which the G-R parameter is calculated (0.005 rad/s) is lower than 0.01 rad/s in Figure 2; therefore, the calculation of the parameter is done in the areas in which the ageing of this binder shows increased phase angle and decreased modulus, which is opposite to conventional ageing tendency. Consequently, the movement of the points in the graph must be different and is contrary to the rest.

4.2. Asphalt mixtures

Figures 7–9 show the evolution of the Black diagrams of the asphalt mixtures with 50% RA content and BB, BP and PMB respectively after different ageing and water conditioning times. Black diagrams

Table 2. Sigmoidal model fitting and ageing parameters.

	PMB				BP				BB			
	Initial	4d	8d	45d	Initial	4d	8d	45d	Initial	4d	8d	45d
β	−1.82	−1.67	−1.70	−1.72	−1.01	−1.07	−1.06	−0.93	−1.31	−1.14	−1.09	−0.95
Éč	−0.49	−0.51	−0.51	−0.51	−0.86	−0.83	−0.83	−0.80	−0.95	−0.96	−0.96	−0.82
Ageing parameter	−3.69	−3.27	−3.34	−3.38	−1.17	−1.29	−1.28	−1.16	−1.39	−1.18	−1.13	−1.16

are used to highlight differences between the LVE properties of bituminous materials at high temperatures (> 50°C) (Mangiafico, 2014). The first observation is that biobinders increase the viscous component of the rheological behaviour of the bio-recycled asphalt mixtures compared to that of the conventional, reaching phase angles up to 70°, which is a sign of the high rejuvenation effect of these materials.

In term of ageing, for the mixture with BB, every step of ageing produced changes in its rheology so the evolution of the Black diagram is progressive. On the other hand, for the mixture with BP, the Black diagram reveals that only after 45 days of ageing the mixture suffered a noticeable change in its LVE properties. In this regard, the two mixtures with biobinders decreased their phase angle with ageing. On the contrary, the mixture with PMB did not exhibit significant changes. In the three Black diagrams, the points measured at 40°C and 3 Hz have been highlighted in red to better appreciate their movement through the Black space.

Figures 10–12 display the master curves of the norm of the complex modulus of the 50% RA content asphalt mixtures with BB, BP and PMB respectively after the different ageing times. These curves did not show a significant change in the complex modulus of the asphalt mixtures after ageing (only a slight increase at low frequencies for the mixtures with biobinders). Table 2 shows the β, γ and the ageing parameter ($-\beta/\gamma$) of the asphalt mixtures after the sigmoidal function fitting of the master curves. Figure 13 displays the ($-\beta/\gamma$) versus γ plot. According to Mensching et al. (2017), a point in this plot should move to the right and down with ageing as the mixture becomes stiffer and lose relaxation capacity. However, this movement is not noticeable in Figure 13 with only in the case of the asphalt mixtures with biobinders moving to the right after 45 days of ageing. For the rest of the cases, the points remain so close to each other that the movement is not detectable. This fact could be expected since the sigmoidal function is fitted using the modulus master curves, and it was shown that the shape of the curves did not meaningfully change.

Nevertheless, the relative position between the points of the mixtures in the plot does reveal the different consistency of the binders used. In this sense, PMB was harder (lower penetration) than the biobinders and therefore the mixture is located at the right and lower part of the plot. This means that the mixture is stiffer and has less relaxation capacity.

The results in Figure 13 suggest that the change in the modulus of the mixtures is not representative of ageing for the materials studied. Nonetheless, in Figures 7–9, the rheology of the mixtures with biobinders was shown to have changed after the ageing conditioning and consequently this change must be due to changes in the phase angle. To observe this, Figures 14–16 show the master curves of the phase angle of the three asphalt mixtures at 15°C respectively. These master curves reveal the decrease in the phase angle of the mixtures with BB and BP due to the ageing process meaning that the mixtures with biobinders lose relaxation capacity faster than the conventional mixture, which may be a disadvantage for these types of asphalt mixtures.

5. Conclusions

The research presented in this paper shows the results of the ageing performance of two biobinders to be used as total replacement of the fresh binder used in bio-recycled asphalt mixtures with high RA content. After the rheological characterisation of binder blends and bio-recycled asphalt mixtures before and after ageing, the following conclusions can be drawn:

- The blend of polymer modified biobinder (BP) and RA binder ages in a similar way to the conventional PMB binder, having different behaviour which depending on the range of frequencies they becoming stiffer with greater elastic response or less stiff with increased elastic response. The comparison of the blend after its recovery from the asphalt mixture and after short-term ageing in the laboratory showed equivalent master curves meaning that RTFOT would effectively simulate the manufacturing of the asphalt mixture in the laboratory for this biobinder.
- The blend of biobinder BB and RA binder has the same ageing tendency as conventional non-modified binders becoming always stiffer and having increased elastic response but appears to be more susceptible to ageing, experiencing greater stiffening during the manufacturing of the asphalt mixtures. For this biobinder, the comparison of the recovered blend after the manufacturing of the asphalt mixture and the short-term laboratory aged blend showed that standard protocols were not able to simulate the ageing of this material. In addition, the solvent used during the recovery might be affecting the biomaterials. In this regard, new protocols should be developed to properly simulate the short-term ageing of this biobinder, which might be a concern for other biobinders.
- The rejuvenation effect of biobinders, displayed in the R-value versus crossover frequency plot, revealed their potential to be used with high RA contents in bio-recycled asphalt mixtures, being even more significant than the rejuvenation capacity of the PMB. This effect is also observed in the Black diagrams of the bio-recycled asphalt mixtures, showing the high viscous component of these materials.
- All the aged blends of RA binder and biobinders, even after long-term ageing, showed adequate properties to resist fatigue cracking according to the Glover-Rowe parameter and thresholds.
- The ageing and water conditioning of the bio-recycled asphalt mixture revealed that they experience a faster change of their properties than the conventional one, becoming slightly stiffer and increasing their elastic component after ageing. This is the main drawback found in the performance of the bio-asphalt mixtures.

The rejuvenation potential of biobinders allows producing bio-recycled asphalt mixtures with high RA content. Although the rheological properties of binders' blends seem adequate for their use, the faster ageing of the bio-recycled asphalt mixtures compared to the conventional one remains a concern for their application. It is important to highlight that due to the different blending scenarios that could take place between the RA binder and the biobinders, i.e. full blending or partial blending, the performance of the asphalt mixtures should always be studied. Future works should focus on the study of the ageing of biobinders in the laboratory to find adequate methods that simulate the ageing that occurs in the mixture, the study of the mechanical properties of these bio-recycled asphalt mixtures and the improvement of their ageing performance.

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