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Use of polymer modified binders as rejuvenators in recycled asphalt mixtures

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Abstract

Road paving recycling has been acquiring more relevance in society, especially within the paradigm of a circular economy. The addition of waste materials in asphalt mixtures is an excellent solution to face the gradual emergence of a great diversity of waste materials and reduce the production costs. This study aims to evaluate the addition of commercial and laboratory-produced polymer modified binders as rejuvenators in recycled asphalt mixtures with high contents of reclaimed asphalt pavement material (RAP). A commercial polymer modified binder (PMB) and a conventional bitumen modified with 5% of styrene-butadiene-styrene (SBS) or 4% of Regefalt were added to RAP aged bitumen and compared with a rejuvenated binder. Fatigue, permanent deformation and water sensitivity tests carried out on recycled mixtures produced with those binders showed that polymer modified binders could be used as rejuvenators to improve their performance significantly. The recycled asphalt mixture produced with the commercial PMB presented the best mechanical performance. The polymer-modified binders revealed an ageing resistance equivalent to that of the control rejuvenated binder, or slightly better in the case of the final binder with SBS polymer.

Keywords: Recycled mixtures; Reclaimed asphalt pavement; Aged bitumen; Rejuvenator; Modified binders; Rheology; Mechanical performance; Ageing resistance

1. Introduction

The recycling of road pavements is a structural rehabilitation technique for damaged pavements that emerged as an alternative solution to traditional paving methods. This technique enables reducing the use of raw materials, the construction costs and the environmental impacts [1,2]. However, the addition of reclaimed asphalt pavement (RAP) in the new asphalt mixtures production could induce some problems due to the bitumen characteristics. The bitumen present in RAP material has lost its fundamental characteristics as a consequence of the ageing process, which requires additional concern in the design and production of new asphalt mixtures [3,4].

According to DeDene et al. [4] and Chen et al. [5], regenerators or chemical additives could be used to minimize the ageing problems since the primary goal of these materials is restoring the original properties of bitumen. There are two types of chemical additives, namely rejuvenating agents and softening agents. The first ones restore the chemical properties of the aged bitumen, while the second ones reduce the viscosity of the aged bitumen.

At short-time, the rejuvenators should reduce the viscosity of the aged bitumen to obtain a workable mixture during the paving and compaction processes [6]. Besides that, the rejuvenators should restore the chemical and physical properties of the aged bitumen, changing its rheological parameters in order to decrease the fatigue cracking problems without compromising the permanent deformation resistance [7]. Thus, the addition of rejuvenators could be a promising solution to increase the content of RAP materials used in recycled asphalt mixtures up to 50% or higher values [1].

However, other materials can be used to improve aged bitumen characteristics, such as polymers, which are one of the best options to improve the performance of asphalt mixtures, according to Becker et al. [8]. A great example of that alternative is Fenixfalt technology that permits nearly 100% RAP material recycling, which is only possible through the elastic properties of the additives used, producing asphalt mixtures with high stiffness modulus, but at the same time with excellent fatigue cracking resistance [9]. The regeneration and modification of the aged bitumen are achieved by using styrene, isoprene and butadiene

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copolymers, known as Regefalt, and a conventional bitumen with high penetration. The copolymers reduce the aged bitumen oxidation and give additional elastic properties, while the high penetration bitumen reduces the aged bitumen viscosity.

By using this alternative solution, it is possible to take advantage of the polymer properties to improve the properties of aged bitumen in RAP and, consequently, the performance of the recycled asphalt mixtures. Based on this assumption, polymer-modified binders with elastomers could be used as rejuvenators, restoring the aged bitumen characteristics and improving the elasticity of the asphalt mixtures. According to Yildirim [10] and Becker et al. [8], styrene-butadiene-styrene (SBS) elastomer is the most suitable polymer for asphalt binder modification because it increases the permeant deformation resistance in high-temperature climates and the fatigue cracking resistance in low-temperature climates [11]. The incorporation of SBS decreases asphalt binder penetration values and increases the softening point temperatures, which justifies an increased stiffness and reduced thermal susceptibility, as explained in Anjan Kumar and Veeraragavan [12] and Dehouche et al. [13] studies. Moreover, the modification with SBS changes the viscoelastic behaviour of asphalt binders through the stiffness modulus increase and phase angle reduction, contributing to high resistance to deformation [14]. Due to that increase in stiffness, a high penetration bitumen should be used for modification, as described in Fenixfalt technology.

Therefore, the main aim of this work is to evaluate the use of polymer modified binders as rejuvenators in recycled asphalt mixtures with high contents of reclaimed asphalt pavements (50%), to evaluate their potential to optimize the properties of the asphalt binder and mixture. Three polymer-modified binders (PMB) were evaluated as rejuvenators, namely a commercial PMB, a conventional bitumen modified with 5% SBS and a conventional bitumen modified with 4% Regefalt. These polymer-modified binders were added to aged bitumen recovered from RAP material and characterized using basic and advanced tests to estimate their future behaviour when used in recycled asphalt mixtures.

Then, recycled asphalt mixtures were produced with the different polymer modified binders previously studied, and their mechanical performance was evaluated and compared to that of a recycled asphalt mixture produced with a commercial rejuvenator. Finally, the asphalt binders were recovered from all recycled mixtures and compared to those initially used in the mixture in order to analyze their ageing resistance.

2. Materials and methods

2.1. Materials used in this study

Different materials were used in this study, namely reclaimed asphalt pavement, natural aggregates, two conventional bitumens, a commercial polymer modified binder and two polymers. These materials are described in the next paragraphs, as well as their selection process.

The reclaimed asphalt pavement (RAP) was a waste material obtained from the milling process of a Portuguese highway surface course during maintenance operations. That material was divided into two main fractions (fine and coarse fraction) using the 10 mm sieve. The exposure of RAP material to environmental elements during the pavement service life caused an advanced ageing stage [3], and the rejuvenation of its aged bitumen is crucial.

After evaluating the availability of the natural aggregates in the region, three fractions of granite aggregates (0/4 mm, 4/10 mm and 8/14 mm) were used in this study to produce the recycled mixtures, together with the previously mentioned RAP material and a commercial filler of limestone origin.

Concerning the conventional bitumen and the commercial polymer-modified binder used in this study, their selection criteria were defined based on cost, availability in the Portuguese market, their expected properties and experience on their use in asphalt mixtures (including recycled ones) over the years. A very soft conventional B160/220 bitumen (with a penetration value of 145 dmm (× 0.1 mm) and a softening point temperature of 42ºC) was selected for the polymer modification process because the two polymers used in this work are predicted to increase the stiffness and ductility of the bitumen [8]. Simultaneously, the use of a soft bitumen reduces the viscosity of the modified binder, improving the workability of the mixture. The polymer-modified binders will act as rejuvenators to the aged bitumen of RAP material, and the use of a soft base bitumen can promote improved flexibility and restore the aged bitumen fundamental properties. Furthermore, another commercial polymer modified binder with a penetration value of 41 dmm, a softening point temperature of 63ºC and a resilience value of 21% was also used as a rejuvenator to be used in recycled mixtures, in order to compare its behaviour to that of the other two polymer modified binders produced in this study.

Finally, the polymers with the most significant potential for asphalt binder modification were selected in order to optimize their application in recycled mixtures. According to Becker et al. [8], the most suitable polymer used as bitumen modifier is the styrene-butadiene-styrene (SBS) elastomer. This polymer increases the permanent deformation resistance and decreases the thermal susceptibility of the modified binder. Meanwhile, another technology (called Fenixfalt) was also used in this work because it was developed to be applied explicitly in recycled asphalt mixtures. This technology uses a reactive copolymer of styrene, isoprene and butadiene (known as Regefalt) that rejuvenates the asphalt binder by triggering a chemical process in the aged bitumen [9].

2.2. Methods

2.2.1. Reclaimed asphalt pavement characterization

The reclaimed asphalt pavement characterization is necessary for a correct design of the recycled asphalt mixtures. This characterization process includes four main steps: i) reclaimed asphalt pavement separation; ii) binder content assessment (EN 12697-39) [15]; iii) aggregate gradation (EN 12697-2) [16]; and, iv) aged bitumen recovery (EN 12697-3) [17]. Part of this study follows a previous work of Palha et al. [18], using the same RAP material and production procedures. Therefore, two fractions of RAP material with dimension 0/6 mm (fine fraction) and 6/12 mm (coarse fraction) were used to produce the recycled asphalt mixtures and recover aged bitumen, in a proportion of 30% and 20%, respectively.

The aged bitumen recovered through the rotatory evaporator method presents a penetration value of 5 dmm and a softening point temperature of 75ºC, which is a very rigid binder. Its lack of flexibility could be pointed out as one of the biggest problems that aged bitumen presents. The addition of RAP material in the production of recycled asphalt mixtures makes it challenging to predict the long term performance of the asphalt mixtures. Consequently, it is crucial to analyze the properties of the binders obtained by blending the recovered aged bitumen with the polymer modified binders (used as rejuvenators), which should be comparable to those of a control bitumen (comprising a blend of aged bitumen, a neat bitumen and a commercial rejuvenator).

2.2.2. *Production of the modified bitumen and their blend with aged bitumen*

The bitumen modification process was carried out using two different production methods, namely the wet and dry process. These processes were used to evaluate their influence in the final characteristics of the blend aged bitumen and modified bitumens, namely in the ability to rejuvenate the aged bitumen.

In the wet process, a high shear mixer (Ultra Turrax T65 from IKA) was used to produce the modified bitumen with conventional bitumen B160/220 and 5% of SBS (the content of polymer most commonly used in bitumen modification). According to Costa et al. [19], this equipment produces a more homogenous blend, in a lower time frame, producing more stable binders even with larger polymer particles. The conventional bitumen B160/220 was heated at the temperature of 180ºC, then the polymer is added, and this blend is placed in the higher shear mixer during 20 min, at a speed of 7000 rpm.

In order to obtain the final binder blends, the commercial modified bitumen (A) or the SBS lab modified binder (B) was mixed with the aged bitumen, at 180ºC, for 5 min, in a low shear mixer (IKA RW20), at a speed of 250 rpm, in order to simulate the recycled asphalt mixture process (50% of modified bitumen and 50% of aged bitumen).

According to the product specifications, the Regefalt polymer should be added directly in the RAP material before the new high penetration bitumen is added. In order to simulate this dry process, the aged bitumen was heated at 180ºC, and 4% Regefalt was added and mixed during 2 min, in the low shear mixer. Then, the conventional bitumen B160/220, previously heated to 150ºC, was introduced in the previous blend and mixed for 5 min at a speed of 250 rpm.

In order to assess the rejuvenating capability of these solutions, all previously mentioned bitumen blends, produced with polymer modified binders, were compared with a rejuvenated bitumen commonly used in pavement recycling. Shen et al. [20] state that the use of rejuvenators is essential to obtain recycled mixtures with better performance. According to Palha et al. [18], the modification of a B70/100 conventional bitumen with 3% of a commercial rejuvenator is an adequate solution for producing recycled asphalt mixtures with 50% RAP material. Thus, this study used the same composition as a control binder. The final binder blends defined in this section were identified as follows:

1. BR (50% aged bitumen + 47% conventional 70/100 pen bitumen + 3% commercial rejuvenator);
2. MA (50% aged bitumen + 50% commercial modified bitumen);
3. MB (50% aged bitumen + 45% conventional 160/220 pen bitumen + 5% SBS); and,
4. MC (50% aged bitumen + 46% conventional 160/220 pen bitumen + 4% Regefalt).

2.2.3. *Characterization of polymer modified binders and final binder blends*

The several binders used in this study, which include the polymer modified binders and their final blend with the aged bitumen of RAP, were evaluated through a series of basic and rheological tests. The basic characterization of binders included: i) softening point test with the ring and ball method, according to EN 1427 standard [21], that measures the temperature at which the binder reaches a specific consistency and quickly deforms and the weight of a small steel sphere; ii) needle penetration test at 25ºC, according to EN 1426 [22], which indirectly measures the binder consistency at room temperature; and, iii) resilience test (EN 13880-3 standard) [23] for the determination of penetration and recovery of the binder.

The rheological characterization was carried out using a rotating spindle apparatus to measure the dynamic viscosity and a dynamic shear rheometer (DSR) to determine the complex shear modulus, phase angle and viscosity. The first test uses a Brookfield viscometer ("cup and bob" rheometer) to evaluate the viscosity in a range of temperatures between 100 and 180ºC (according to EN 13302 standard) [24]. Then, the DSR test applies a parallel plate configuration (diameter of 25 or 8 mm and a gap of 1 or 2 mm) to determine additional rheological parameters (complex modulus, phase angle and viscosity) in a different range of temperatures between 19 and 90ºC, based on the EN 14770 standard [25].

2.2.4. *Production and characterization of recycled asphalt mixtures*

The production of recycled asphalt mixtures with the polymer modified binders was based on a procedure previously presented by Palha et al. [26]. According to that work, the coarse fraction of RAP material (20% of the mix) is heated 30ºC above the mixing temperature defined for each final binder blend. Then it is mixed with the raw aggregates at the same temperature for one minute. The fine fraction of RAP material (30% of the mix) is introduced in the mixture at room temperature, being mixed for two minutes to homogenize the different materials. Finally, the modified binder (2.5% of the mix) is incorporated in the mixture and mixed for two additional minutes. The mixing temperature is obtained in the viscosity test results for each final binder blend. It should be noted that Regefalt polymer was developed to be used in a dry modification process. Thus, it is incorporated after the fine fraction RAP, and before adding the B160/220 conventional bitumen.

The recycled asphalt mixtures produced in this work are classified as AC 14 surf according to the Portuguese specifications, and they were produced with a total binder content of 5.1% (2.6% are obtained from RAP). The dense grading curve of AC 14 surf was obtained by using 50% RAP and the following raw materials: fraction 8/14 (38.80%), fraction 4/10 (5.50%), fraction 0/4 (4.75%) and filler (1.00%).

The mechanical performance of the different recycled asphalt mixtures produced in this work was evaluated using the following tests: i) water sensitivity (according to EN 12697-12); ii) permanent deformation resistance at 50ºC (according to EN 12697-22) [27]; iii) fatigue cracking resistance at 20ºC, using a four-point bending beam configuration (based on AASTHO TP 8-94) [28]. The results from these tests were compared to those of the recycled asphalt mixture presented by Palha et al. [18], which was produced with a B70/100 conventional bitumen and 3% of a commercial rejuvenator, as previously mentioned.

2.2.5. *Ageing resistance characterization of the final binders*

The process of bitumen ageing presents different phases, in which the production stage has an enormous influence. The production phase causes an intense and quick oxidation process of the bitumen, as a result of the high temperatures used and the presence of oxygen while the mixture is in a loose state [29].

Therefore, after production and characterization of the recycled asphalt mixtures, their final binders were recovered using the same process described in section 2.2.1. for recovery of aged bitumen from RAP material. Then, these recovered binders were evaluated through basic and rheological tests and the results were compared to those of the corresponding final binders before ageing (caused during the mixture production). The names of these recovered binders are similar to those of the related binders but preceded by R letter. The variation of binder properties between those two phases will be used to evaluate the ageing resistance, and the capacity of the modified bitumens to rejuvenate the aged bitumen in RAP.

3. Results and discussion

3.1. Modified bitumens characterization

Taking into account that this study aims to evaluate the use of modified bitumens as rejuvenators of asphalt mixtures with high contents of RAP material, the main properties of the modified binders produced in this study must be evaluated. Thus, Fig. 1 shows the basic characteristics of the commercial polymer modified binder (A) and the modified binder produced with conventional B160/220 bitumen and 5% SBS (B). The addition of 5% SBS into the B160/220 bitumen decreased its penetration value from 145 dmm to 67 dmm, while its softening point temperature increased from 42ºC to 89ºC. Furthermore, this modification with 5% of SBS allows the B160/220 bitumen to acquire a new relevant characteristic (resilience). The commercial PMB (A) presents lower values of penetration, softening point temperature, and resilience when compared with the modified binder produced in this study.

As mentioned above, polymers can also be added during the recycled asphalt mixture production together with the RAP material (dry method). Consequently, the effect of the polymer in this process can only be observed in the final recycled mixture, similarly to when producing mixtures with rejuvenators. Thus, the impact of Regefalt on the binder properties was only assessed when the modified binders were added to the aged bitumen.

The rheological analysis of a binder evaluates its complex modulus, phase angle and viscosity for a range of temperatures between 19ºC and 180ºC. Since bitumen is the most influent material on the performance of an asphalt mixture [30], it is crucial to evaluate its advanced characteristics to estimate the behaviour the asphalt mixture, e.g., in terms of fatigue or permanent deformation resistance. Additionally, dynamic viscosity using the Brookfield viscometer may be used to define the mixing and compaction temperatures, according to the ideal viscosities of the 3 Poise and 20 Poise, respectively.

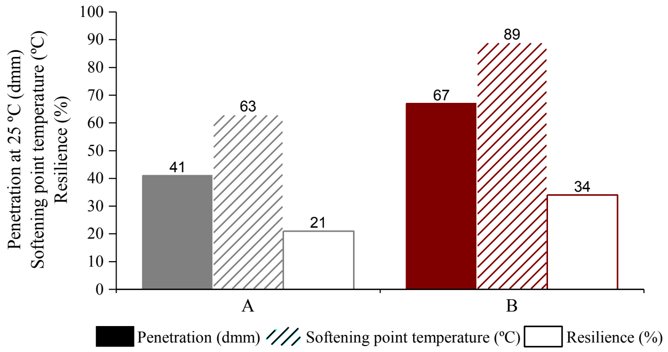

Fig. 1. Basic characterization of the modified binders produced using the wet process.

Therefore, as shown in Fig. 2, in comparison to the bitumen modified with SBS, the commercial PMB (A) presents a lower complex modulus and phase angle, at 20ºC, which could indicate improved fatigue cracking performance. At high temperatures (above 50ºC), the bitumen modified with 5% SBS (B) may exhibit the best permanent deformation resistance since it shows a higher complex modulus and a lower phase angle when compared to the commercial PMB.

Concerning viscosity (Fig. 3), both binders A and B show a similar viscosity up to 50ºC. Above that temperature, the commercial PMB (A) presents a higher viscosity, which shows that this bitumen is less susceptible to thermal variations. At temperatures above 100ºC (Fig. 3(b)), the bitumen modified with 5% SBS presents a similar viscosity to the commercial modified bitumen (A). Both modified binders exhibit a mixing temperature of 180ºC, indicating which temperature should be used when blending them with the aged bitumen to guarantee a homogeneous mixture.

In the next phase of this study, these modified binders were combined with the aged bitumen recovered from RAP material, and their blends were characterized. The modified binder produced using the dry process was also combined with the aged bitumen and compared to those resulting from the wet process and to the control bitumen.

3.2. Characterization of the blends of modified and aged bitumens

3.2.1. Basic characterization

Fig. 4 contains the basic characteristics of the bitumens resulting from the addition of the modified binders to the aged bitumen using the dry or wet process. It can be observed that all modified and aged bitumen blends (MA, MB and MC) present a higher

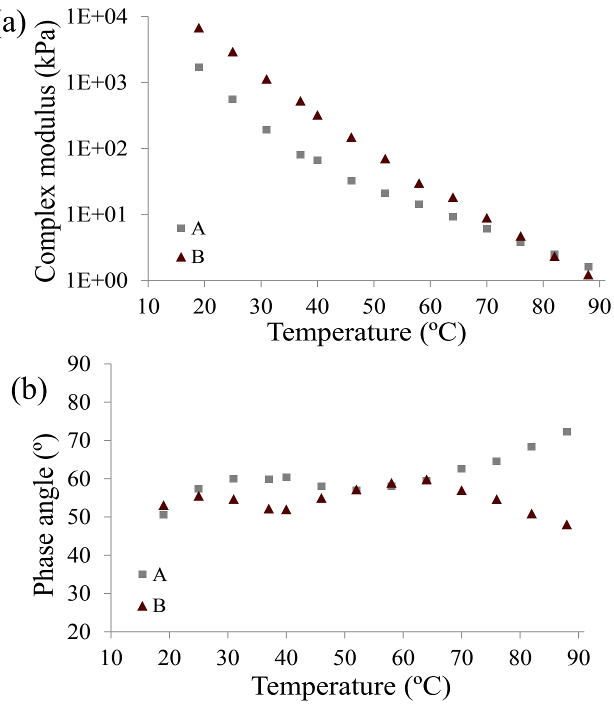

Fig. 2. Rheological results: (a) complex modulus and (b) phase angle of the modified binders produced using the wet process.

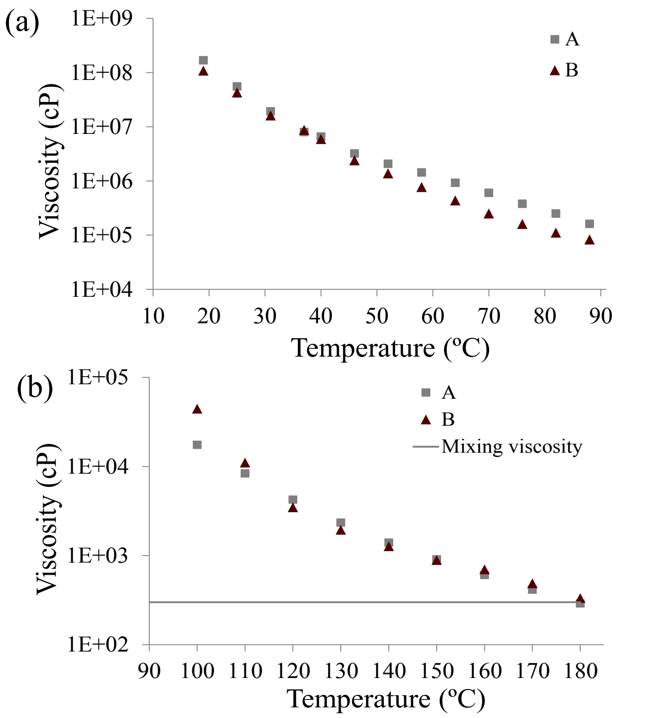

Fig. 3. Viscosity results by (a) DSR and (b) Brookfield viscometer of the modified binders produced using the wet process.

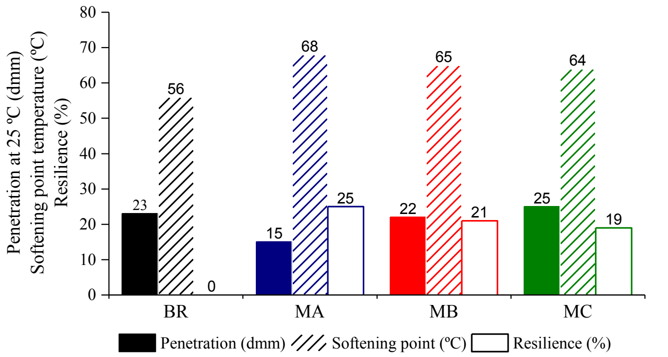

Fig. 4. Basic characteristics of the control bitumen and the modified and aged bitumen blends.

softening point temperature than the control bitumen (BR) and similar penetration values, except for the bitumen MA. The lower penetration value of the bitumen MA could be related to the lower penetration value of the modified bitumen (A) used as a rejuvenator. The addition of PMB to the aged bitumen provides it with a resilience capacity that the control bitumen (BR) does not present. The aged bitumen becomes more flexible in the presence of polymers with elastic capacity than with the addition of a rejuvenator.

According to the results obtained, the aged bitumen shows a low penetration (5 dmm) and a high softening point temperature (75ºC), which confirms its high stiffness and lack of flexibility due to the oxidation process that it was subjected during its service life. As expected, the aged bitumen does not show any resilience. When the commercial modified bitumen (A) is added to the aged bitumen, the softening point temperature presents an intermediate value between the softening point temperatures of the aged bitumen and modified bitumen A. Furthermore, the resilience of bitumen MA slightly increased compared to the modified bitumen used as a rejuvenator.

However, in the blend of aged bitumen and modified bitumen with SBS (MB), the softening point temperature is lower than that of its composing bitumens (aged bitumen and modified bitumen B). The resulting penetration value corresponds to an intermediate value between the penetration of the bitumens used in its production. Concerning the resilience, bitumen MB shows a reduction compared to the bitumen modified with SBS.

When Regefalt polymer is added (using the dry process), the corresponding bitumen (MC) presents basic characteristics similar to those of the blend of aged bitumen and conventional bitumen modified with 5% of SBS, even though a small amount of polymer was added (4%). Thus, penetration and resilience increased, while the softening point temperature of the aged bitumen decreased when 4% Regefalt and bitumen B160/220 were added through the dry process.

3.2.2. *Rheological characterization*

The rheological characteristics of the modified and aged bitumen blends can be observed in Fig. 5 and Fig. 6. At 20ºC, a temperature that may be associated to the fatigue cracking behaviour of asphalt mixtures, all binders MA (with commercial modified bitumen), MB (with 5% of SBS), MC (with 4% of Regefalt) and BR (control bitumen) present similar complex modulus. At that temperature, the phase angle of binder MA is the lowest, followed by that of binders MC, MB and control bitumen. Is should be pointed out that the control bitumen shows the lowest complex modulus and the highest phase angle for all the temperatures studied since it does not comprise polymers in its composition.

Performance of the blend of aged bitumen with commercial modified bitumen (MA) should be highlighted since, at high temperatures, it shows a considerable increase in complex

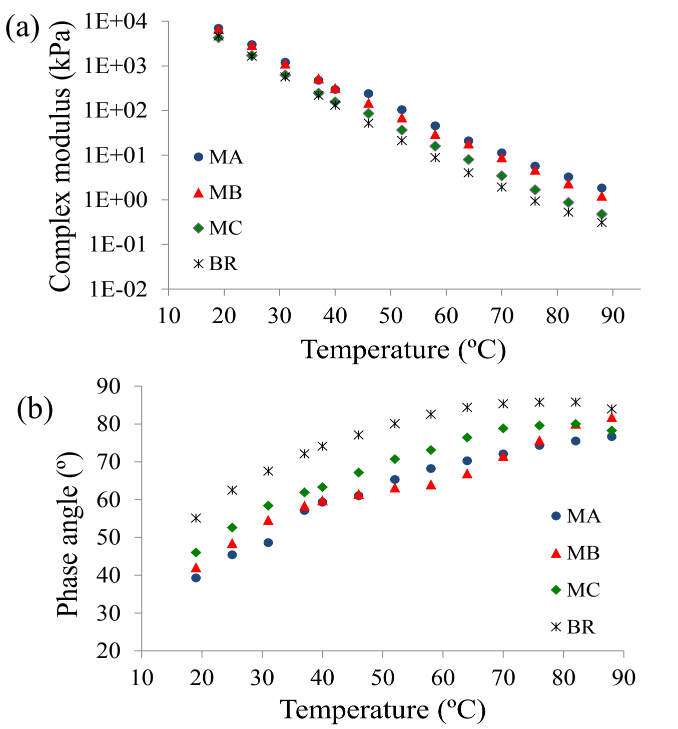

Fig. 5. Rheology test results: complex modulus (a) and phase angle (b) of the control bitumen and the modified and aged bitumen blends.

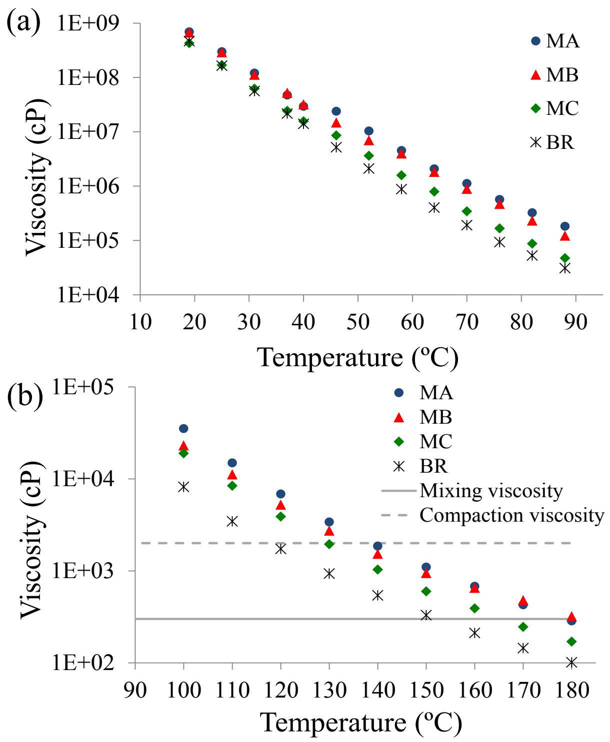

Fig. 6. Viscosity results by DSR (a) and Brookfield viscometer (b) of the control bitumen and the modified and aged bitumen blends.

modulus value while presenting the lowest phase angle. This behaviour at high temperatures could indicate an adequate permanent deformation resistance when used in asphalt mixtures. On the other hand, the control bitumen (BR) presents the lowest complex modulus and highest phase angle at high temperatures, which could affect the permanent deformation performance of the asphalt mixture.

From the analysis of Fig. 6, it is possible to see that the blends of aged and modified bitumens exhibit a higher viscosity than the control bitumen, which is more visible at temperatures above 100ºC (Fig. 6(b)). It should be highlighted that the blend of aged bitumen and commercial PMB (MA) is the bitumen with the highest viscosity, at almost all the temperatures studied, followed by the blend of aged bitumen and bitumen modified with 5% SBS (MB).

Mixing and compaction temperatures of the modified and aged bitumen blends MA and MB are approximately 180ºC and 135ºC, respectively. On the other hand, the modified and aged bitumen blend produced using the dry process (MC) shows a mixing temperature of 165ºC and a compaction temperature of 130ºC, while the control bitumen (BR) presents a mixing and compaction temperatures of approximately 150ºC and 120ºC, respectively.

3.3. *Mechanical characterization of recycled asphalt mixtures*

In order to confirm the results obtained in the study of the different bitumens, it is essential to evaluate their behaviour when incorporated in recycled asphalt mixtures. Therefore, three recycled asphalt mixtures were produced with modified bitumens A, B and C and compared with a control mixture produced with a commercial rejuvenator. The terminology used for the recycled asphalt mixtures produced with the corresponding modified binders are the following:

1. AC 14-BR (recycled asphalt mixture with control bitumen BR, from Palha et al. [18]);
2. AC14-MA (recycled asphalt mixture with modified binder A);
3. AC 14-MB (recycled asphalt mixture with modified binder B); and,
4. AC 14-MC (recycled asphalt mixture with modified binder C).

3.3.1. *Water sensitivity*

According to Table 1, all the recycled asphalt mixtures present high tensile strengths (TS) and low deformation, which could be related to the presence of RAP material (containing aged bitumen with low penetration). When the mixtures produced with modified bitumens are compared to the control mixture (AC 14-BR), it could be seen that the mixtures AC 14-MA, AC 14-MB and AC 14-MC present similar deformations values, which vary between 2.1 and 2.3 mm. On the other hand, the recycled asphalt mixture with commercial modified bitumen (AC 14-MA) shows the higher tensile strength (TS) value (2804 kPa) that could be related with the lowest penetration value of its bitumen (MA) when compared to the other bitumens used to produce the other recycled mixtures, including the control mixture. Furthermore, the recycled mixture produced using the dry process (AC 14-MC) presents a tensile strength similar to that of the control mixture (2401 kPa), while the recycled mixture with 5% of SBS (AC 14-MB) shows the lowest tensile strength value (2203 kPa). This behaviour confirms the tendency observed for the complex modulus results, where bitumen MA shows the highest complex modulus at the test temperature, contributing to the high stiffness and tensile strength of the recycled mixture produced with this modified bitumen.

All studied mixtures exhibit a low sensitivity to water since they present tensile strength ratio (TSR) values above 80% (minimum value required in Portuguese standards). However, the recycled mixture AC 14-MC (produced through the dry process) reveals a lower performance when compared to the control mixture, while the mixtures produced using the wet process (AC 14-MA and AC 14- MB) present slightly higher TSR values (91 and 93%, respectively). Thus, these results could indicate that the modification by the wet process is more efficient than the dry process in improving water sensitivity of the recycled mixtures.

3.3.2. *Permanent deformation resistance*

Resistance to permanent deformation is one of the tests that allow evaluating the performance of asphalt mixtures, being particularly relevant in countries with hot climate since high temperatures tend to reduce bitumens viscosity under traffic loads. Permanent deformation parameters, such as wheel tracking slope (WTS_{AIR}), proportional maximum rut depth (PRD_{AIR}) and maximum rut depth (RD_{AIR}) obtained in wheel tracking tests can be seen in Table 2.

The results show all the recycled mixtures developed in this study have a better permanent deformation performance than the control mixture AC 14-BR. Furthermore, mixture AC 14-MA

Table 1
Water sensitivity parameters of the studied mixtures.

Mixtures	Tensile strength (kPa)	Deformation at peak (mm)	Tensile strength ratio (%)
AC 14-BR	2401	2.1	90
AC 14-MA	2804	2.2	91
AC 14-MB	2203	2.3	93
AC 14-MC	2409	2.1	86

presents the lowest wheel tracking slope (0.05 mm/10^3 cycles), followed by mixtures AC 14-MB and AC 14-MC that present the same wheel tracking slope (0.09 mm/10^3 cycles). A similar behaviour could be seen in the other two parameters, confirming that mixture AC 14-MA presents the best permanent deformation resistance. However, the recycled mixture AC 14-MB (with 5% of SBS) is the mixture with the second-best permanent deformation behaviour, with RD_{AIR} and PRD_{AIR} values of 3.10 mm and 7.55%, respectively.

It should be highlighted that the recycled mixtures produced with modified bitumen by the wet process exhibit better performance than the recycled mixture produced with the dry process. Moreover, the addition of modified bitumens in the recycled asphalt mixtures, both by wet or dry process, improve the asphalt mixture resistance to permanent deformation when compared to the recycled mixture with commercial rejuvenator (control mixture).

3.3.3. *Fatigue cracking resistance*

Fatigue cracking resistance is a pavement design criterion since the fatigue cracking is one of the primary pavement distresses. The fatigue law developed by Monismith [31] is obtained in lab tests by determining the number of cycles (N) at which the mixture reaches failure, for a given tensile strain (ε). Fig. 7 shows the fatigue laws of the recycled asphalt mixtures with modified bitumens and the recycled asphalt mixture with commercial rejuvenator.

Based on the fatigue test results, the recycled mixtures with modified bitumens (AC 14-MA, AC 14-MB and AC 14-MC) presents a fatigue cracking resistance higher than that of the control mixture (AC 14-BR). The addition of elastomeric polymers could contribute to the higher flexibility of the mixture and, consequently, the excellent fatigue cracking performance.

The high stiffness of the RAP material (due to the ageing process) is mitigated by the modified binder properties, resulting in more flexible mixtures. Thus, their fatigue performance is better than that of the mixture obtained by the addition of a commercial rejuvenator and a high penetration bitumen to the aged bitumen present in RAP.

Table 2
Permanent deformation parameters of the studied mixtures.

Mixtures	WTS_{AIR} (mm/10^3 cycles)	PRD_{AIR} (%)	RD_{AIR} (mm)
AC 14-BR	0.15	9.34	3.82
AC 14-MA	0.05	4.89	2.05
AC 14-MB	0.09	7.55	3.10
AC 14-MC	0.09	7.90	3.30

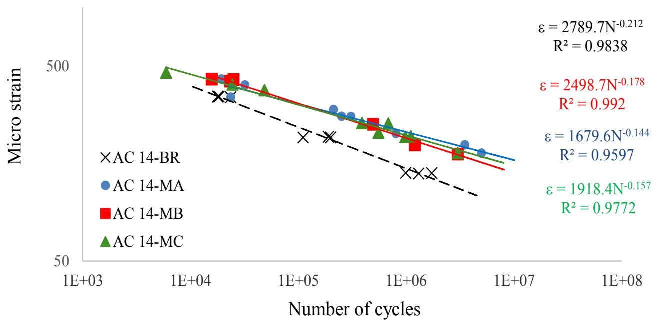

Fig. 7. Fatigue test results of the studied mixtures.

The recycled mixtures with modified binders exhibit similar fatigue cracking resistance performance. However, the addition of commercial modified bitumen in the recycled asphalt mixture (AC 14-MA) increased the fatigue cracking resistance at low strains, followed by the addition of Regefalt using the dry process (AC 14-MC). Thus, it can be concluded that the type of modification process does not influence fatigue cracking resistance since both processes resulted in recycled mixtures with similar performance.

3.4. *Ageing resistance characterization of the final binders*

3.4.1. *Basic characterization*

Table 3 shows, as expected, that after the production process, the bitumen penetration values decrease and the softening point temperatures increase, which confirms the binder ageing process caused by this phase. On the other hand, only the final bitumen with commercial PMB (RMA) presents an increase in the resilience value. The other final bitumens with modified binders (RMB and RMC) keep their values after the production process. The control bitumen does not present any resilience before and after the production process.

Regarding the penetration values, the final bitumen with commercial modified bitumen (MA) presents the lowest variation, which could be related to the polymeric matrix that is still present in the recovered binder. On the other hand, the final bitumen with Regefalt (MC) shows the highest variation, even higher than the control bitumen (BR), which could be due to the lower interaction between the polymer and the bitumen during the dry process. Concerning the softening point variation, bitumen MB presents the lowest value, while bitumen MC shows the highest variation. The presence of SBS in bitumen MB could contribute to the lower temperature susceptibility. Lastly, binders MB and MC do not present any variation in the resilience values, but bitumen MA (with commercial PMB) shows an increase in this property. Generally, the bitumen recovered from mixture AC 14-MB (with SBS) is less influenced by the ageing from the production process, while the bitumen with Regefalt from mixture AC 14-MC is the most affected. The dry process was not able to modify the bitumen as effectively as the wet process, not maximizing the polymer properties.

3.4.2. *Rheological characterization*

Fig. 8 shows that the production process leads to an increase in the complex modulus and a reduction in the phase angle of the final binder with commercial PMB. However, at the temperature of 20ºC (typically used in fatigue cracking resistance tests), the complex modulus and phase angle variation (before and after

Table 3
Variation of the basic characteristics before and after the production process.

Final bitumen	Penetration (dmm)	Δ (%)	Softening point (ºC)	Δ (%)	Resilience (%)	Δ (%)
BR	23	-22	56	11	0	0
RBR	18		62		0	
MA	15	-13	68	15	25	12
RMA	13		78		28	
MB	22	-18	65	8	21	0
RMB	18		70		21	
MC	25	-36	64	19	19	0
RMC	16		76		19	

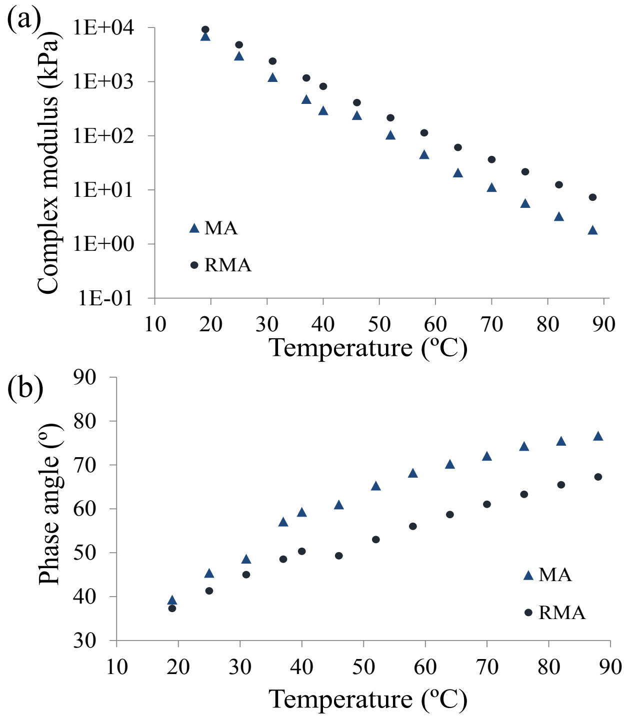

Fig. 8. Rheology test results: complex modulus (a) and phase angle (b) of final bitumen with PMB before (MA) and after (RMA) production process.

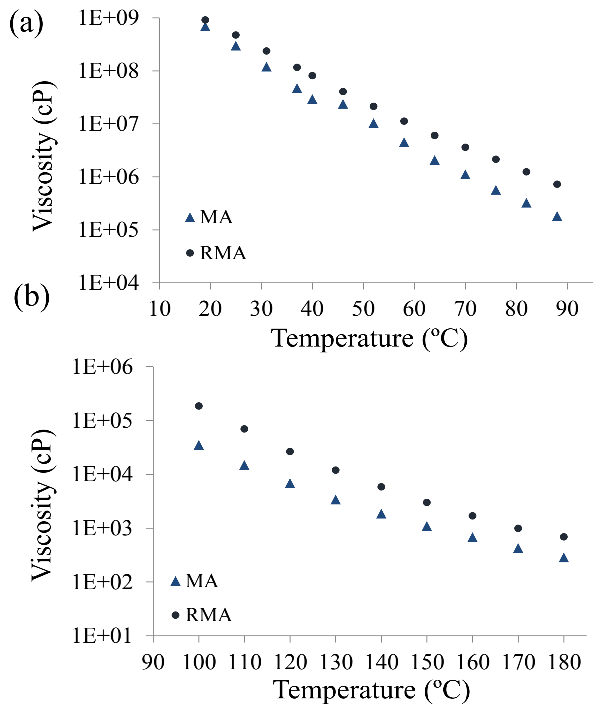

Fig. 9. Viscosity results by DSR (a) and Brookfield viscometer (b) of final bitumen with PMB before (MA) and after (RMA) production process.

production process) almost does not exist. This behaviour could indicate that after the production process, the final RMA binder maintains its fatigue cracking resistance characteristics. At high service temperatures (50ºC), an increase in the complex modulus and a decrease in phase angle could be observed, promoting the elastic behaviour of the asphalt mixture and increasing the permanent deformation resistance. As expected, the binder viscosity experiences a typical increase due to the production process, more visible at intermediate and high temperatures, as shown in Fig. 9.

With regards to the final binder with 5% SBS, the complex modulus and phase angle are almost the same after the production process both at low and high service temperatures, although at high temperatures there is a slight increase in the complex modulus (Fig. 10). Thus, this final bitumen with 5% SBS (RMB) is not significantly affected by the short-term ageing, confirming the previous results.

A similar behaviour could be seen in the dynamic viscosity results (Fig. 11), namely the fact that this binder maintains its properties after the production process. Thus, it can be mentioned that the production process did not significantly influence the performance of this bitumen.

After the production process, the final binder with Regefalt produced using the dry process (RMC) presents a similar complex modulus at low temperatures, while the phase angle suffers a reduction, which could result in a decrease in fatigue cracking resistance (Fig. 12). At high temperatures, the complex modulus shows an increase and the phase angle a more significant decrease, which could lead to an increment in the permanent deformation resistance.

It should be further noted that this final binder exhibits the most significant variation in the complex modulus and phase angle values. This fact could indicate that it is more affected by the production process ageing, possibly due to the process used in its

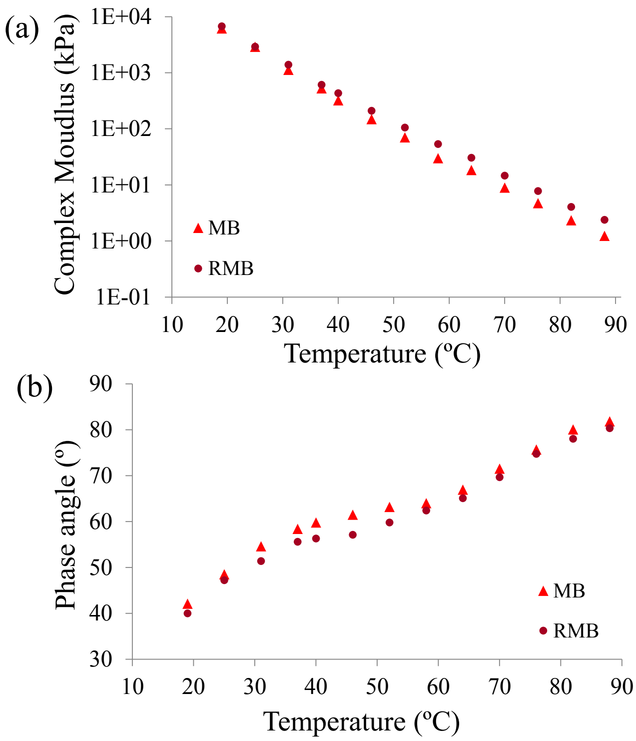

Fig. 10. Rheology test results: complex modulus (a) and phase angle (b) of final bitumen with 5% SBS before (MB) and after (RMB) production process.

modification (dry process). Concerning the dynamic viscosity, the recovered binder RMC presents the highest variation in viscosity when compared to the other final binders modified with polymers, as can be observed in Fig. 13.

With regards to the rheological parameters of the control bitumen (Fig. 14), the complex modulus does not present a significant variation, at low temperatures (20ºC). However, there is a reduction in the bitumen´s loss modulus (viscous component of the complex modulus) after the production process that reveals a lower fatigue cracking resistance. At high service temperatures (50ºC), the high complex modulus and the low phase angle values represent the elastic capacity of the binder, increasing the permanent deformation resistance. According to Fig. 15, there is a slight increase in the viscosity of the control bitumen after the production process (RBR) that is barely noted at low temperatures.

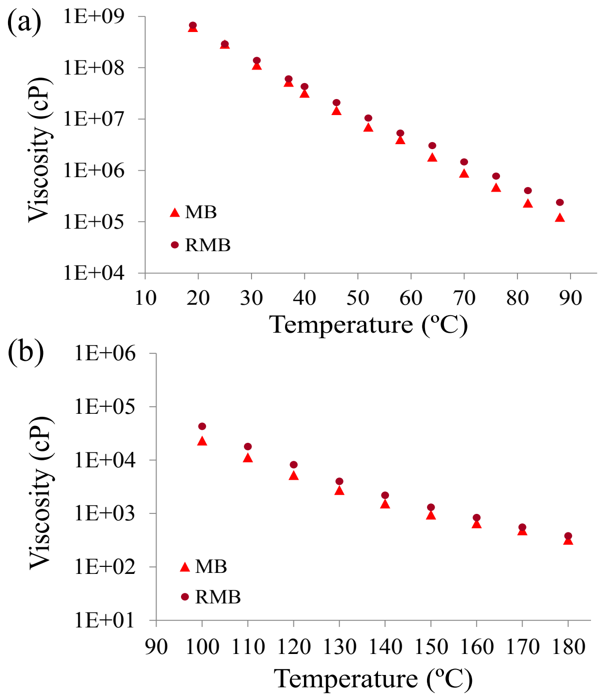

Fig. 11. Viscosity results by DSR (a) and Brookfield viscometer (b) of final bitumen with 5% of SBS before (MB) and after (RMB) production process

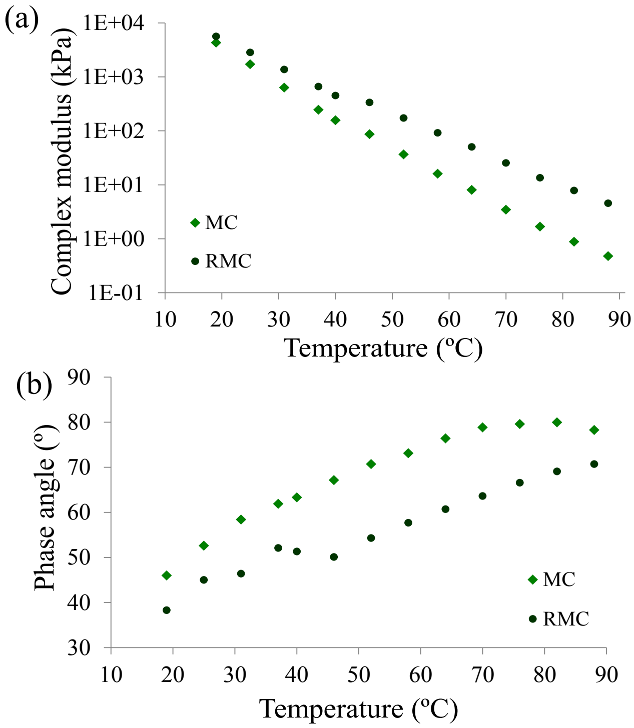

Fig. 12. Rheology test results: complex modulus (a) and phase angle (b) of final bitumen with 4% of Regefalt before (MC) and after (RMC) production process.

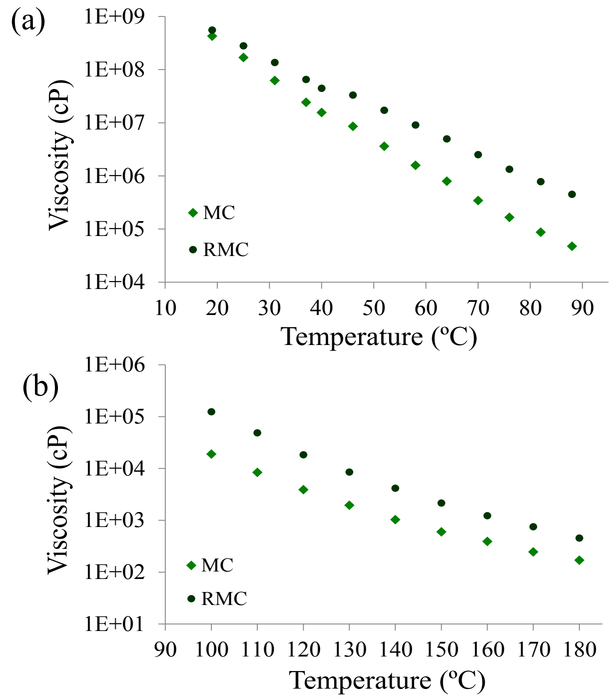

Fig. 13. Viscosity results by DSR (a) and Brookfield viscometer (b) of final bitumen with 4% of Regefalt before (MB) and after (RMB) production process.

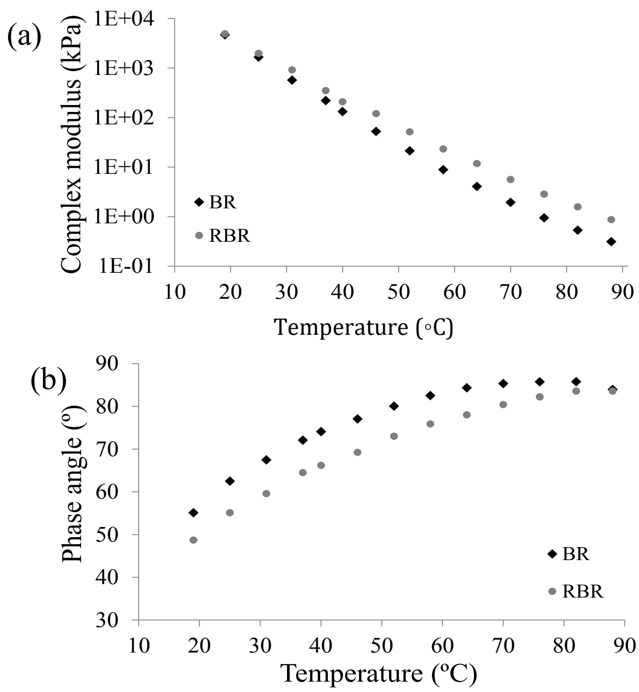

Fig. 14. Rheology test results: complex modulus (a) and phase angle (b) of control bitumen before (BR) and after (RBR) production process.

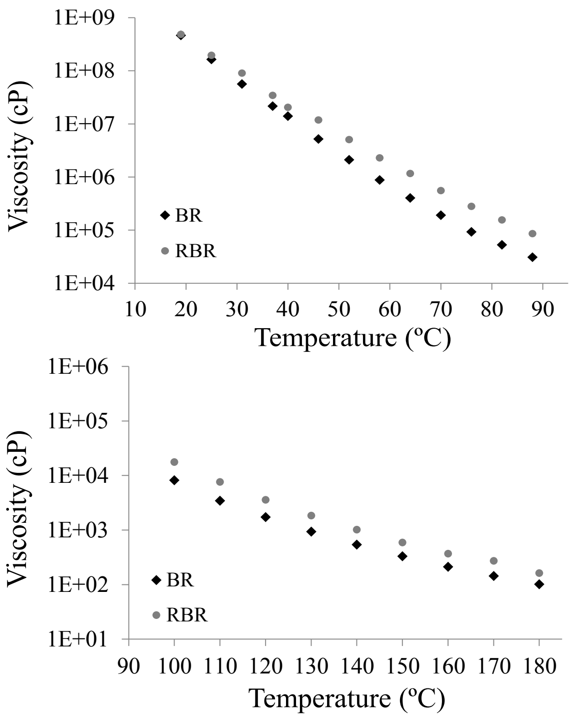

Fig. 15. Viscosity results by DSR (a) and Brookfield viscometer (b) of control bitumen before (BR) and after (RBR) production process.

Therefore, the final binder modified with 5% SBS (wet process), which presents the lowest variation in complex modulus and phase angle at the studied temperatures, proved to be the binder with the best resistance to ageing caused by the production process. On the other hand, the final bitumen modified with Regefalt (dry process) is the bitumen that shows the higher variation in the rheological parameters, being the bitumen with the lowest resistance to ageing. As previously mentioned, the dry process did not result in a significant interaction between the polymer, the high penetration bitumen and aged bitumen, contributing to lower resistance to ageing.

4. Conclusions

This work aims at adding modified binders as rejuvenators in a recycled asphalt mixture with a high content of RAP material (50%) to maximize its properties. Three modified binders were evaluated and compared to a commercial rejuvenator used in control recycled mixture. When added in recycled asphalt mixtures, the modified binders studied in this work improved the mechanical performance compared to the control recycled mixture. The main conclusions of this study are drawn as follows:

1. The addition of polymers could be seen as an alternative to commercial rejuvenators in recycled asphalt mixtures with high rates of RAP material. The high resilience of the modified binders improves the behaviour of the corresponding final blends with aged bitumen at service temperatures.
2. The study of the final blends of the modified binder with aged bitumen is a crucial tool to predict the expected behaviour of the recycled asphalt mixtures during production, compaction and in service.
3. The mechanical performance of the recycled mixtures with modified binders is globally better than that of the control recycled asphalt mixture with commercial rejuvenator.
4. The production of recycled mixtures using the dry process of modification with Regefalt presented the best water sensitivity performance. Meanwhile, the remaining characteristics (permanent deformation and fatigue cracking resistances) are similar using both modification methods, although the commercial modified bitumen have presented the most promising behaviour.
5. Concerning the ageing resistance, the recovered binder modified with SBS shows the lowest variation in the rheological properties after the production process, which demonstrates its high resistance to short-time ageing. In opposition, the recovered binder modified with Regefalt has the lowest short-time ageing resistance, since this bitumen presents a high variation in its rheological properties after the production process. The dry process of modification does not seem to be as efficient as the wet process to reduce the binder ageing in recycled mixtures.
6. Although the bitumen (with commercial rejuvenator) of the control mixture has an excellent ageing resistance, its low complex modulus (even after production process) justifies the insufficient permanent deformation resistance of that recycled asphalt mixture.
7. The results of this paper point out to a new perspective concerning bitumen's regeneration and production of recycled asphalt mixtures with high contents of RAP material, where polymer-modified binders can play a vital role to improve the performance of recycled asphalt mixtures as an alternative to commercial rejuvenators.

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Conflicts of interest

There is no conflicts of interest

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