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Evaluation of the Mechanical Performance of Warm Bio-Recycled Asphalt Mixtures

Daniah Alsarayreh and Ana Jiménez del Barco Carrión *

Laboratory of Construction Engineering (LabIC.UGR), Construction Engineering and Engineering Projects Department, University of Granada, 18071 Granada, Spain; daniah@correo.ugr.es
* Correspondence: ajbc@ugr.es

Abstract: Currently, approximately 90% of road pavement mixtures are derived from fossil fuels, a major source of the greenhouse gases contributing to global warming. This fact, together with the scarcity of raw materials in pavement engineering, has prompted recent investigations into sustainable alternatives. Biobinders, serving as substitutes or modifiers for petroleum-based asphalt binders, have gained attention, alongside the integration of recycled materials in recycled asphalt (RA). This study addresses these concerns by combining three techniques: (1) substituting a bitumen-based binder with a biobinder; (2) incorporating a high RA percentage (>30%); and (3) manufacturing the asphalt mixture at a reduced temperature (140 °C). These approaches result in the production and evaluation of warm bio-recycled asphalt mixtures. Materials were assessed at both the binder and mixture levels. The control binder, RA binder, and biobinder underwent conventional and rheological characterization. In terms of mixtures, warm bio-recycled asphalt mixtures employed a biobinder as the only virgin binder, with RA contents of 50% and 70%. Mechanical characterization focused on bearing capacity, cohesion, permanent deformations, and moisture damage. The warm bio-recycled asphalt mixtures exhibited adequate outcomes in bearing capacity through the stiffness modulus being 18,120 MPa and 15,683 MPa for bio-recycled asphalt with 50% RA and bio-recycled asphalt with 70% RA, respectively. Bio-recycled asphalt with 50% RA and bio-recycled asphalt with 70% RA showed low permanent deformation percentages, specifically 0.5% and 0.7%, respectively, in comparison to the reference recycled asphalt mixture with 1.5%, allaying concerns in practical applications due to the biobinder's soft consistency. The bio-recycled asphalt mixture with 70% RA displayed good mechanical performance regarding the studied mechanical characterization, especially exhibiting the least susceptibility to water-induced damage with 97% of the retained indirect tensile strength ratio, addressing concerns related to moisture damage in warm asphalt mixtures with high RA content and biobinders. These findings offer valuable insights into the adoption of more sustainable practices in the asphalt pavement industry, reducing the concerns associated with warm bio-recycled asphalt mixtures.

Keywords: biobinder; reclaimed asphalt; sustainability; warm mix asphalt

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1. Introduction

Roads are the most crucial infrastructure in every nation, and they must be constructed to provide an adequately strong and durable surface for the smooth movement of traffic during their design life to ensure the safety of their users. Regarding this, the asphalt mixtures used to build road pavements are designed to be able to endure climatic fluctuations and traffic loads. Aggregates and bitumen are the main components of an asphalt mixture. Bitumen is a viscoelastic component that provides tensile resistance and cohesion. Aggregates are mineral particles that provide the mixture with resistance to compression due to friction between them. Aggregates and binders need to work together to ensure the combination performs as intended.

Sustainability is currently a growing requirement and a fundamental objective included in international policies and strategies. Current concern about environmental issues has motivated the asphalt paving industry to look for more efficient utilization and management of energy and resources, which has led to the development of mixtures processed at lower temperatures and containing an increasing quantity of reusable aggregates, such as the use of reclaimed asphalt (RA) [1].

Reclaimed asphalt (RA) is produced by grinding or completely removing the original pavement when it has reached the end of its useful life. Since reusing RA lowers CO_2 emissions and does not deplete nonrenewable aggregate and asphalt binder supplies, it has positive environmental and energy-saving effects. The authors of [2] showed that utilizing 30% RA in hot-mix asphalt (HMA) reduces CO_2 emissions by 20% and energy requirements by 16%. Therefore, the higher the percentage of RA used in the mix is, the greater the environmental benefits that can be obtained are. Regarding mechanical performance, several works noticed that the inclusion of low percentages of RA (less than 15%) would not affect the behavior of new asphalt mixes [3,4]. Therefore, several European Union projects have mainly focused on using a high percentage of more than 50% RAP in the mix design [5]. On the other hand, it must be highlighted that there are some negative effects of using high percentages of RA and the aged binder that it contains. Oxidation occurring during the service life of pavement alters the binder chemical composition by decreasing the level of maltenes and increasing the asphaltenes-to-maltenes ratio, leading to a stiffening effect in the binder [6], which may adversely affect the mechanical performance of the asphalt mixture [7].

On the other hand, petroleum-based binders are the main binding materials used in the paving sector. As a result of high consumption worldwide, the scarcity of this raw material is an important concern in this industry nowadays. In addition, the heating of bitumen at high temperatures for HMA production results in high greenhouse gas emissions [8]. For these reasons, many researchers have focused their work on studying alternative sources and technologies for binders in asphalt mixtures, such as using biobinders and bio-oils derived from different biomass resources, such as cooking oil residues [9], soy oil [10], wood residues [11], or the usage of swine manure [12,13], for paving applications. Research has shown [14] that biobinders have great potential not only to reduce bitumen demand but also to exhibit acceptable behavior, with responses similar to that of petroleum-based asphalt binders; therefore, biobinders could be used as the binders in mixtures for the surface layers of road pavements if they have been previously characterized. Similarly, other researchers have found that the inclusion of the biomodifier improved the fatigue characteristic by decreasing the loss modulus of asphalt binder samples [15] and showed that that the addition of modified bamboo fiber as a biomodifier increased the stability and the tensile strength of the asphalt mixture [16]. Utilizing bio-asphalt serves to positively impact the environment by preventing air and water contamination by repurposing urban waste and animal refuse. Additionally, biomaterials can be used to decrease the viscosity of asphalt binders, subsequently resulting in reduced mixing temperatures, energy consumption, and greenhouse gas emissions [17]. When compared to petroleum asphalt, biobinders offer a more advantageous solution in terms of environmental benefits. However, the authors of [18,19] have indicated that despite the abundance of sources for obtaining bio-bitumen and its good environmental impact, there are still many restrictions that limit bio-bitumen's widespread use in the pavement industry for several reasons. Each biobinder shows different properties depending on its source and processing. This means that there is still a lack of comprehensive and sufficient standards for the use of biobinders in asphalt mixtures, and their long-term performance has not been adequately proven and reported yet. The current tendency for biobinders in the road industry is focusing on studying them as a partial replacement for bitumen.

The recent quest to create solutions to promote sustainability and minimize costs in asphalt paving has prompted researchers to investigate novel ways to use more recycled materials and biobinders in mixtures. While the RA contains an aged binder, the concern regarding increasing RA rates in new mixtures is that it leads to the production of stiff overlay asphalt mixtures. Biobinders can be used as soft binders in new asphalt mixtures with high RA rates to try to compensate such an issue. In fact, laboratory performance tests and full-scale experiments [20] on HMA containing 50% RA and biobinders (i.e., bio-recycled asphalt mixtures) have shown that the bio-recycled asphalt mixtures outperformed the traditional one. Similar results were obtained by other authors [21], who presented the full-scale RA validation of asphalt mixtures with the incorporation of biomaterials as a reclaiming agent. Consequently, in terms of durability and property evolution, the bio-asphalt mixtures outperformed the control mixture.

Within this framework, and to go a step further towards more sustainable asphalt mixtures, the main purpose of this investigation is to use biobinders as total bitumen replacement in new asphalt mixtures with high RA content manufactured at decreased temperatures. The combination of these three points leads to the production and evaluation of warm bio-recycled asphalt mixtures. The laboratory campaign was focused on characterizing both the binders and the warm bio-recycled asphalt mixtures. Bearing capacity, cohesion, resistance to moisture damage, and resistance to permanent deformations were studied as the main distresses affecting such asphalt mixtures.

2. Materials and Methodology

2.1. Materials

2.1.1. Binders

To achieve the purpose of this study, three different binders were studied: BT50/70, biobinder, and RA binder. BT 50/70 (BT) was selected as the control binder for the study. This binder is a 50/70 penetration-grade bitumen modified with waxes to achieve decreased manufacturing temperatures. It has a penetration between 50 and 70 dmm [22] and a softening point higher than 46 °C [23]. This binder is commonly used to manufacture warm asphalt mixtures. The biobinder is named Biophalt® (BP) and was provided by Eiffage (Corbas, France). This material is made of by-products of the paper industry and modified with SBS polymers. In order to extract the RA binder from the RA substance, a method involving the dissolution of bitumen in di-chloromethane has been employed. Once the RA substance has been separated from the bitumen solution, undissolved solids are eliminated, and the remaining solution is subjected to vacuum distillation using a rotary evaporator. This process results in the recovery of bitumen from the solution. By utilizing this technique, the RA binder can be effectively removed from the RA substance, allowing for further analysis of the substance [24]. The conventional properties of these three binders are shown in Table 1. It can be observed that the RA binder shows low penetration and a high softening point because it is extracted from a very aged aging source, while BP has a high penetration value while maintaining a high softening point. This is due to the SBS polymer, which enables a soft binder with a high softening point to exist.

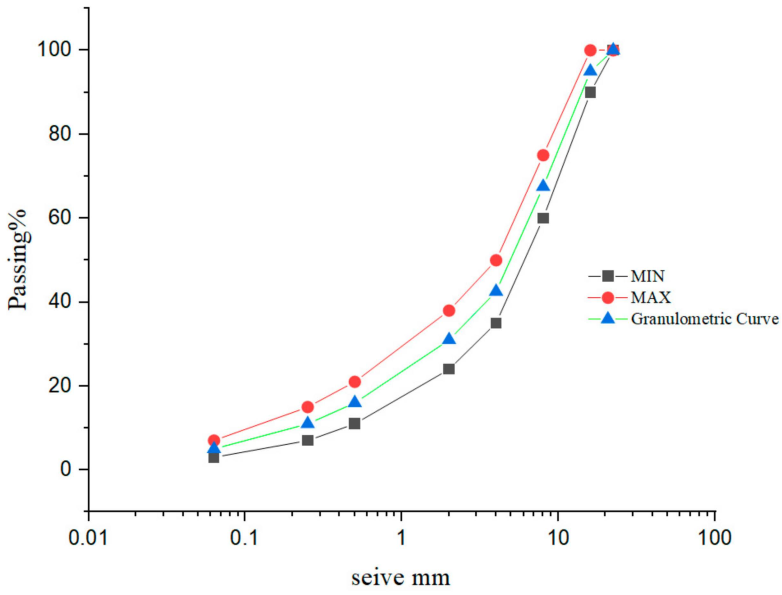
Table 1. Conventional properties of binders.

Binder	Penetration at 25 °C (×0.1 mm)	Softening Point (°C)
BT	50.3	46
BP	150.0	68
RA binder	8.8	125

2.1.2. Asphalt Mixtures

The asphalt mixture type selected for this study was an asphalt concrete (AC)16 [25], which is a semi-dense mixture with a maximum aggregate size of 16 mm. It is a mixture with a 0/16 continuous granulometry. This mixture design was selected due to its common application for the surface layer of new construction and the maintenance of road pavements for any type of traffic.

The control asphalt mixture was manufactured using BT as the virgin binder and 50% RA content (AC16BT). This RA percentage is already a high RA rate not commonly used, and therefore, the control mixture was manufactured using it, and not a higher RA percentage, to keep its purpose as control. Then, two asphalt mixtures using the BP as a virgin binder were manufactured using 50% and 70% RA contents, namely AC16BIO50 and AC16BIO70, respectively. As virgin aggregates, limestone aggregates were used for the fine fraction (0/6 mm), ophitic aggregates were used for the coarse fraction (12/18 mm), and cement was used as the filler. Mixture gradations fit within the limits of the AC16, as is shown in Figure 1. The optimum binder content was designed and varied with the design for each asphalt mixture to obtain 3% void content. The RA heating temperature was selected to ensure binder interaction, while aggregate and bitumen temperatures followed the recommendations of the binders' providers. In this regard, the binder type, RA content, and manufacturing temperature were the variables to study, as shown in Table 2.



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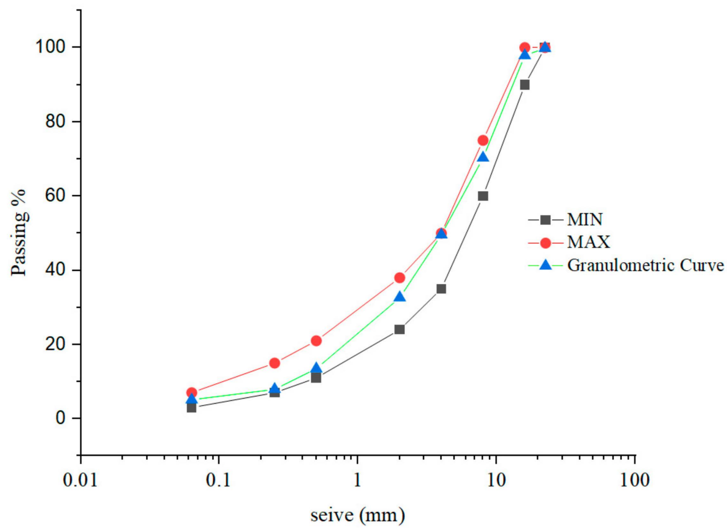

(**b**)

Figure 1. AC16 asphalt mixture gradation. (**a**) AC16BT, (**b**) AC16BIO50 and AC16BIO70.

Table 2. Manufacturing variables.

	AC16BT	AC16BIO50	AC16BIO70
Binder Type	BT	BP	BP
Optimum Binder Content (%)	2.5	2.0	2.4
RA Content (%)	50	50	70
Aggregate Temperature (°C)	140	160	160
RA Temperature (°C)	140	140	140
Binder Temperature (°C)	160	140	140
Manufacturing Temperature (°C)	140	140	140

2.2. Methods

In response to the main objectives of this paper, the laboratory testing plan was divided into two phases, (1) the rheological characterization of the binders and (2) the characterization of the asphalt mixtures. The purpose of the first phase is to understand the performance of the binders under the influence of various factors and analyze the effect of the binder properties on the asphalt mixtures' performance. The second phase is dedicated to the study of the influence of totally replacing the bitumen with the biobinder and the high RA content on the mechanical properties of the asphalt mixtures as there are concerns about the performance of biobinders with bearing capacity and permanent deformations due to their high penetration and with moisture damage due to the warm manufacturing temperatures. All the tests were performed according to European standards and thus tested as many specimens or samples as each specific standard requires.

2.2.1. Binder Rheological Characterization

The rheological testing procedure for testing the asphalt binders consisted of three tests, (1) frequency and temperature sweeps, (2) the multiple stress creep recovery test, and (3) the determination of rotational viscosity.

The purpose of the frequency sweeps is to comprehend the viscoelasticity and consistency of the binders [26]. The test was carried out with the following particular parameters: temperatures between 10 °C and 80 °C and frequencies between 0.1 Hz and 10 Hz. Multiple stress creep recovery (MSCR) tests are a widely used technique for analyzing the mechanical performance of asphalt binders at high temperatures between 40 °C and 80 °C. Most of the test's applications have been in analyzing binder resistance to permanent deformation (rutting), which typically results from slow and heavy traffic. Before performing MSCR tests, the binder samples were subjected to short-term aging with the rotating thin -film oven test (RTFOT) [27], and then 10 cycles consisting of a 1 s creep shear load were applied to the sample, and during the next 9 s, the sample was allowed to recover at 64 °C. The 3.2 kPa stress level was used to analyze the binder's mechanical performance in a non-linear range [28]. From this test, the results obtained are a measure of the resistance of the asphalt binder to permanent deformation under repeated loading conditions by measuring the non-recoverable creep compliance and the percent of strain recovery [29]. A Brookfield viscometer was utilized to measure the rotational viscosity of the materials across a temperature range of 60 to 200 °C. However, testing hard binders at lower temperatures was not feasible due to the excessive torque associated with the process. To ensure consistency, the torque was maintained at approximately 50% of the maximum torque in accordance with [30].

2.2.2. Asphalt Mixture Characterization

This phase deals with the study of the influence of the RA content and the type of binder on the different asphalt mixtures. For this purpose, the manufactured and compacted asphalt mixtures are analyzed and compared in terms of bearing capacity, moisture damage, and permanent deformation.

The bearing capacity was studied by determining the stiffness modulus of the asphalt mixture using the indirect tensile strength modulus (ITSM) test in accordance with Annex

C in [31]. The standard target parameters pertaining throughout the testing are shown in Table 3. Cylindrical specimens with a diameter of 101 mm and a thickness of 63 mm are used in this test. For each specimen, the stiffness modulus is the average of the measurement of the two perpendicular diameters. For the asphalt mixture, the stiffness modulus is the average of three specimens, which are stored in the conditioning cabinet at the test temperature of 20 °C for at least two hours prior to testing.

Table 3. ITSM standard parameters.

Parameters	Standard Value
Test temperature	20 °C
Rise time	124 ± 4 ms
Horizontal deformation	5 ± 2 µm (for diameter 100 mm)
	7 ± 2 µm (for diameter 150 mm)
Poisson's ratio for bituminous mixtures	0.35

The indirect tensile strength ratio (ITSR), which is the ratio between the indirect tensile strength of dry specimens (ITSd) and the indirect tensile strength of specimens after wet conditioning (ITSw), was used to calculate the water sensitivity of the asphalt mixtures. According to [32], six specimens for each type of asphalt mixture were used in the ITS, and they were split into two groups: three specimens were used for dry conditioning, and the remaining three specimens were used for wet conditioning. Before the test begins, the dry set is conditioned for four hours at 15 °C in the conditioning cabinet. Wet specimens are subjected to vacuum at 6.7 ± 0.3 kPa. The three wet specimens were then conditioned in a hot water bath at 40 °C for 72 ± 2 h, and after the time elapsed, the samples were placed in a cold-water bath at 15 °C for four hours before the test.

Finally, the resistance to permanent deformations of the asphalt mixtures was characterized using triaxial tests [33]. The permanent deformation and creep ratio are determined as the average of the results of three cylindrical specimens, where each specimen is subjected to an axial load (300 kPa) and confinement load (120 kPa) at a frequency of 3 Hz for 10,000 cycles at a test temperature of 60 °C.

3. Results and Discussion

3.1. Binder Rheological Characterization

3.1.1. Brookfield Viscometer Test

Figure 1 displays the results for the viscosity of the binders at different temperatures, and the BP shows high viscosity when compared to the BT. Such high viscosity is due to its SBS-polymer modification, which increases the viscosity of the binders. In terms of the Superpave specification (SHRP 1994) (3000 mPa.s at 135 °C) for the use of binders in the manufacturing of asphalt mixtures, it can be observed that all the binders meet the requirement having viscosity ≤3000 mPa.s at 135 °C.

3.1.2. Frequency and Temperature Sweep Test

The Black diagram for the binders, which resulted from the temperature and frequency sweep tests, is shown in Figure 2. For every tested temperature and frequency, the complex modulus of a material is shown against its phase angle in the black diagram. The ratio of the highest stress to the maximum strain is known as the complex shear modulus (G*). It provides the material's total resistance to deformation. The ratio of the elastic and viscous components determines the phase angle (δ), which is the time lag between the asphalt's stress and strain during the test condition [34]. Thus, the different viscoelastic behaviors of the materials can be deduced by this diagram since materials that exhibit very viscous behavior have an increase in phase angle and a decrease in complex modulus (located at the bottom right corner of the graph), while elastic materials have a decrease in phase angle and an increase in complex modulus (located at the upper left corner). The BT and RA binders exhibit thermorheologically simple behavior by having a smooth and unique curve over the entire range of temperatures and frequencies. The BP, however, shows a non-unique nor smooth curve, probably due to its high polymer content, which is also responsible for the increase in elastic response (decrease in phase angle) at high temperatures. The authors of [35] confirmed that in a Black diagram, a smooth curve serves as a helpful signal of time–temperature equivalency, while a disjointed curve indicates the presence of a high asphaltene structured bitumen, a high-polymer modified bitumen, or a high-wax-content bitumen, as in the case of the BP. Figure 3 shows that while the phase angle of the BP reaches its maximum at 30 °C, suggesting that the viscous component has reached its maximum, the phase angle of the RA binder and BT increases when tested at a higher temperature, which indicates that the viscous component increases gradually with the increase in temperature. Because of this binder's SBS modification, the elastic response rises (phase angle decreases) at high temperatures. However, as the temperature keeps increasing, polymers become softer and more viscous, which causes the phase angle to increase again. In comparison to the other binders, the RA binder had the smallest phase angle at 30 °C, as seen in Figure 4. This indicates that using the RA binder would increase the elastic response in the asphalt mixtures because of its high stiffness. The soft consistency of the BP raises the concern about its use as a full replacement for the bitumen but justifies the utilization of high RA rates. It is therefore necessary to study the bearing capacity of the bio-recycled asphalt mixtures of such combinations.

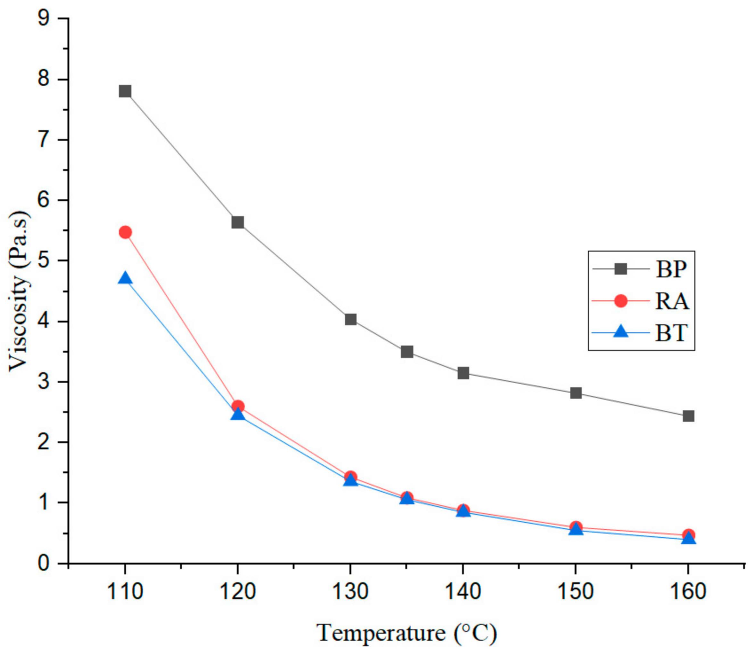

Figure 2. Binders' rotational viscosity.

This result can also be concluded from Figures 5 and 6, which show the relationship between the rutting (G*/sinδ) and fatigue (G*sinδ) parameters and the test temperatures. This parameter was used to evaluate the rutting and fatigue resistance of the binders. The RA binder has the maximum rutting factor and fatigue factor, and this indicates that the use of the RA binder increases the anti-rutting ability, but on the other hand, the high fatigue factor leads to the low fatigue resistance of the RA binder, which would be improved by using the biobinder. Regarding the BT and BP rutting resistance, the BT and BP exhibit a similar response, showing lower resistance to rutting than the RA binder, which could be expected due to their soft consistency. Comparing the BT and BP, given the high difference between their penetration values, the BP keeps a comparable resistance to rutting due to its polymer content, which would be beneficial for the asphalt mixture performance. The lower rutting resistance of the BP motivated the increase in the RA content up to 70%

and motivated the further study of the bio-recycled asphalt mixtures and the resistance to permanent deformation with the MSCR tests.

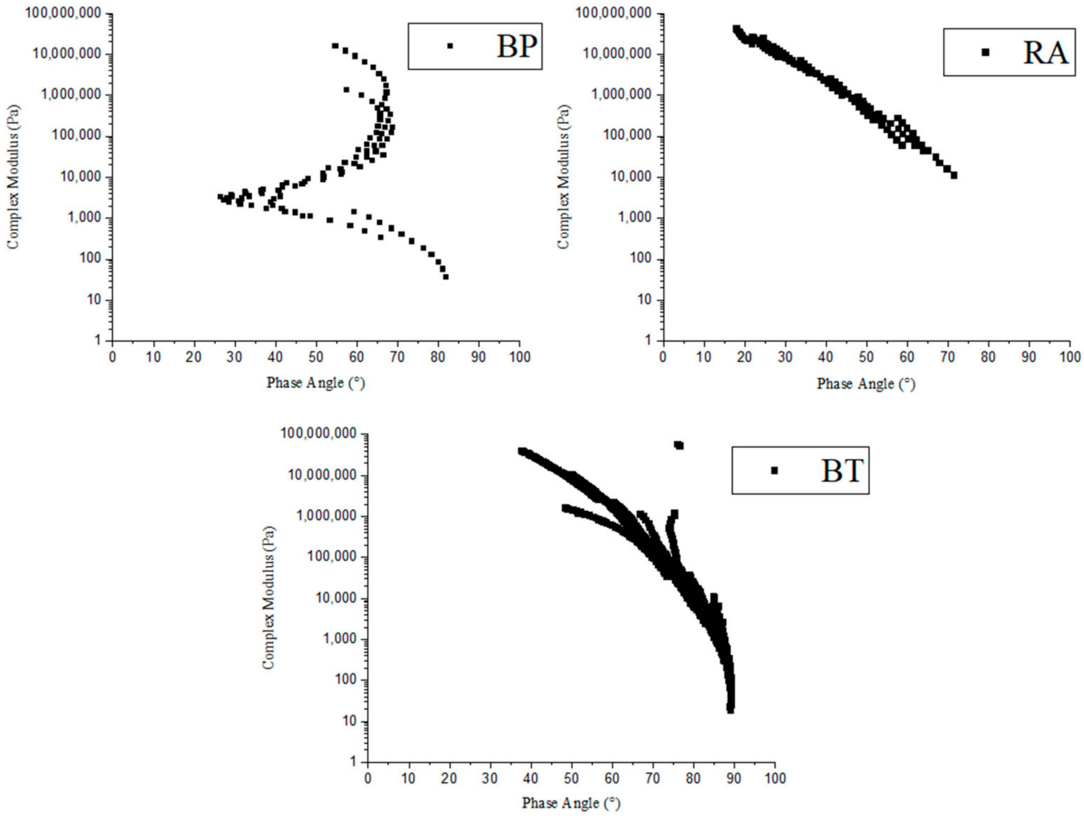

Figure 3. Binders' Black diagrams.

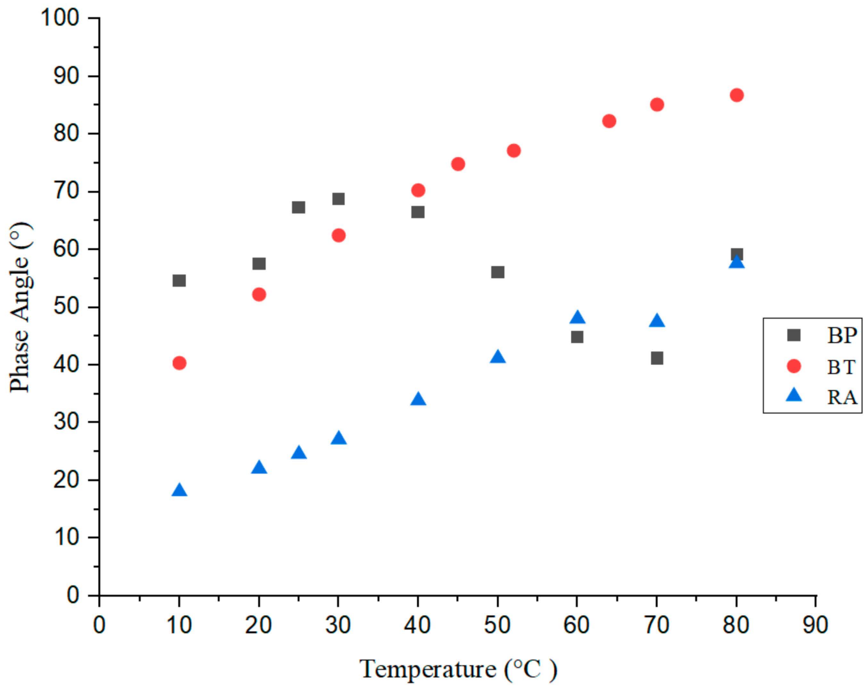

Figure 4. Phase angle of binders at testing frequency of 10 rad/s.

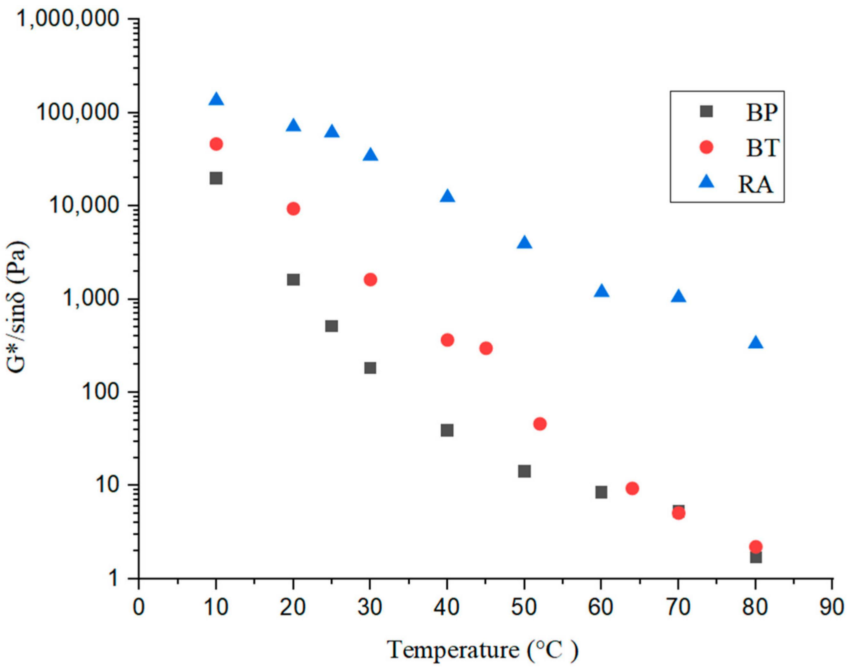

Figure 5. G*/sinδ of binders at a testing frequency of 10 rad/s.

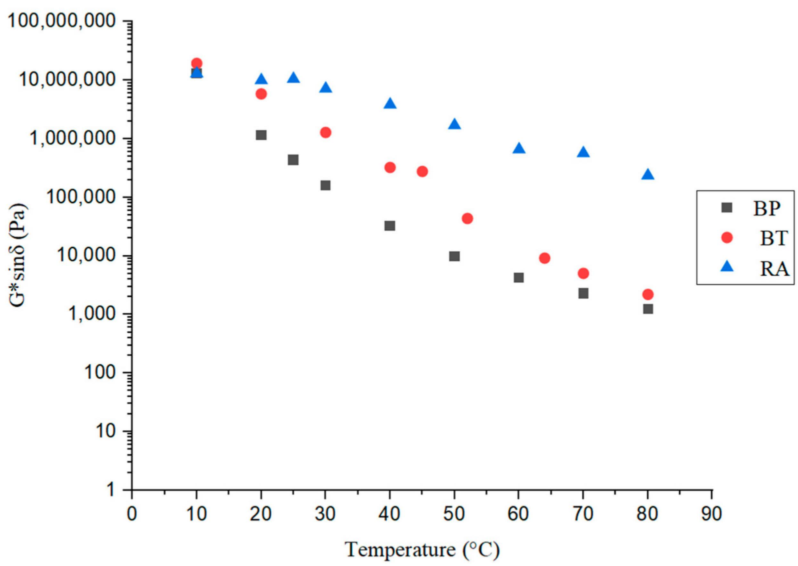

Figure 6. G*sinδ of binders at a testing frequency of 10 rad/s.

3.1.3. Multiple Stress Creep Recovery Test

Based on the results of the MSCR test, as shown in Figure 7, it can be observed that the type of bitumen plays a very important role in the resistance to plastic deformations of the asphalt mixture, where the degree of recovery for the RA and BP is high compared to the control binder BT. This result reflects that RA and BP exhibit more elastic behavior: the degree of recovery increases and the non-recoverable creep compliance decreases. This can be explained by the presence of SBS polymers for the BP, which increases the elasticity at high temperatures, as previously seen in Figures 3 and 4, which makes softer bitumen remain more resistant to plastic deformation, while in the case of the RA binder, it is due to its stiffness, which would not allow practically any deformation. However, the BP presents a high J_{nr} in comparison to both the RA binder and BT due to its soft consistency and ability to deform, which still could imply rutting resistance problems in the bio-recycled asphalt mixtures.

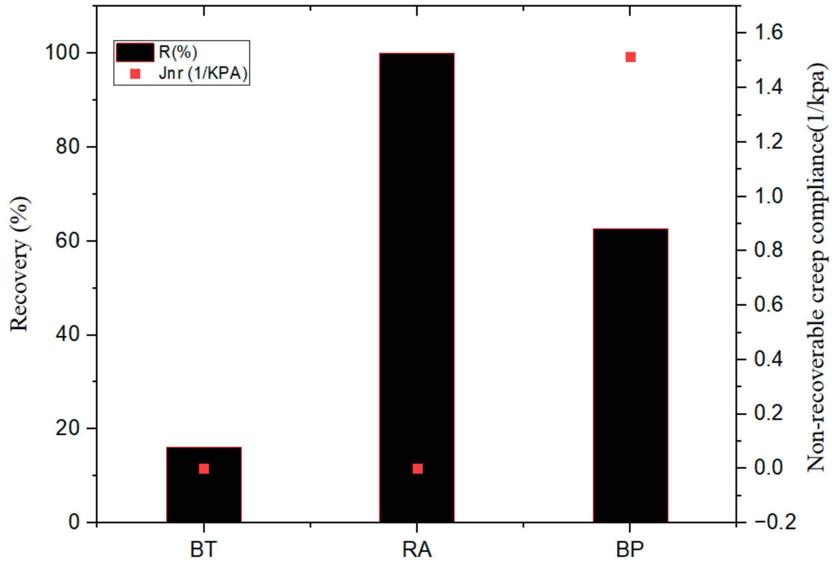

Figure 7. MSCRT parameters results.

3.2. *Asphalt Mixture Characterization*

3.2.1. Bearing Capacity

Figure 8 shows the results of the ITSM tests regarding the bearing capacity of the three asphalt mixtures. The three asphalt mixtures show very high stiffness in comparison to conventional AC16 asphalt mixtures and could be classified as high-modulus mixtures meeting the requirements of the Spanish specifications of a stiffness modulus higher than 15,000 MPa at 20 °C. This high stiffness was not expected for the bio-recycled asphalt mixtures, which contains the BP as the only virgin binder, with a very high penetration. Therefore, the high stiffness should be attributed to two reasons: (1) the high RA content containing a low penetration the RA binder and (2) the aging of the BP and the decrease in its penetration in the case of the bio-recycled asphalt mixtures.

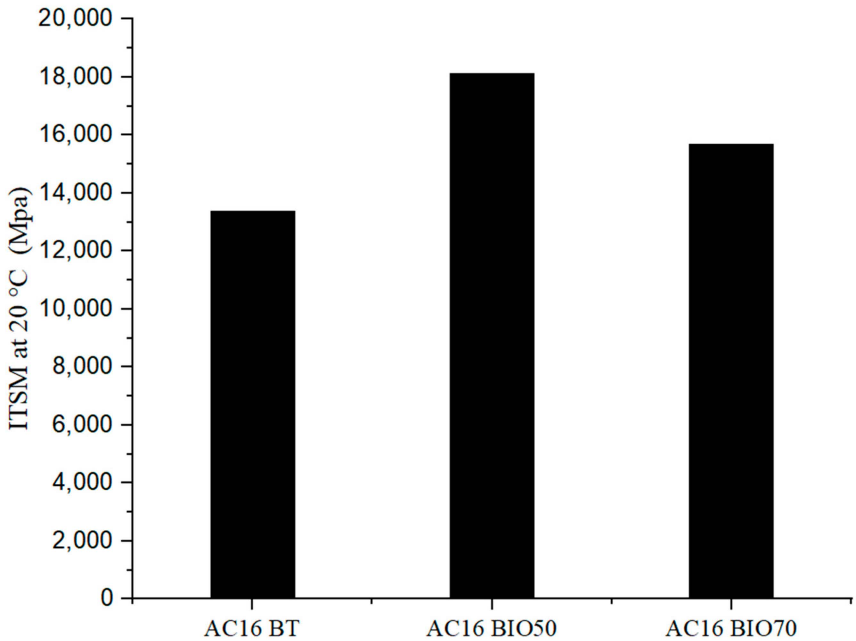

Figure 8. Stiffness modulus of asphalt mixtures.

On the other hand, the bio-recycled asphalt mixtures appear to have slightly higher stiffness than that of the reference mixture with the BT, being statistically meaningful only for the 50% RA content (AC16BIO50). Such an increase in stiffness would improve the bearing capacity of the pavement layer in which they would be installed.

3.2.2. Permanent Deformations

The results of the triaxial tests can be seen in Figure 9 in terms of the percentage of permanent deformation and creep ratio. The results are the average of two specimens, and the error bars represent the standard deviation. It can be observed that the bio-recycled asphalt mixtures show an improved resistance to permanent deformations in comparison to the recycled asphalt mixture containing the BT. The improvement in plastic deformation resistance can be related to the increase in the elastic response of the BP, as was observed in the rheology of the binders (Figure 2), which may reduce the permanent deformation that they suffer and is in accordance with that observed in the MSCR tests for the recovery values of the BP and BT, respectively (Figure 7). Furthermore, the highest-RA-content bio-recycled asphalt mixture exhibited the highest resistance to this distress.

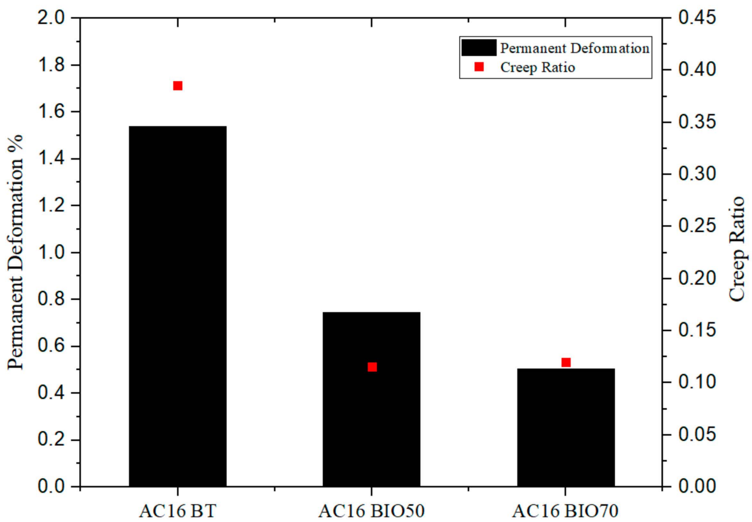

Figure 9. Creep ratio and permanent deformation of asphalt mixtures.

The favorable results regarding the bearing capacity and permanent deformation resistance of the warm bio-recycled asphalt mixtures reduce the concerns related to such issues in the field due to the soft consistency of the BP revealing that its combination with high RA rates and decreased manufacturing temperatures is a suitable option.

3.2.3. Water Sensitivity

The asphalt mixtures' resistance to moisture damage is shown in terms of ITSR in Figure 10. Regarding moisture damage, the authors of [36] concluded that asphalt mixtures containing high percentages of RA and RA aggregates and already coated with aged binder have decreased water sensitivity. Similar results were reached by the authors of [37]. However, the results in Figure 10 reveal that the three warm asphalt mixtures with high RA content have acceptable ITSRs for this type of asphalt mixture according to Spanish specification [38]. In addition, it is noteworthy that all asphalt mixture samples exhibited cohesive breakdown following wet conditioning, which is indicative of the persistence of the bond between the aggregates and the binder, and that the wet conditioning did not impair the integrity of the bond. Figure 10 also shows the higher ITS in both the wet and dry conditions of the bio-recycled asphalt mixtures, which reveals that the cohesion of the asphalt mixture was improved by the use of BB, which may compensate for the low inner cohesion of the RA due to its aging state [39].

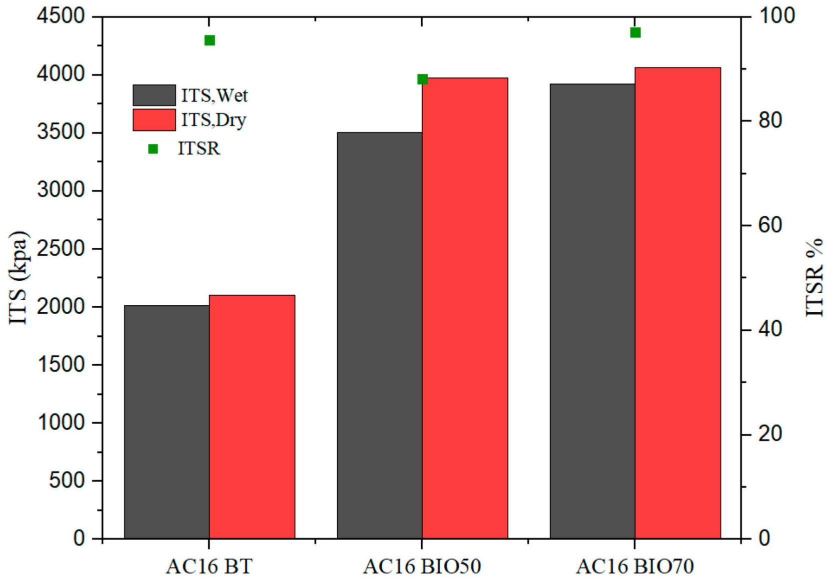

Figure 10. Moisture damage of asphalt mixtures.

In particular, the warm bio-recycled asphalt mixture with 70% RA exhibits the lowest water sensitivity. These results shed light on the concerns related to moisture damage for warm asphalt mixtures and high RA content with biobinders.

4. Conclusions

This study analyzed the performance of asphalt mixtures produced using biobinders as the only virgin binders, high reclaimed asphalt rates, and reduced manufacturing temperatures, i.e., warm bio-recycled asphalt mixtures. Based on the results, the following conclusions can be drawn:

- At the binder level, the rheological characterization of the binders showed that the combination of the stiff RA binder and the soft biobinder might be suitable to achieve a compromise for the rutting and fatigue resistance of the warm bio-recycled asphalt mixtures.
- At the mixture level, the warm bio-recycled asphalt mixtures exhibited adequate mechanical properties, including enhanced bearing capacity and resistance to permanent deformations, shedding light on the possible issues regarding these distresses and the use of soft biobinders. The improvement in cohesion and water sensitivity reduced the concern about moisture damage in these types of asphalt mixtures.
- The soft consistency of the biobinder combined with the high stiffness of the RA provided favorable results and allowed the positive reduction in manufacturing temperatures. This temperature reduction implies energy consumption savings and decreased greenhouse gas emissions, which must be specifically measured in future research.

These findings reveal that warm bio-recycled asphalt mixtures might be viable solutions for flexible road pavements. The innovative approach of manufacturing warm bio-recycled asphalt mixtures may represent a pivotal advancement in sustainable pavement engineering. The utilization of biobinders and the strategic integration of reused materials, coupled with reduced manufacturing temperatures, not only aligns with sustainable goals but also demonstrates promising performance characteristics. Future research will be focused on incorporating further low-temperature manufacturing technologies for bio-recycled asphalt mixtures, studying their aging and evaluating their reduced environmental impact.

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