

Article

Building Sustainable Pavements: Investigating the Effectiveness of Recycled Tire Rubber as a Modifier in Asphalt Mixtures

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Abstract: Building more sustainable pavements for the future requires knowledge of alternative and innovative materials for utilization in future road construction and maintenance activities. Being mindful of this need, the present study investigates a Reacted and Activated Rubber (RAR) compound modifier with the aim of defining an optimal RAR percentage in Asphalt Concrete (AC) mixes. It is acknowledged that when this type of modifier is incorporated within an AC mix as an alternative for the bituminous binder material, the associated economic, environmental and social benefits are significant. Simply put, the use of RAR modifiers provides the potential to utilize a waste product (rubber tires) as a more sustainable alternative to bitumen within AC mixtures. However, it seems that the information about the overall performance of AC mixes modified with RAR is currently limited. On these grounds, the present study focuses on the surface course layer and evaluates (a) achieved physical characteristics (compaction degree/voids), (b) mechanical characterization results (stiffness moduli) and (c) friction-based properties of tested mixtures incorporating varying RAR levels and different test temperatures. From the evaluation, it is concluded that for the case of the surface course mixture under investigation, the optimal percentage by weight of bitumen for inclusion of the RAR modifier is 10%.

Keywords: pavement; sustainability; modifier; surface course; rubber; RAR



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1. Introduction

Road pavements and roadway assets, in general, are a vital part of the overall transportation framework. During pavement design, construction and maintenance procedures involved in transportation infrastructure asset management, there are a lot of factors to take into consideration. One of these factors most recently brought into focus is the concept of sustainability and the utilization and valorization of innovative building materials that may have been, up until now, thought of as waste products, which would have most likely ended up disposed of in landfills.

In the framework of implementing increasingly environmentally friendly processes, and with the defining aim to improve levels of sustainability, pavement engineers within the construction sector have turned their focus towards the reincorporation of AC-based materials for pavements subjected to rehabilitation or reconstruction procedures [1]. Similarly, Abreu et al. [2] stated that the incorporation of sustainable methods for construction is progressively turning into a societal necessity. Georgiou and Loizos [3] stated that redefining the “end-of-life” approach with the approach of the reduction, reutilization and reprocessing of materials, in concurrence with the inclusion of waste by-products for industrial processes, must be systematically initiated with the goal of consolidating the circular economic approach amongst pavement stakeholders. In this manner, the recycling of waste by-products will grow with technology and be continuously improved through the investigation of modern solutions for waste valorization and the increase of waste by-product reuse.

Around the world, flexible pavements are the most favored pavement types, and a large volume of virgin materials (aggregates, bitumen, cement, lime and other additives) are exhausted with the construction, operation and maintenance of these pavement systems. The extraction, processing and production of these non-renewable materials are not sustainable [4]. For the future, more sustainable construction and maintenance techniques need to be adopted. In order for this to happen, sufficient research needs to be undertaken to define the choice of the most suitable techniques and materials.

One way to assess this is through a life-cycle sustainability assessment. Zheng et al. [5] recently investigated a sustainability assessment comparing various techniques, including thin asphalt (TA), warm mix asphalt (WMA) and hot mix asphalt (HMA) with RAP (reclaimed asphalt pavement), concluding that HMA including RAP was the most sustainable both from an economical and societal viewpoint. Oreto et al. [6] reached a similar conclusion in regards to the incorporation of RAP-based materials. For RAP-based materials, Antunes et al. [7] investigated the effect of RAP on bituminous mix characteristics concluding on the viability of multi-recycling towards a more sustainable pavement structure. Miro et al. [8] studied the usage of increased modulus mixture behavior with significant RAP level percentages for sustainable road construction.

Beyond this, many other materials have been investigated as a replacement for traditional virgin aggregates. Zhao et al. [9] concluded that the assessment from an environmental perspective for the alternative strategies indicated that increased percentages of recycled materials lead to increased reductions in greenhouse gas (GHG) emission output, energy usage and water consumption. Thus, the inclusion of recycled materials produces more sustainable construction. For a more in-depth review of these potential materials, Rahman et al. [10] provided a review of alternative materials that have the potential to be included in bound pavement structural layers. These materials included: plastic waste, quarry by-products, construction demolition waste, waste oil from cooking, fiber-based waste, glass, waste ceramic material and bricks, waste fly-ash and waste tire rubber. Similarly, Plati [11] provided a comprehensive review of pavement sustainable practices and materials that include RAP, recycled concrete aggregate, reclaimed asphalt-based shingles, steel furnace slag, foundry sand waste, waste glass, bricks and waste tire rubber.

Furthermore, Shu & Huang [12] stated that waste tires have direct health-based and environmental issues if left not recycled and/or discarded incorrectly. Similarly, Sienkiewicz et al. [13] stated that the inclusion of crumb rubber (CR) from waste vehicle tires into AC mixtures for paving purposes contributes to the disposal of significant volumes of end-of-life tires, which could potentially lead to environmental risks if not properly disposed of.

Recently, the recycling of end-of-life tires within civil engineering construction, specifically AC mixtures and Portland cement-based concrete (PCC), is increasingly gaining more interest. In addition, it was stated that a significant percentage of waste tires end up in the landfill. This offers the pavement engineering community an opportunity to turn these waste products into innovative and sustainable materials for pavement construction projects, provided that information is available regarding their influence on asphalt mixtures.

Recycled rubber from vehicles tires in the form of crumb rubber has a significant capability to be 100% reutilized. Lo Presti [14] provided an in-depth overview of recycled waste vehicle tires with their inclusion as a component of AC mixtures. In this research, the value of waste vehicle tires and their engineering characteristics are examined. Thus, several processes to convert waste vehicle tires into a material suitable for inclusion within AC pavement mixtures are presented. These processes include ambient grinding of the tires at normal temperatures, cryogenic tire grinding at increased temperatures and other less implemented procedures. Beyond describing the transformation processes for end-of-life tires, the research also describes procedures for the incorporation of rubber in AC mixes.

In addition to describing the overall processes, in-depth research has been carried over the years to define the mechanical characteristics of rubber-modified mixtures. Chaves et al. [15]

investigated, in the laboratory, the strength characteristics of materials through an evaluation of the mechanical characteristics of AC mixtures with rubber incorporated from dry, wet and semi-wet processes. The research concluded that the incorporation of CR has positioned itself as an alternative material to decrease the environmental impact of transport infrastructure assets and by the operation caused by periodical tire changes. Cong et al. [16] conducted an in-depth research study on a combination of bitumen types and percentages. From the results of laboratory-based research investigations, it may be concluded that the inclusion of CR leads to increases in the value of the softening point, elastic recovery, viscosity, complex modulus and rutting results and decreases penetration values and ductility. Kezhen et al. [17] also investigated the laboratory-based performance of AC mixes including waste tire rubber through testing, including Marshall stability, wheel tracking, Marshall immersion, freeze-thaw splitting, indirect tensile strength (ITS), indirect tensile fatigue (ITFT) and Marshall stability with long-term aging tests concluding the optimum mixture components. Fontes et al. [18] researched issues in regards to permanent deformation and concluded that AC rubber-based mixes improved their resistance to permanent deformation when compared to commonly utilized conventional AC mixes, regardless of the type of asphalt rubber or gradation adopted.

Arabani et al. [19] provided an overview of the issues concerning CR in dry material incorporation. With this process, the inclusion of CR creates issues concerning the bonding of the rubber and bituminous materials and the mixture homogeneity. The research incorporated a nano-material with the aim to improve in these areas. Zhaoxing and Shen [20] investigated the performance of porous European-mix (PEM) pavements with CR included in the dry process focusing on rutting. In addition, Świczko-Żurek et al. [21] provided an overview and state-of-the-art method for poroelastic pavement structures and issues that still remain. Venudharan et al. [22] provided an examination of recent AC mixture design practices and included a review of recent studies and a look into the outlook of waste rubber materials in gap-graded AC mixes. The paper concluded more research is required to better understand the effect of rubber materials on AC mixes. Other researchers have investigated the WMA and the inclusion of CR to lower energy consumption and pollution levels. Wang et al. [23] provided a review of warm-mix rubberized AC with a goal towards a sustainable pavement technique stating that the combination is an interesting and promising paving technique capable of reaching sustainability of pavements from principles to practices. Saberi et al. [24] investigated the utilization of CR and RAP within WMA with the aim to enhance the performance of AC pavements and reduce the environmental effects resulting from waste tires and aged asphalt pavements.

Several researchers have also investigated the rheological mix properties that incorporate CR. Rochlani et al. [25] investigated the effect of CR types on various rheological and mechanical characteristics of CR Bitumen (CRB) through Dynamic Shear Rheometer (DSR) tests. Zhang et al. [26] investigated the rheological properties of sulfur-extended asphalts with/without crumb rubber. Rodríguez-Alloza et al. [27] studied the effect of warm mix additive on crumb rubber modified bitumen with a goal to reduce emissions by lessening manufacturing and construction temperatures without compromising the mechanical characteristics of the bituminous mixes. Kebria et al. [28] included a laboratory-based study on the effect of CR on the characteristics and rheological behavior of the asphalt binder.

In addition to the available studies regarding the mechanical and rheological characteristics of CR modified mixes, more recent investigations have focused on energy consumption levels and environmental impacts of the applied techniques. Wang et al. [29] studied the energy consumption of mixtures and arrived at the conclusion that consumption is reduced when modified mixes are compared to conventional ones. They demonstrated that the associated technique is a green technology that reduces GHG emissions, lowers energy consumption, reduces the levels required for virgin materials and emphasized that the concept be applied to achieve environmental benefits. Thus, Bressi et al. [30] presented a comparative environmental impact analysis on AC mixes incorporating CR and RAP

through a life-cycle assessment to potentially reduce the usage of non-renewable resources in the future.

Furthermore, researchers have also investigated potential improvements to the traditional technique. Ma et al. [31], for example, investigated the combination of trans-polyoctenamer rubber (TOR), crumb rubber, and other additives to establish a new type of crumb rubber (CRT) to determine its effect on performance. Beyond this technique, and with the positive outcomes regarding potential advantages of rubber-based material inclusion within AC mixes, a newer technique has emerged that included the end-of-life rubber material within AC mixes. The technique involves a Reacted and Activated Rubber (RAR) compound. The material, which is relatively new, is an elastomeric asphalt extender that aims to overcome issues and more effectively and homogeneously incorporate these materials into AC mixes. To achieve this, the RAR-modified material is proposed to enhance the rubber and bitumen bond and ensure that it is achieved before mix processes are initiated. To achieve this, the RAR material is composed of CR, bitumen and filler in percentages of between 60–65%, 20–25% and 15–20%, respectively. The combination is designed to assist in the mitigation issues between bitumen and rubber bonding issues.

This type of RAR material is more recent and has been investigated less, and therefore, limited in-depth research is available. Sousa et al. [32] provided an overview of the RAR material and technique while providing an explanation of the potential benefits when compared to traditional CR materials considering compositions with varying RAR percentages. The research studied changes in viscosity and the effect on fatigue and permanent deformation of RAR-based mixes. Multiple other researchers have investigated the rheological properties of RAR-based AC mixes. Kedarisetty et al. [33,34], for example, studied the rheological characteristics of RAR-based AC mixtures. The more recent investigation [34] concluded that the mixture displayed notable improvements in mixture performance and recommended more aggregate mixture gradations and types be studied within the laboratory and in-situ. Saha et al. [35] evaluated and characterized the performance of RAR-modified dense-graded AC mixes to recommend a suitable modifier content to produce a mix that can provide improved pavement performance characteristics. Chen et al. [36] investigated the rheological characteristics and chemical characterization of RAR-modified asphalt binders.

Plati et al. [37] was one of the first research studies investigating the inclusion of RAR material into a surface course mixture to evaluate performance. Pomoni et al. [38] has also recently investigated course pavement surfaces, including RAR and RAP, with an emphasis on the frictional properties of the materials. Therefore, building upon previous research, the current investigation aims to provide more knowledge on the RAR technique. Specifically, the objective of the research is an investigation into achieved physical characteristics (compaction degree/voids) and mechanical characterization results (stiffness modulus) for various test temperatures with mixtures incorporating varying RAR levels for a course asphalt surface layer. In addition, friction-based properties will also be investigated. It is worthwhile mentioning that until now, limited research has been available concerning the viability of RAR within course surface layers, and the present research aims to provide more information on the subject.

2. Materials

2.1. Surface Course Mixture Design

For the investigation, an asphalt concrete course surface layer material was investigated. The design mixture had a 12.5 mm maximum aggregate size. Figure 1 is an overview of both the design limit specifications and the actual gradation of the material under investigation.

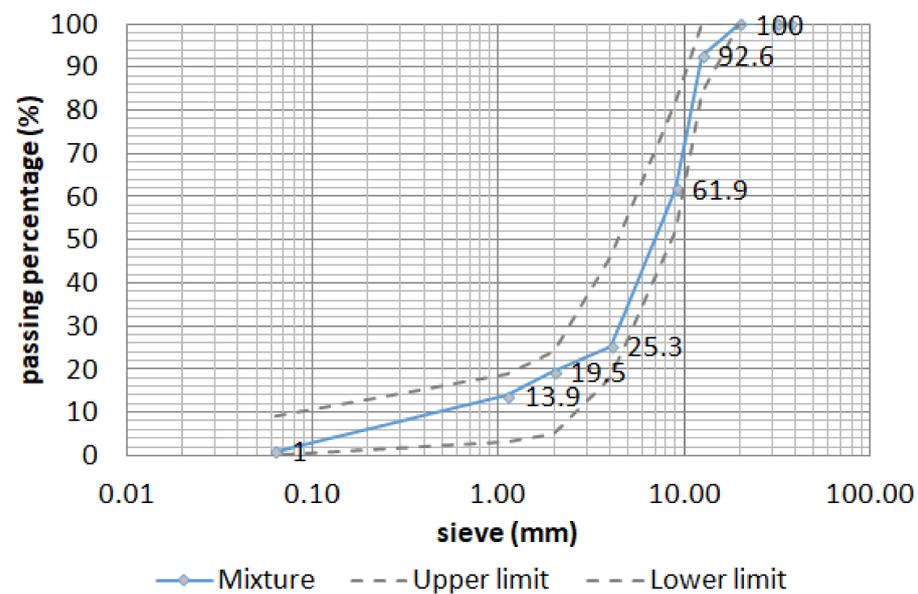


Figure 1. Mixture gradation.

Table 1 shows the results concerning both the properties of the bitumen and the properties of the design mixture without the RAR additives as described in [36]. The design mixture (reference mixture) has a maximum dry density (MDD) of 2520 kg/m³.

Table 1. Properties.

Bitumen Information			Mix Design (Reference Mixture)		
Type	[39]	25/55-70	Stability (KN)	[40]	11.3
Penetration (25 °C)	[41]	44	Flow (mm)	[40]	4.4
Softening point (°C)	[42]	75.8	Air voids (%)	[43]	10.9
Elastic recovery	[44]	94.8	Density (kg/m ³)	[45]	2245
Density	[46]	1.03	Water sensitivity	[47]	0.82

2.2. Reacted and Activated Rubber (RAR) Properties

The RAR utilized for the investigation is an elastomeric asphalt extender and is a combination of finely ground crumb rubber particles from processed scrap vehicle tires, an activated blend of mineral stabilizer and soft bitumen. Overall, the material in its physical state before inclusion into mixtures is a dry gray/black substance with a bulk density in the range of 0.6 gr/cm. The material on average consists of 62% fine rubber, 22% soft bitumen and 16% mineral stabilizer. The RAR material has individual particle sizes below 600 µm, with the majority concentrated in the 250–600 µm range. The RAR material to be incorporated into the design mixture is shown in Figure 2, while Figure 3 shows a close-up of individual RAR particles.

The inclusion of RAR materials aims to improve the overall AC mixture performance. The areas for improvement include increased resistance to fatigue, reduced susceptibility to permanent deformation and potential effects to the frictional properties of the produced AC materials.



Figure 2. RAR Mixture (4) components and mixing: RAR (1), aggregates (2) and bitumen (3).

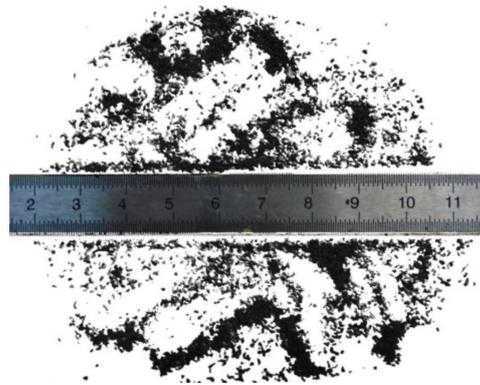


Figure 3. Reacted and activated rubber (RAR) particles.

3. Laboratory Investigation

The investigation commenced with the in-laboratory production of the specimens required for testing. Both the physical and mechanical characteristics, as well the frictional properties related to road safety, were tested.

The first stage of the investigation consisted of the production of the specimens to be evaluated. For the study, three levels of RAR additives by weight of bitumen (10, 20 and 40%) were tested in addition to the 0% reference design mixture containing 5.4% bitumen (by mass aggregate mass). The addition of RAR additives in contrast to other crumb rubber techniques was added in a dry process, which is more energy-efficient and more readily incorporated into existing mix design devices. For the dry process, the RAR additive was initially incorporated into the heated aggregates, with the additives being introduced at 25 °C. The mixture was then agitated for 20 s to achieve the distribution of the RAR additive and the heated aggregates. This was then immediately followed by the inclusion of the 25/55–70 penetration grade bitumen. The mixture was then re-agitated for 45 s to achieve complete and homogeneous coverage of the bitumen of the aggregates and RAR additive. Upon completion of this process, the produced mixture was then re-placed in an oven for an hour, with the mixture mechanically stirred multiple times to ensure a homogeneous distribution of the RAR additive within the investigated asphalt mixtures.

After completion of this process, the RAR-modified asphalt mixtures were then immediately compacted within a rolling compactor. The device is purpose-built and can compact the constructed asphalt slabs within a laboratory-based setting with conditions and results capable of simulating in-situ compaction. The device consists of a large curved steel roller that pivots, applying a force similar to field-based rolling machines. For the current investigation, a static compaction force was applied to the surface of the materials within a mold until pre-specified heights were achieved. For the compaction process, a

mold with dimensions of 305 mm × 305 mm and 50 mm in height was utilized. The material and mold were pre-heated to the desired temperature, and then the compaction of the materials was carried out. For the production of the slabs, batches of the AC mixes were taken out of the oven and placed in the steel molds required for compaction. The AC mix weight that was placed into the slab mold was determined based on the design asphalt mixture maximum density and the target voids. Compaction procedures were carried out according to EN 12,697 [48]. An overview of a rolling compactor procedure is outlined in Figure 4.



Figure 4. Rolling compactor procedure.

The produced asphalt slabs from the rolling compaction procedures were cooled sufficiently to room temperature (25 °C) and then extracted from the metallic mold. Depending on the test being carried out, the asphalt was ready for either testing or further procedure, where required. For testing the physical characteristics of the investigated materials, cores needed to be extracted. For this purpose, an extracted slab was secured and secured beneath a coring machine, where four 100 mm diameter cores from each slab were extracted. For accurate determination of investigated characteristics, the distance between the cores and the slab edges was maximized. A representation of this procedure is shown in Figure 5. The final core dimensions were between 39–42 mm (in height) with a 100 mm diameter.



Figure 5. Extracted slab, coring and extracted cores.

The initial stage of the investigation was to determine the physical mixture characteristics achieved for each of the investigated mixtures. Two of the most deterministic characteristics for the production of asphalt mixture are the achieved bulk densities and the corresponding percentage of air voids within the asphalt mixture. For the investigation, the goal was to initially define the effect of introducing various RAR percentages (10, 20 and 40% by weight of bitumen) in comparison to the reference mixture containing 0% RAR additives. These were carried out in accordance with the EN 12697-6 [45] and EN 12697-8, respectively [43].

The next stage of the investigation was to determine the strength-based (mechanical) characteristics of the RAR-based mixtures and to compare them to the reference mixture. The most often utilized method for determining these properties is through laboratory-based modulus testing of the asphalt cores. For the current investigation, these were achieved by determining the stiffness of the materials through indirect tensile stiffness modulus (ITSM) testing based on the EN 12697-26 [49] testing protocol for cylindrical specimens. All test specimens were investigated along two axes separated by 90°, with the average result considered as the modulus for each specimen. The test sets a target rise

time (124 ± 4 ms) as well as a target peak transient horizontal deformation (0.005%) for the investigation in the range of 4.8–5.2 μm . Tested specimens not meeting specifications were excluded from the analysis of the stiffness modulus.

All specimens were tested at four temperatures (15, 20, 25 and 30 °C), with specimens being acclimated in a climate chamber (4–6 h) to stabilize at the test temperatures. Tolerance for testing was equal to ± 0.5 °C. Test specimens once were stabilized at target temperature and then immediately tested. Figure 6 provides an overview of the testing machine and setup.

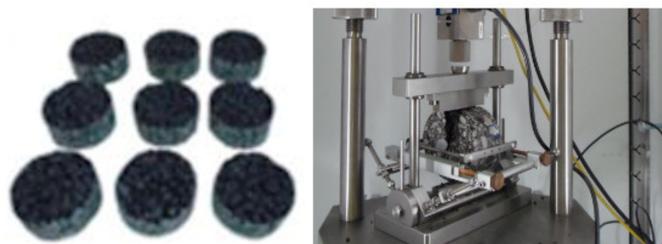


Figure 6. Overview of the ITSM testing machine and setup.

Beyond the testing of the physical and mechanical characteristics of the investigated mixtures, the next stage of the investigation was to evaluate the achieved friction-based properties of the RAR-based mixtures in comparison to the reference asphalt material. These frictional properties are important factors related to overall road safety. With increased frictional properties, the materials can assist better during vehicle braking. Both the micro-texture and macro-texture were evaluated, which in combination, can represent the friction properties of the materials.

In the current investigation, the British Pendulum Tester (BPT) was utilized to measure the micro-texture of the RAR asphalt surface course mixtures. The extracted slab was tested according to the ASTM E-303 [50] standard. The BPT system is a portable friction device with extensive usage over the years. For the device, a smooth rubber slider is mounted to the arm of the pendulum. The slider is released from the horizontal position, reaching speed through gravity and the rubber slider interacts with the asphalt surface over a defined distance. The slider is then allowed to continue, and the post-swing height is measured in terms of British Pendulum Number (BPN). The BPN values are unitless. A zero-value of BPN corresponds to a smooth, frictionless surface, while a value of 150 is the upper limit corresponding to an abnormally rough surface. The slabs were tested at three temperatures (10, 15 and 25 °C) to represent potential road surface conditions. For the testing procedure, the slabs were placed within a temperature-controlled cabinet and allowed at least 6 h to reach the testing temperature. Testing was carried out in a climate-controlled room set to the testing temperature. For each slab, measurements were taken radially at four points on the slab, and BPN was calculated as the average of these numbers. Figure 7 shows an overview of the procedure.

In addition, the ASTM E-965 [50] standard (sand patch method) was utilized to measure the macro-texture of the RAR surface course mixtures in terms of Mean Texture Depth (MTD). The sand patch method is probably the most known and utilized method to define the macro-texture of the pavement surface. A set amount of filler (e.g., sand, glass beads) is spread over the surface of the material in a circular pattern, and the average texture depth of the surface is determined for the testing (Figure 8).



Figure 7. BPT measurement.



Figure 8. Overview of the sand patch method.

For the current investigation, measurements were taken on the surface of the produced asphalt slabs containing the varying RAR percentages. A total of six tests were carried out for each of the test mixture slabs. The average of the six measurements was then recorded as the MTD value (mm).

4. Laboratory-Based Results

Compaction of the specimens and assessment of the bulk density were carried out in accordance with the EN 12697-6 [45] standard, while the void contents were determined in accordance with the EN 12697-8 [43] standard.

Figure 9 presents the achieved bulk density (kg/m^3) for the percentages of RAR modifiers investigated in comparison with the reference material (0% RAR). For the bulk density results, the highest bulk density was achieved with a 10% inclusion of the RAR-based elastomeric asphalt extender. While with the inclusion of a 20% RAR-based elastomeric asphalt extender achieved results comparable (slightly higher) to the non-modified design mixture. However, as the RAR modifier increased to the level of 40% (by weight) of bitumen, the achieved bulk density levels fell below the reference level, indicating that between 20–40% is the maximum level to which the RAR modifier can be added. Increases in the bulk density of the mixtures can have positive effects in regards to the potential for the course surface to resist deformation and rutting from vehicle traffic loadings.

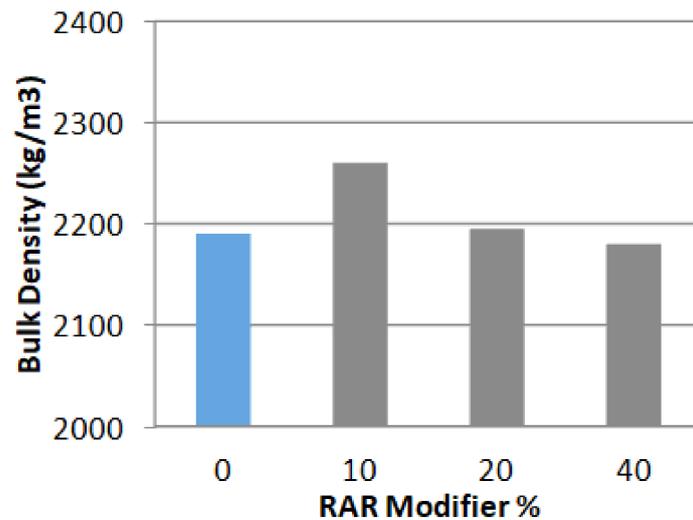


Figure 9. Average bulk density for investigated RAR mixtures.

Figure 10 presents the achieved air voids for the percentages of RAR modifiers investigated in comparison with the reference material (0% RAR). For the air void % results, the lowest air void % was achieved with a 10% inclusion of the RAR-based elastomeric asphalt extender. Meanwhile, as the RAR percentage increased to 20% and above, the results indicated higher air voids than the reference mixture. The combination of both the achieved bulk densities and air voids indicate that the maximum allowable percentage of RAR-based modifier is in the range of 20%, as levels higher than this had results below those of the reference asphalt material. Decreases in air voids are inversely related to the increased bulk density of the materials and thus, lead to increased protection against rutting in the course surface, increased road safety in the long term and potentially lower future operating costs of road assets.

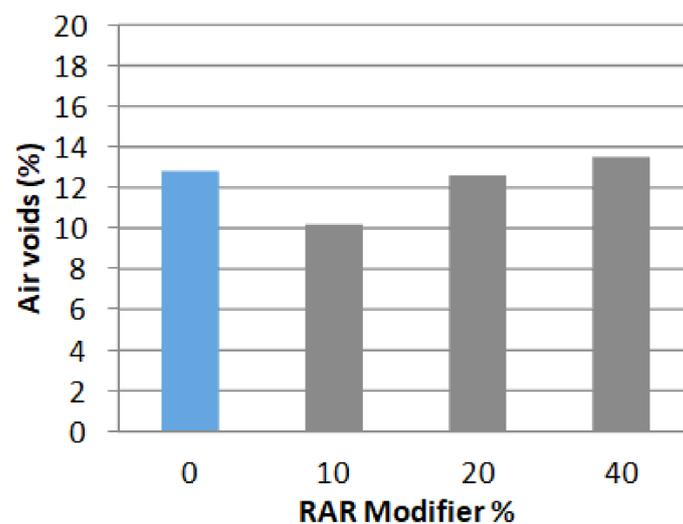


Figure 10. Air void % for investigated RAR mixtures.

The next stage was to investigate strength-based (mechanical) characteristics through the EN 12697-26 948] standard for the indirect tensile stiffness modulus (ITSM). Figure 11 shows the results according to the Annex C protocol.

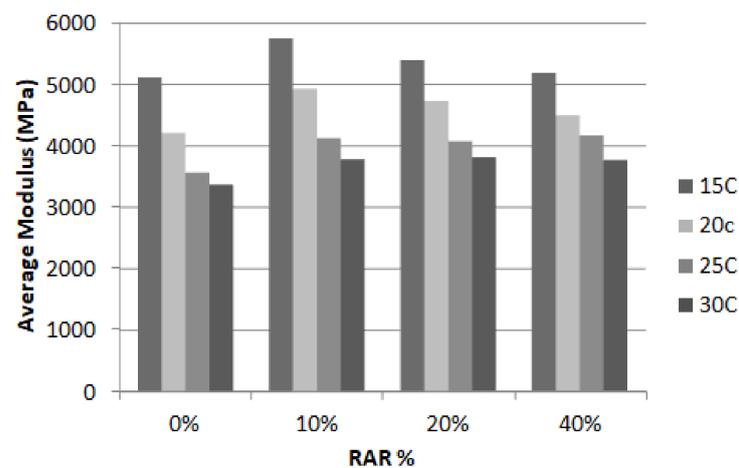


Figure 11. Average modulus versus temperature for investigated RAR mixtures.

The results shown in Figure 11 are for all four temperatures (15, 20, 25 and 30 °C). For the results at 15 °C, as the RAR increased from 0–10%, and the bitumen decreased to 90%, there was an increase of ~12% in the average modulus values. When looking at 20 °C, there is a 17% relative increase, with a corresponding 16% increase at the 25 °C test temperature and a 12% increase at 30 °C. Overall, for all temperatures tested, the modulus increased 12–17% when the RAR % was increased to 10% (90% bitumen) from the design mixture. However, when the RAR % was increased from 10 to 20% (80% bitumen), there was a 1 to 6% decrease in modulus values for the 15–25 °C test temperatures. Finally, looking at 30 °C, there was a minimal increase of ~1%. Analogous results can be seen when increasing the RAR% from 20–40% (80–60% bitumen) with the average modulus value lower by up to 5%.

Figure 12 provides an overall graphic representation of the effect of temperature and RAR modifier percentages on average modulus values. It is clear that as the test temperature is increased to 30 °C, the RAR mixture average modulus values approach nearly identical values. Similarly, all RAR mixture average modulus values are 12–13% greater than the corresponding reference asphalt mixture. This increase is true for all test temperatures and provides evidence that RAR modifiers have a positive effect on average modulus values based on ITSM testing protocol. Increased modulus values can have a positive influence on the expected life of a pavement. As the pavement has a higher modulus, lower strain levels are introduced into the pavement structure and, thus, there is less fatigue in the asphalt layer, and lower levels of permanent deformation will be present in the pavement's unbound layers. Thus, looking at the inclusion of the RAR modifier, it can be seen that this positively affects both the overall sustainability of the construction process and potentially provides a longer life for the pavement. Significant increases in modulus are noted for all test temperatures. This indicates that the incorporation of these RAR modifiers can be implemented in a wide range of climatic conditions.

In regards to the micro-texture of the slabs produced with varying RAR %, the results of the ASTM E-303 [50] testing standard can be seen in Figure 13. Based on the results of the previous section of the investigation (modulus, density, voids) and the potential for surface raveling of the material, testing was not continued for the 40% RAR level.

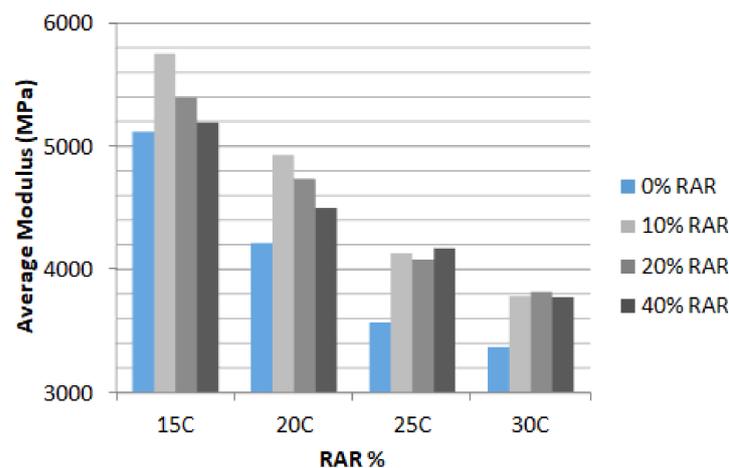


Figure 12. Comparison of RAR mixtures versus reference mixture (0%).

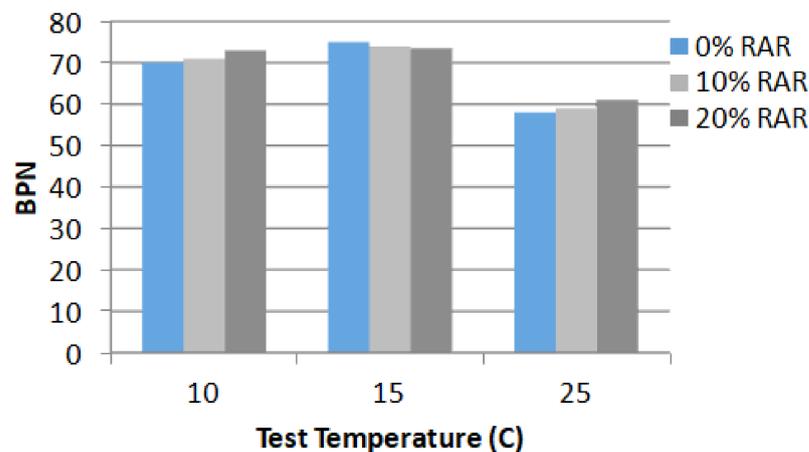


Figure 13. Micro-texture—results of the BPN testing.

As can be seen in the results, the BPN values of the RAR-based mixtures are similar to the traditional asphalt mixture utilized for comparison purposes. Slight variation exists between the temperature ranges, but overall, they can be considered insignificant. However, it can be seen that the slight increase in temperature from 10 °C to 25 °C has resulted in a notable decrease in the available tire–pavement friction of the testing slabs, which averaged ~25%. It is well known that temperature has a role in friction levels [38], and this decrease occurred regardless of the inclusion of the RAR-based materials. All in all, the RAR-based mixtures can be considered equal to the reference (traditional mixture) in regard to the achieved micro-texture levels.

Figure 14 presents the results of the laboratory testing of the macro-texture based on the ASTM E-965 [51] standard. As can be seen, significant reductions in the mean texture depth were noted as the % of RAR was increased in the mixture. Based on the results of the investigation, with the inclusion of 10% RAR-based materials, a 4% reduction in MTD was noted, while as the level increased to 20%, the decrease of MTD reached 10% versus the non-RAR reference material. It seems that the inclusion of RAR-based materials has a significant effect on the macro-texture.

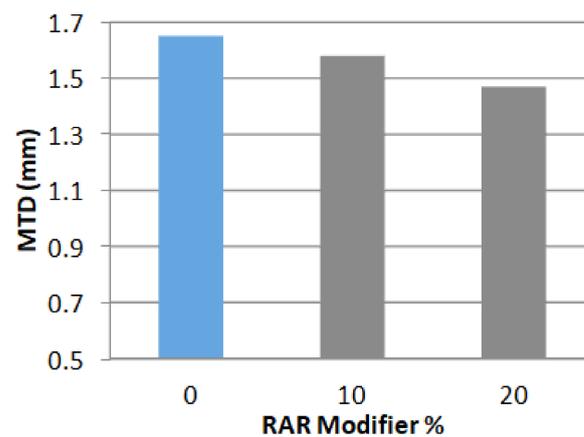


Figure 14. Macro-texture—results of the sand patch testing.

Friction levels are interrelated with pavement road safety and, thus, are considered an area of major interest with transportation engineers. As friction components, both the micro-texture and macro-texture levels are important for vehicle braking. For the surface of asphalt pavement, the macro-texture is mainly affected by the AC mixture, air void %, binder and/or modifier properties. On the other hand, the aggregate composition and shape properties have a large effect on micro-texture levels. For the current investigation, the micro-texture was not significantly affected by the addition of RAR modifiers, while the MTD was shown to have an inverse effect with the addition of RAR. The significance of these findings and their relation to hysteresis and adhesion, in regards to friction and road safety, need further investigation to more accurately determine their effects on road safety. It should be noted that these findings are initial laboratory-based friction values with no simulated polishing and/or abrasion designed to simulate long-term in-situ conditions. However, the research indicates a positive effect in general.

5. Concluding Remarks

In regards to the bulk densities and air void percentages, the best results in comparison to the reference material were produced by the mixture containing 10% RAR-based materials. While as the rate of RAR materials increased above 20%, both values were below those of the reference material. Based on the results of the design evaluation, it can be concluded that mixtures containing at least 10% and less than 20% overall produced the best mechanical characteristics when compared to the original design mixture.

Based on the results of the current investigation, it is clear that surface asphalt mixtures containing RAR modifiers had increased stiffness moduli in comparison with the initial design mixture (0% RAR). Differences in stiffness were most notable at a lower temperature (15–20 °C) and decreased as the testing temperature reached 30 °C. Even at 30 °C, all tested RAR mixtures (10, 20, 40%) had stiffness modulus values > 12% in comparison to the design mixture. In regards to the achieved bulk density results, the 10% RAR modifier produced both the highest achieved bulk modulus and lowest air void percentage. Meanwhile, the 20% RAR modifier produced values similar to the design mixture (0% RAR).

In regards to the micro-texture, the addition of RAR-based materials had a limited effect on the BPN values. In contrast, for the macro-texture, the addition of RAR-based materials had a significant role in reducing the MTD. As both of these combine to provide friction for the road-tire surface interaction, more investigation is needed to determine the overall effect of these results.

Generally, the current investigation was designed to determine optimal percentages of elastomeric asphalt extenders that can be added to a course surface layer. Based on both the physical and mechanical characteristics and the achieved frictional properties (micro-/macro-texture) determined in the present investigation, it can be concluded that the optimal percentage by weight of bitumen for inclusion of the RAR modifier is 10%.

In addition, it was shown that RAR levels of 40% resulted in reduced strength (modulus) of the materials and increased brittleness of the produced AC mixtures. These results are an important step to build upon the knowledge for the inclusion of this novel material in course surface layers both for sustainability purposes as well as for increased physical and mechanical characteristics of the mixture and improved friction properties. Further investigation of these types of material and for crumb rubber—for instance, to conduct leachate analysis in an effort to classify the RAR material—is required to have sufficient available data for the inclusion of such innovative and sustainable construction materials and techniques into future pavements.

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