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Experimental Investigation of Rejuvenated Asphalt Mixtures Using Bio-Oils from Different Biomass Sources

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Abstract
Asphalt mixes containing Recycled Asphalt Pavement (RAP) materials are generally harder than traditional mixes. Different rejuvenators are used to soften recycled asphalt pavement by reducing this hardness. In this study, recycled asphalt pavement was added to bituminous hot mixtures at 3 different rates (25%, 50% and 75%). To rejuvenate bituminous hot mixtures containing RAP, three different rejuvenators (pine cone, olive pomace and wheat straw) were added to the mixtures. This study investigated the effect of asphalt mixtures containing RAP and rejuvenator on the mechanical properties. Marshall test and moisture damage test were performed to examine the mechanical properties of asphalt mixture samples. As the bio-oil content in asphalt mixtures increases, the stability values of the mixtures decrease. As the bio-oil ratio in asphalt mixtures increases, tensile strength (TS) values decrease in both unconditioned and conditioned mixtures. While the increase in bio-oil reduces the tensile strength ratio, the shrinkage ratio of mixtures prepared with RAP increases. The bio-oil derived from pomace has been identified as the most effective rejuvenator among those tested.

1. Introduction

The cost of bitumen derived from petroleum has significantly increased as a result of its use in road building and maintenance [1-4]. Furthermore, the upkeep of ecologically appropriate pavement has become popular [2, 5-8]. Research is being done on alternate binders as a substitute for bitumen, which is often used in traditional processes. One efficient method of lowering bitumen use is to use Recycled Asphalt Pavement (RAP) material [9]. An important problem in infrastructure engineering is highlighted by the aging of asphalt binders throughout construction and service life [10–12]. Oxidation and volatile component loss are the main aging mechanisms of asphalt binders. As a result, asphalt binders become more viscous and tougher than when they were first created [13, 14]. To address these issues, various types of regenerating RAP mixes have been utilized [9,15–19]. Because of its many sources, high efficiency, and low cost, bio-oil is becoming more and more popular among other renewable energy [2, 20, 21]. The paragraph indentation should be used at the start of any subsequent paragraphs after the first.

Using pyrolysis techniques, biomass is the main source of bio-oil. Slow pyrolysis and rapid pyrolysis are the two categories of pyrolysis techniques. The residence time during the pyrolysis process is what distinguishes slow pyrolysis from quick pyrolysis. Fast pyrolysis has a residence period of less than 10 seconds, whereas slow pyrolysis has a residence time of 5 to 12 hours [22]. Three primary products of the pyrolysis process are produced: liquids, gases, and charcoal. The substance is regarded as bio-oil [23–25]. The use of bio-oils to alter or partially replace asphalt binders has grown [2, 26, 27].

According to earlier research, bio-oils can improve the low-temperature performance of asphalt

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binders by softening them [21-22, 28]. Furthermore, the possibility of restoring reclaimed asphalt binder to its initial condition has been investigated by certain researchers. As modifiers, a variety of bio-oils can be employed, including distilled tall oil, organic oil, waste vegetable oil, and others. Depending on the type of source, different rejuvenating effects apply. Specifically, it has been demonstrated that rejuvenation with waste vegetable oil at a concentration of 12% by weight can increase the aged asphalt's resistance to cracking, lowering its performance grade from PG 94-12 to PG 72-33 [17]. By adding 1.75-2% by weight of bio-oil, a bio-oil rejuvenator made from biodiesel residue makes up for the light components lost in aged binders and improves crack resistance at low temperatures [29]. The physical and rheological properties of 40/50 penetration grade bitumen can be enhanced with 3-4% by weight of waste cooking oil, approaching the characteristics of 80/100 penetration grade bitumen [30]. Rzek and associates used the pyrolysis of used tires to create a rejuvenator for their investigation. They supplemented three distinct ratios of recycled asphalt mixtures with these rejuvenators. They consequently discovered that recovered asphalt mixtures were used at a higher rate when the recently created alternative rejuvenator was added at a 20% rate. They discovered that adding this alternative rejuvenator might raise the percentage of reclaimed asphalt to 60% by the application of routine mechanical and rheological tests to the asphalt mixtures [27]. Avsenik and his colleagues looked at how aged bitumen was affected by bio-oils made from burning discarded tires. The bitumen, which was laboratory-aged and had undergone both short- and long-term aging operations, was 50/70 penetration grade. They evaluated the effect of rejuvenator addition on aged and unaged bitumen using standard mechanical and rheological tests at four different rates (3%, 5%, 10%, and 20%). The rejuvenator was found to be appropriate for altering aged bitumen by the researchers based on their mechanical and rheological testing [28]. In their studies, Oruc et al. prepared mixtures containing 10%, 25% and 40% RAP. Marshall tests were applied to these mixture samples, density and void analyses were performed, and the findings were compared with samples without recycling and core samples taken from the field [31]. In their study, Kumandas et al. added 2-8 wt% waste cooking oils (WCO) to bitumen modified with 1.5% reactive ethylene terpolymers (RET) and 0.2% polyphosphoric acid (PPA) as catalysts, in increments of 2%. It was observed that WCO addition increased the workability of RETMBs and their resistance to fatigue and low-temperature cracking [32].

In general, the properties of bio-rejuvenators are dependent on the biomass source. There is no study available on rejuvenating RAP binders using a bio-oil rejuvenator produced from wheat straw, pine cones, and rice husks. The rejuvenators used in the study were obtained through the pyrolysis method. In the pyrolysis method, biomass is burned at high temperatures in an oxygen-free environment to produce bio-oils. The use of this method also enhances the uniqueness of the study. Furthermore, utilizing bio-oil as a rejuvenator to recycle aged binders supports the repurposing of waste biomass and construction materials, promoting environmental sustainability and development. This study aims to offer an overview of RAP recyclability, focusing on the proportions of added RAP material, as well as performance, economic, and environmental considerations. The main goal is to promote the use of this material in similar applications and thereby maximize its use, contributing simultaneously to an environmentally and economically sustainable circular economy. Therefore, in the study, recycled asphalt pavements were added to bituminous hot mixtures at different percentages, and their mechanical properties were investigated. Additionally, three different bio-oils produced in the study were used to rejuvenate recycled asphalt mixtures. Subsequently, asphalt mixtures containing RAP and rejuvenator were compared with bituminous hot mixtures to investigate the effect of RAP and rejuvenator on mixtures.

2. Material and Method

2.1. Unmodified bitumen and Recycled Asphalt Pavement

The study used B 50/70 class bitumen from the TUPRAS\Batman refinery. Table 1 presents the general characteristics of the bitumen employed in the research. In this investigation, only one source of recycled asphalt pavement (RAP) material obtained from the Elazig Municipality in Turkey was utilized. To minimize its impact on the environment, the obtained RAP material was kept in impermeable containers. The original bitumen of the RAP material in the construction phase is B 50/70 class bitumen. The purpose of this study is to add rejuvenators to the RAP binder to raise its hardness to that of the bitumen utilized during the first building phase. 50/70 was therefore chosen as the pure bitumen. The penetration, softening point and viscosity test results at 135℃ of the aged binder obtained from RAP are 10, 79.3℃, and 6338 cP, respectively.

Table 1. General properties of bitumen

Specification	Unit	Standard	Results
Penetration	mm^{-1}	EN 1426	56
Softening point	˚C	EN 1427	53.3
Flash point	˚C	EN ISO 2719	245
Specific weight	g/cm^3	ASTM D70 - 18a	1.015
Elastic recovery	%	EN 13398	30
Viscosity 135°C /165°C	cP	ASTM D4402	737.5/225
Mixing temperature	˚C	-	159-165
Compression temperature	˚C	-	145-151

2.2. Biomass

The biomass materials for the study, namely ground wheat straw, ground pine cones, and bran, were procured from Cambaylar Co. Ltd. situated in the province of Elazig. For use in this investigation, the biomass materials were filtered through a No 30 sieve to guarantee a consistent particle size distribution. This was done to ensure that the experimental results would not be impacted by the biomass's size.

2.3. Properties of the Reclaimed Asphalt Pavement (RAP) Material

The EN 932-1 standard was followed while sampling from the RAP material [33]. To ascertain the gradation of the recycled asphalt pavement material, an extraction test was conducted (Figure 1a). The amount of bitumen contained in the RAP material was ascertained after the extraction test. The recycled asphalt mixture was found to contain 4.6% bitumen. Following the TS EN 12697-3+A standard [34], the aged binder extracted and separated from the recycled asphalt binder was recovered utilizing a rotary evaporator (Figure 1b). To find the bitumen content in this investigation, 50 extraction tests were carried out. The entire investigation was conducted with the recycled and old binder.

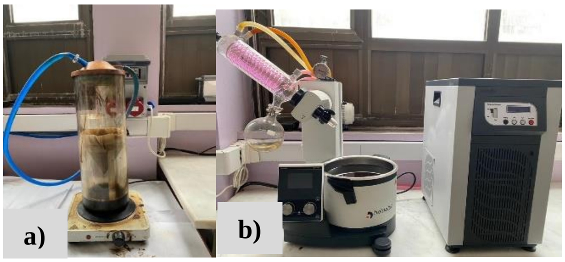

Figure 1. a) Extraction apparatus b) Rotary evaporator

2.4. Bio-oil Production

In this investigation, three distinct rejuvenators will be employed. These rejuvenators come from agricultural materials and are bio-based. The project will make use of bran bio-oils, pine cones, and wheat straw. In this investigation, materials that had been through a No. 30 sieve were employed to guarantee that the biomass produced had a consistent particle size distribution. This was done to ensure that the experimental results would not be impacted by the biomass's size. The biomass was subjected to a slow pyrolysis process using a device. The laboratory slow pyrolysis experimental setup comprises several components: a water cooling system, a programming device box for temperature adjustment during the experiment, a high-temperature-resistant cylindrical container with dimensions of 150 mm inner diameter and 240 mm height, and a tank where the condensed biogas is collected as oil after cooling. Figure 2 depicts the general design of the slow pyrolysis experimental setup.

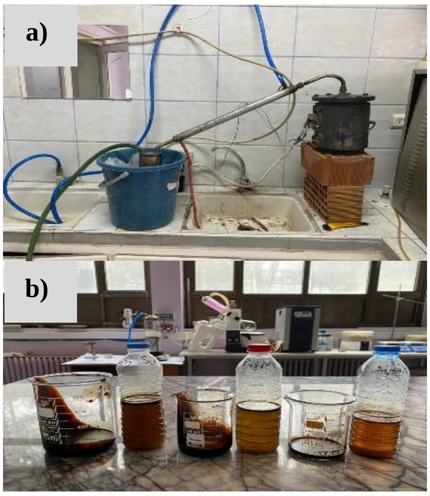

Figure 2. a) General view of the laboratory slow pyrolysis experimental setup, b) samples of bio-oil and water obtained as liquid products after pyrolysis

Before commencing the pyrolysis process, 1000 grams of biomass were consistently introduced into the chamber of the device to mitigate the influence of biomass quantity on carbonization. As a result, a fixed-bed slow pyrolysis system operating at 500°C was used to pyrolyze 1 kg of dry biomass sample, as shown in Figure 2. Based on research published in the literature, this temperature was selected. The system's pyrolysis vapors were burned in a chimney inside the system outlet, while the uncondensed pyrolysis gases were condensed into liquid pyrolysis products (bio-oil) by a condenser cooled with water. The pyrolysis process kept going until no more gas was released. To calculate the quantities of biochar, the liquid pyrolysis products and the pyrolysis residue were weighed after cooling. The non-condensed gas product quantity was then determined by deducting the total weight of these products from the dry biomass amount that was initially used. Table 2 displays the results that were achieved. To extract water and organic acids from the oil phase, the produced liquid products (Figure 2), which contained a high percentage of water, were vacuum-extracted at 80°C and 200 mmHg pressure using a Heidolph rotary evaporator. The goal of this procedure was to remove water and organic acids like acetic acid from high-viscosity oil products. Consequently, oil products with weight ratios of 12.75%, 11.56%, and 10.95% of water and organic acids eliminated were obtained for pine cones, bran, and waste wheat straw, respectively, in comparison to the amount of dry biomass.

Table 2. The results of biomass pyrolysis include yields of liquid bio-oil, biochar, and non-condensable gas

Biomass	Bio-oil yield (%)	Bio-char yield (%)	Gas yield (%)
Pine cone	37.92	32.09	29.99
Olive pomace	31.83	32.52	35.65
Wheat straw	27.13	31.57	41.30

Table 3 shows the analysis results determined by EDS analysis in rejuvenators. However, the elemental compositions determined by EDS analysis are not accepted as quantitative results because the presence of single-electron hydrogen cannot be determined by this technique. In other words, it is not possible to determine the hydrogen content due to the presence of hydrocarbons in the structure of all these materials. On the other hand, it can be considered as an idea about the carbon and oxygen composition other than hydrogen. Another importance of EDS analyses is that they provide information about the presence of elements other than C, H and O.

Table 3. Elemental analysis of rejuvenators

Element	Weight (%)		
	K	P	S
C	56.41	75.86	57.82
O	35.57	24.14	34.81
Al	0.07	-	1.21
N	3.60	-	-
S	0.25	-	-
Fe	4.10	-	-
Ca	-	-	1.06
K	-	-	0.13
Si	-	-	2.20
Mg	-	-	0.49

2.5. Preparation of Hot Mix Asphalt Samples

For combinations made with pure bitumen, the Marshall technique was used to determine the ideal bitumen content (Table 4). Using the Marshall method, 75 blows were delivered to each side of the specimens to create mixture samples. The limestone came from Elazig's Karayazi area. The ideal bitumen concentration was established for mixture samples made entirely of bitumen. Initially, bituminous hot mixes were treated with RAP material at three different percentages (25%, 50%, and 75%) of the overall mixture. They are named 2R, 5R and 7R, respectively, according to the percentages they contain. The same bitumen content was used to prepare modified mixes. For mixtures generated with 4.9% bitumen content, both with pure and modified mixtures, Table 4 gives the bulk specific gravities (Gmb), air voids (Va), voids filled with asphalt (VFA), voids between aggregates (VMA), and mixing-compaction temperatures. Using a rotational viscometer on the binder, the mixing-compaction temperatures of the mixtures were found to correspond to viscosity values of 170 ± 20 and 280 ± 30 cP [35]. In terms of volumetric qualities, it was found that the mixtures satisfied the specification requirement (KTS).

Table 4. Volumetric properties of mixture specimens

Mixture	Bitumen (%)	Mixing temperature (ºC)	Compaction temperature (ºC)	Va (%)	VFA (%)	VMA (%)	Gmb
Unmodified bitumen	5	171	158	3.78	74.3	14.7	2.292

Equation 1 was used to determine the bitumen contents for mixtures containing RAP. The optimum bitumen content determined for the reference bitumen will be used for all mixtures. Table 5 provides the optimum bitumen contents. The purpose of using this ratio is to compare the experimental results accurately.

$$Pr= Pc-(Pa*Pp) \quad (1)$$

Here, Pr represents the percentage of unmodified bitumen to be added to the mixture containing RAP, Pa denotes the percentage of RAP binder in the mixture, Pc indicates the total binder percentage in the mixture, and Pp signifies the percentage of RAP in the mixture.

In the second stage, three different percentages of RAP will be added to HMA samples, and for each of these mixtures, three different rejuvenators will be added during mixing. Different asphalt mixture specimens (pure/pure+RAP+rejuvenator) have been prepared. The rejuvenator ratio was chosen as 20% according to the study. In the figures, “K” indicates the use of pine cone bio-oil, “P” indicates the use of olive pomace bio-oil, “S” indicates the use of waste wheat straw bio-oil and finally “pure” indicates the use of unaged 50/70 penetration pure binder.

Table 5. Optimum binder contents

RAP content (%)	Pc (%)	Pa (%)	Pr (%)
25	4.9	4.6	3.75
50	4.9	4.6	2.6
75	4.9	4.6	1.45

2.6. Marshall Stability and Flow Test

The Marshall Stability and Flow Test applied to HMA samples is conducted to determine the maximum resistance to deformation (stability) and the vertical deformation (flow) that occurs in the sample when the maximum load is reached. Before starting the test, the heights of the compacted and cooled samples are measured and recorded. Then, the samples are kept in a water bath at a temperature of 60±1°C for 40-60 minutes. At the end of this period, the sample is removed from the water and placed in a manner that aligns the breaking jaws, then loaded at a rate of 50±2 mm/min. Samples subjected to the Marshall Stability and Flow Test are shown in Figure 3.

Figure 3. HMA specimens subjected to Marshall stability and flow test

In the test, the maximum load and the deformation values at the time of reaching this load are recorded. The test should be completed within 40 seconds after the sample is removed from the water. It is assumed that the standard sample height is 63.5 mm in the test. Correction factors for stability are used for samples with different heights. At the end of the test, the average stability and flow values obtained are calculated. Samples with stability values deviating more than 15% from the average stability and flow values deviating more than 20% from the average flow are excluded from the evaluation. The remaining samples are averaged again, and if there are samples with the same deviation (15% for stability, 20% for flow), this sample series is canceled, and the test is repeated on a new set of samples. The Marshall quotient (MQ), serving as an indicator of the stiffness and resistance to deformation of bituminous hot mixtures, is calculated by dividing the Marshall stability value by the flow value.

2.7. Resistance to Moisture Damage Test

Various tests have been devised to assess the resistance of asphalt mixtures to moisture damage. Although these developed tests do not fully reflect real field conditions, they provide us with close information. The adhesion of bitumen to aggregate is one of the significant factors affecting the performance of the pavement over time. Water penetrating between bitumen and aggregate over time reduces the effectiveness of adhesion, leading to premature failure in asphalt mixture overlays. Factors affecting the resistance of asphalt mixtures to moisture damage can be listed as follows:

a) An effective factor in moisture sensitivity is the thickness of the asphalt film. Mixtures with thin asphalt film thickness are more sensitive to the negative effects caused by water compared to mixtures with thicker asphalt film thickness.

b) Another factor affecting the moisture damage of the mixture is the refining process used in the production of asphalt cement and crude oil. However, many asphalt cements do not have a significant impact on moisture damage.

c) Another factor affecting the stripping potential of the asphalt mixture is traffic and environmental indicators.

d) Another factor is the characteristic of the asphalt concrete mixture. Qualities such as permeability, porosity, asphalt cement, and aggregate gradation are important factors because they control the saturation level and drainage of water. Mixtures with more than 6% void content are more prone to moisture damage.

e) The type of coarse and fine aggregate significantly affects the potential moisture damage in the mixture.

In this method, 6 Marshall specimens with an air void content in the range of 6-8% are used. These specimens are divided into conditioned and unconditioned groups. Conditioned specimens are placed in a pycnometer, and a vacuum process is applied until approximately 70-80% of the air voids in the specimen are filled with water. The water-filling ratio in the voids should not be less than 70%. If it exceeds 80%, those specimens should not be used.

The degree of saturation of the specimens is determined using the following formulas:

$$J = B' - B \quad (2)$$
$$I = Va * V / 100 \quad (3)$$
$$S' = J / I * 100 \quad (4)$$

J represents the absorbed water volume in cubic centimeters, B' is the saturated surface-dry weight of the specimen after the vacuum process in grams, B indicates the dry weight of the specimen before the vacuum process in grams, I signifies the volume of air voids in cubic centimeters, Va refers to the air voids percentage, and V represents the volume of the specimen in cubic centimeters.

After the vacuum process, the cylindrical specimens are tightly wrapped with stretch film. These wrapped specimens are initially kept in a water bath at -18°C for 16 hours, followed by another period of 60°C (Figure 4). Once the waiting period is over, the stretch films are removed. Conditioned and unconditioned specimens are then immersed in water at 25°C for 2 hours before being subjected to axial loading for fracture.

Figure 4. Wrapping and incubation of specimens with stretch film

3. Results and Discussion

3.1. Marshall stability and flow test results

Marshall stability and flow test specimens were prepared following EN 12697-34 and submerged in water at 60°C for 40 minutes before undergoing the test. Each asphalt mixture had a constant 20% bio-oil addition. Moreover, Figure 5 shows how the use of bio-oil causes fluctuations in Marshall stability values.

The use of bio-oil lowers the Marshall stability values, as seen in Figure 5. It was discovered that the combinations made with 7R 75% RAP had the highest stability values. The 7P asphalt combination has the lowest stability value. It was found that the bio-oil produced by pyrolyzing olive pomace was the most efficient. In comparison to the pure mixture, the stability values of the 2R, 5R, and 7R mixtures increased by 1.12, 1.17, and 1.57 times, respectively. These findings suggest that the stability values can be raised by including recycled asphalt mixtures in the pure mixture at specific percentages. The stability values of the asphalt mixtures drop and get closer to the stability value of pure mixtures when three distinct rejuvenators are introduced to HMA samples with three different amounts of RAP. The stability ratings of the asphalt mixtures decline as the amount of bio-oil in the mixtures increases. In comparison to the stability value of the 2R asphalt mixture, the Marshall stability values of the 2P, 2K, and 2S mixes drop by 7.83%, 9.60%, and 1.26%, respectively. The rejuvenator added to the 2R mixture is responsible for the observed decline. The Marshall stability values of the 5P, 5K, and 5S asphalt mixtures drop by 22.33%, 13.99%, and 10.50%, respectively, in relation to the stability value of the 5R mixture. In a similar vein, the Marshall stability values of the 7P, 7K, and 7S asphalt mixtures drop by 44.26%, 37.23%, and 43.74%, respectively, with respect to the stability value of the 7R asphalt mixture. It has been determined that P bio-oil is the most useful bio-oil for affecting the stability values of the asphalt mixtures.

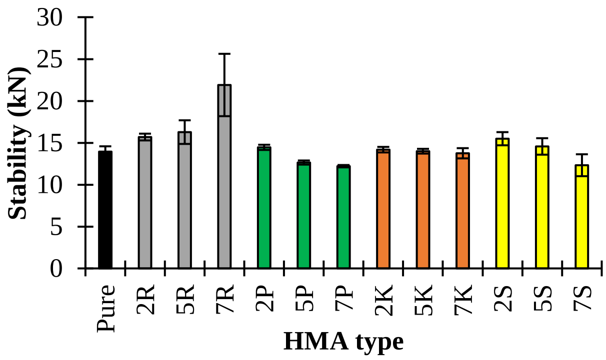

Figure 5. Variation in the stability values of asphalt mixtures with the use of bio-oil

When the flow values of the mixtures given in Figure 6 are examined, it is observed that as the proportion of bio-oil added to the aged binder increases, the flow values of the asphalt mixtures decrease. Among the mixtures, the lowest flow value is obtained from the 7R mixture, while the highest flow value is obtained from the 2R mixture. The mixtures with S bio-oil have lower flow values compared to other mixtures containing bio-oil. Adding bio-oil as a rejuvenator to RAP-containing asphalt mixtures decreases the flow values of these mixtures. The Marshall ratio values of the mixtures are shown in Figure 7.

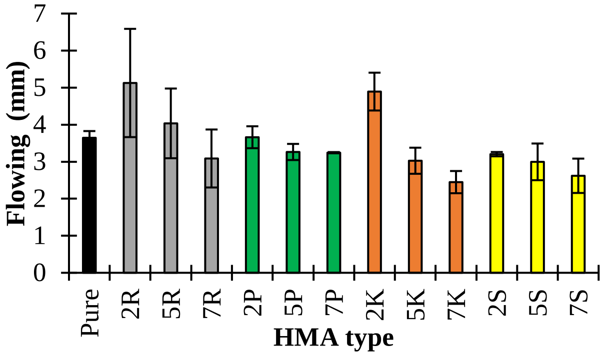

Figure 6. Variation in the flowing values of asphalt mixtures with the use of bio-oil.

When the Marshall quotient (MQ) values given in Figure 7 are examined, it is observed that, except for the K bio-oil, the use of bio-oil generally increases the MQ values. As the proportion of RAP mixtures added to pure mixtures increases, the MQ values also increase. The addition of P and S rejuvenators to the asphalt mixtures decreases the MQ values. Adding rejuvenators to RAP-containing mixtures generally causes a decrease in the MQ values of the mixtures. Evaluating the results of the Marshall stability and flow tests, it is determined that the use of bio-oil generally decreases the stability and MQ values while significantly reducing the flow values.

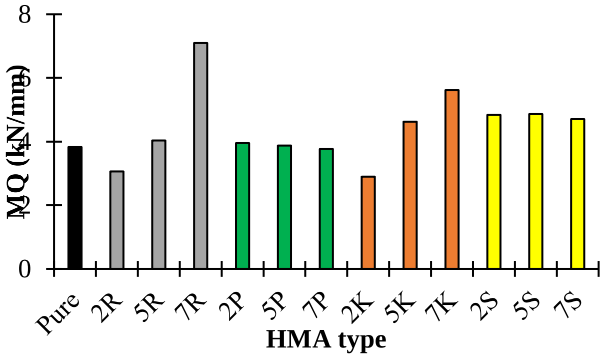

Figure 7. Variation in the MQ values of mixtures with the use of bio-oil

3.2. Tensile strength ratio test results

Tensile strength ratio tests were conducted on mixture samples prepared with rejuvenator and RAP following the AASHTO T 283 standard to determine their resistance to moisture damage. Six samples were prepared for each type of mixture, each having a void content of 7 ± 0.5%. During the preparation of the mixture samples to be used for determining resistance to moisture damage according to the standard, compaction was applied with a gyratory compactor for 40 revolutions. In the short-term aging of the mixtures, the samples were kept in an oven at 60ºC for 16 hours, followed by two hours at the compaction temperature. The samples were then left to cool at room temperature for 24 hours, and their volumetric properties were determined to group them with similar void contents. Three samples from each mixture were subjected to a vacuum to allow them to be filled with water to a saturation level of 70-80%. To achieve this saturation level, all samples underwent conditioning and were subjected to a vacuum for 10 minutes. Samples that did not reach the desired saturation level were subjected to vacuum again. Saturation levels greater than 80% in any sample resulted in their removal from the test and replacement with fresh samples. After being vacuum-treated, the samples were wrapped in cling film, and put into bags with 10 milliliters of water, and the bags were sealed tightly.

The samples went through a particular process: they were submerged in water at 60°C for 24 hours after spending 16 hours in a freezer at -18°C. The samples were then removed from the cling film and bags, and they were immersed in water at 25°C for two hours before breaking. In the case of unconditioned materials, indirect tensile strength jaws were used to fracture them in the Marshall testing apparatus after they had been soaked in water at 25°C for two hours. The samples were loaded at a constant pace of 2 inches per minute (50.8 mm/min) during the breaking process. A selection of the test-submitted samples is shown in Figure 8.

Figure 8. Appearance of some of the samples subjected to the moisture damage test

The tensile strength (TS) values of the mixture samples were assessed using the maximum load values derived from the tensile strength ratio tests performed on both unconditioned and conditioned asphalt hot mix samples, illustrated in Figure 9. As depicted in the figure, the tensile strength

(TS) values of both unconditioned and conditioned mixtures exhibited an increase with the addition of recycled asphalt compared to the pure (reference) mixture. Incorporating 20% bio-oil into these mixtures led to a reduction in the tensile strength (TS) values of both unconditioned and conditioned mixtures in comparison to the RAP mixture. With a higher proportion of bio-oil in the asphalt mixtures, there is a noticeable decrease in the tensile strength (TS) values observed in both unconditioned and conditioned mixtures. As the content of bio-oil increases, the tensile strength ratio diminishes, whereas mixtures prepared with RAP demonstrate an enhancement in the tensile ratio. This observation indicates that in unconditioned mixtures, the 7R mixture has the highest tensile strength ratio, whereas the 7K mixture has the lowest tensile strength ratio. Tensile strength (TS) values of the 2R, 5R, and 7R mixtures were found to rise 1.02, 1.07, and 1.22 times, respectively, above the pure mixture's TS values prior to conditioning. In contrast, when compared to the unconditioned TS value of the 2R asphalt mixture, the unconditioned TS values of the 2P, 2K, and 2S mixtures dropped by 8.22%, 14.14%, and 11.91%, respectively. The rejuvenator that was added to the 2R mixture is responsible for the reported decrease. In particular, when compared to the unconditioned TS value of the 5R asphalt combination, the unconditioned TS values of the 5P, 5K, and 5S mixtures dropped by 20.08%, 33.28%, and 23.39%, respectively. Comparing the unconditioned TS value of the 7R asphalt mixture to that of the 7P, 7K, and 7S mixtures, respectively, showed a decrease of 34.94%, 39.43%, and 31.96%. Following conditioning, it was found that, in comparison to the conditioned TS values of the pure mixture, the TS values of the 2R, 5R, and 7R mixes increased by 1.024, 1.04, and 1.34 times, respectively. In comparison to the conditioned TS value of the 2R asphalt mixture, the unconditioned TS values of the 2P, 2K, and 2S mixtures dropped by 1.32%, 9.80%, and 7.16%, respectively. In addition, when compared to the conditioned TS value of the 5R asphalt combination, the conditioned TS values of the 5P, 5K, and 5S mixtures dropped by 14.63%, 20.60%, and 18.75%, respectively. Comparing the conditioned TS value of the 7R asphalt mixture to that of the 7P, 7K, and 7S mixtures, respectively, showed a decrease of 36.02%, 44.56%, and 39.71%. Figure 10 shows the tensile strength ratios (TSR) of the mixture samples using samples of conditioned and unconditioned asphalt hot mix.

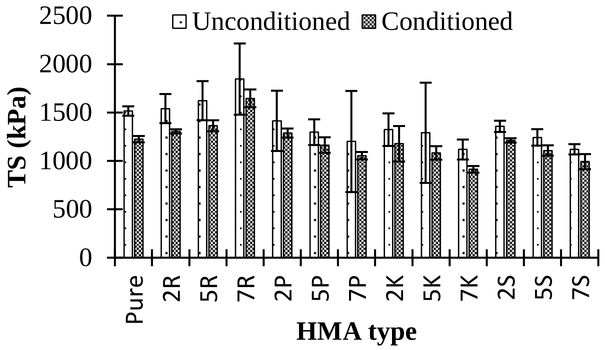

Figure 9. Tensile strength values of mixtures before and after conditioning

The addition of RAP to the mixes improved their resistance to moisture damage, as evidenced by the tensile strength ratios (Figure 10), which act as markers of resistance to moisture damage. Increasing the amount of RAP in the combinations often strengthened their resistance to moisture degradation. However, increasing the percentage of each of the three bio-oils in the mixtures led to a reduction in their ability to withstand moisture degradation. Tensile strength ratio (TSR) values of hot bituminous mixtures should preferably be above 80%, as per the Superpave method, to protect against moisture damage. The TSR values of all the created mixes were found to be either near or above 80% when the acquired values were examined.

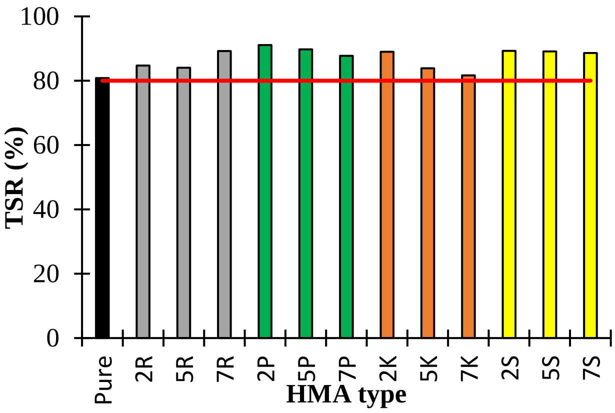

Figure 10. Variation of the tensile strength ratios of the mixtures

4. Conclusion

In this study, to meet the properties of the selected reference bitumen (B50/70-grade pure bitumen was chosen as the reference binder for the rejuvenation of recycled asphalt (RAP) binder), three different rejuvenators were added in varying proportions to the aged bitumen obtained from RAP, and the physical and rheological properties of the binders were examined. Physical and mechanical tests were conducted on the prepared HMA (Hot Mix Asphalt) samples to assess the impacts of the rejuvenators and RAP (Recycled Asphalt Pavement) material on the physical and mechanical properties of the reference mixtures.

• It was determined that the aged bitumen obtained from the recycled bituminous mixture softened as a result of the addition of rejuvenators.

• It has been determined that adding recycled asphalt mixtures to the pure mixture at certain percentages increases the stability values. When three different rejuvenators are added during the mixing process to HMA samples containing three different proportions of RAP, a decrease in the stability values of the asphalt mixtures occurs, approaching the stability value of the pure mixtures. As the bio-oil content in the asphalt mixtures increases, the stability values of the mixtures decrease.

• Adding recycled asphalt to hot bituminous mixtures led to an increase in the tensile strength (TS) values of both unconditioned and conditioned mixtures compared to the pure (reference) mixture. However, when 20% bio-oil was introduced to these mixtures, the tensile strength (TS) values of both unconditioned and conditioned mixtures decreased in comparison to the RAP mixture. As the proportion of bio-oil in the asphalt mixtures increased, the tensile strength (TS) values decreased in both unconditioned and conditioned mixtures. Additionally, while the increase in bio-oil content reduced the tensile strength ratio, the tensile strength of the mixtures prepared with RAP increased.

Consequently, it may be said that using bio-oil lessens stiffness. Because of this, choosing the right dosage needs to be done carefully to prevent rutting resistance from being compromised and eventual failure. According to the findings of this study, bio-oils derived from pine cones, olive pomace, and wheat straw are viable rejuvenators. Among the rejuvenators investigated, the bio-oil obtained from olive pomace was identified as the most effective.

Contributions of the authors

M.Y and B.F.Y. designed the study, performed the experiments and wrote the article. H.S.A. performed the calculations, checked the language and contributed to the writing of the manuscript.

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Conflict of Interest Statement

There is no conflict of interest between the authors.

Statement of Research and Publication Ethics

The study complies with research and publication ethics.

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