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Using bio-oil as a rejuvenator for asphalt extracted from reclaimed asphalt pavement

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Abstract. Every year, huge quantities of asphalt pavement resulting from road rehabilitation are crushed. To address the threat of waste accumulation and achieve a sustainable environment, the world has turned to recycling these asphalt wastes by treating them with renewable materials for reuse. In this research, bio-oil, which is a green liquid composed of oils extracted from biomass (corn oil, hill oil, sunflower oil, soybean oil, rapeseed oil and vegetable oil), was used. Many studies have employed different types of bio-oil as rejuvenators, showing good results for aged asphalt treated with bio-oil. Therefore, this type of bio-oil was used to demonstrate its effect on the physical condition and physical properties of bio-oil. One of the characteristics of the reclaimed asphalt was tested by adding bio-oil in different weight percentages (1 %, 2 %, 3 % and 4 %) to a blend of 70 % virgin asphalt and 30 % reclaimed asphalt to determine the ideal bio-oil proportion. Physical tests (penetration, softening point, ductility and viscosity) were conducted on the mixture. The results showed that adding bio-oil at an optimum rate of 1.31 % to the mixture increased penetration and ductility by 15.6 % and 34 %, respectively; reduced the softening point by 7 % and decreased viscosity at 135 °C and 165 °C by 33 % and 58 %, respectively. According to the results, aged asphalt can be renewed to a condition similar to virgin asphalt, offering both environmental and practical benefits by reducing waste.

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1. *Introduction*

Roads are the main arteries that connect cities, and their construction according to international standards is evidence of a country's development. Iraq has begun rehabilitating and rebuilding roads due to its economic openness to other countries. With this urban revolution in road rehabilitation and construction, the quantities of aged asphalt pavement waste have increased. As environmental sustainability gains prominence in academics and industry, and with the delayed use and accumulation of these materials, a way must be found to benefit from these materials and reuse them by mixing them with rejuvenators [1].

Recently the use of waste materials in construction as partial or complete replacement for virgin materials has increased for several reasons. Reclaimed asphalt pavement (RAP) materials are created by scraping off the top layer of aged asphalt pavements, which are then dumped in landfills, causing environmental issues [2]. During the recycling process, RAP components are mixed with virgin materials to create fresh asphalt mixture. Therefore, recycling RAP materials is a common approach to reducing manufacturing costs and energy consumption, as well as natural resources, while protecting the environment [3, 4].

As more RAP is used in asphalt mixes, concerns about the possible detrimental influence of the aged RAP binder on field performance are growing. To address these challenges, rejuvenators are increasingly

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used to improve RAP mix performance. In [5], the effectiveness of waste vegetable oil (WVO) as rejuvenator in restoring the desired properties of recycled asphalt mixes. The effectiveness of rejuvenators was first evaluated based on aging resistance, rutting, and fatigue performance. Rejuvenated bitumen, when evaluated based on a linear amplitude sweep test, has shown inferior fatigue resistance compared to virgin bitumen. Such behavior of rejuvenated bitumen could be attributed to the presence of a high concentration of more reactive unsaturated fatty acids inherited from WVO. However, from indirect tensile fatigue tests on the asphalt mixes, it was found that the fatigue performance of rejuvenated recycled asphalt mixes is satisfactory.

In [6], the performance characteristics and workability of high RAP mixtures in the presence of a bio-modified binder was investigated. The data indicated that the addition of the bio-modified binder helped reduce the stiffness of the control mixture with 40 % RAP to a level closer to the stiffness of the same mixture without RAP. In addition, the presence of the bio-binder led to improving the workability of the mixtures, especially this was very evident at high-RAP content of 40 %. The data indicated that the bio-modified binder improved the fatigue properties and cracking characteristics and had no negative effect on the moisture susceptibility/rutting characteristics of the control mixture with 40 % RAP. Overall, data indicated that there was a good degree of blending between the virgin/bio-modified and RAP binders.

In [7], the recycling and restoration of RAP using two types of renovators, waste cooking oil (WCO) and asphalt cement (AC) 85–100, were studied. Five percentages (1 %, 1.5 %, 2 %, 2.5 % and 3 %) by weight of both types of renovators were added to the RAP, separately, for the purpose of rejuvenation. Marshall Test was performed on the renovated samples to obtain the optimum percentages, which will be adopted in subsequent tests, which include: indirect tensile strength, tensile strength ratio and duple punch shear strength test – to evaluate the performance of rejuvenated RAP mixes and compare them with the original RAP. The results indicated that 1.5 % of WCO and 2.5 % of AC 85–100 are the optimal percentages.

Other researches have been conducted to explore the use of materials, such as organic montmorillonite clay, fractionated bio-oil, cottonseed oil, crude glycerin and microalgae-derived bio-binders [8–11]. In [12], the effectiveness of an asphalt binder, produced from thermochemical conversion of swine manure, was examined. According to the test results, the addition of bio-binder can improve low temperature properties of asphalt binder significantly.

Bio-oil from renewable biomass can partially replace asphalt binder, because it is comparable to asphalt binder in terms of viscosity, elasticity, chemical composition and color [14, 15]. Adding bio-oil to asphalt binder may enhance its low-temperature properties and stress-cracking resistance [16–18].

In [19], it was found that adding 3–4 % of jatropha curcas oil (JCO) reduced age-hardening.

In [20], date seed oil (DSO) was used to modify binders containing different amounts of RAP binder varying from 20% to 40%. The moisture susceptibility, rutting performance, stiffness modulus and fatigue resistance of the mixtures were evaluated, and the results showed that the addition of DSO improved fatigue life of the specimens containing 20 % RAP up to 15 %.

This study uses a blend of 70 % virgin asphalt (VA) and 30 % RAP, following prior research [21].

The study's significance lies in mitigating environmental harm from obsolete asphalt waste, while repurposing it for road paving. The research will also help in establishing an economical and sustainable method for manufacturing RAP, which may ultimately lead to reducing waste and promoting greener infrastructure in the country.

The current study aims to study the effect of using bio-oil, consisting of a group of oils extracted from biological materials, on the properties of extracted asphalt RAP (30 %) mixed with VA (70 %) [1]. Various bio-oil ratios were tested to identify the optimal rejuvenation percentage. The methodology is outlined in Fig. 1.

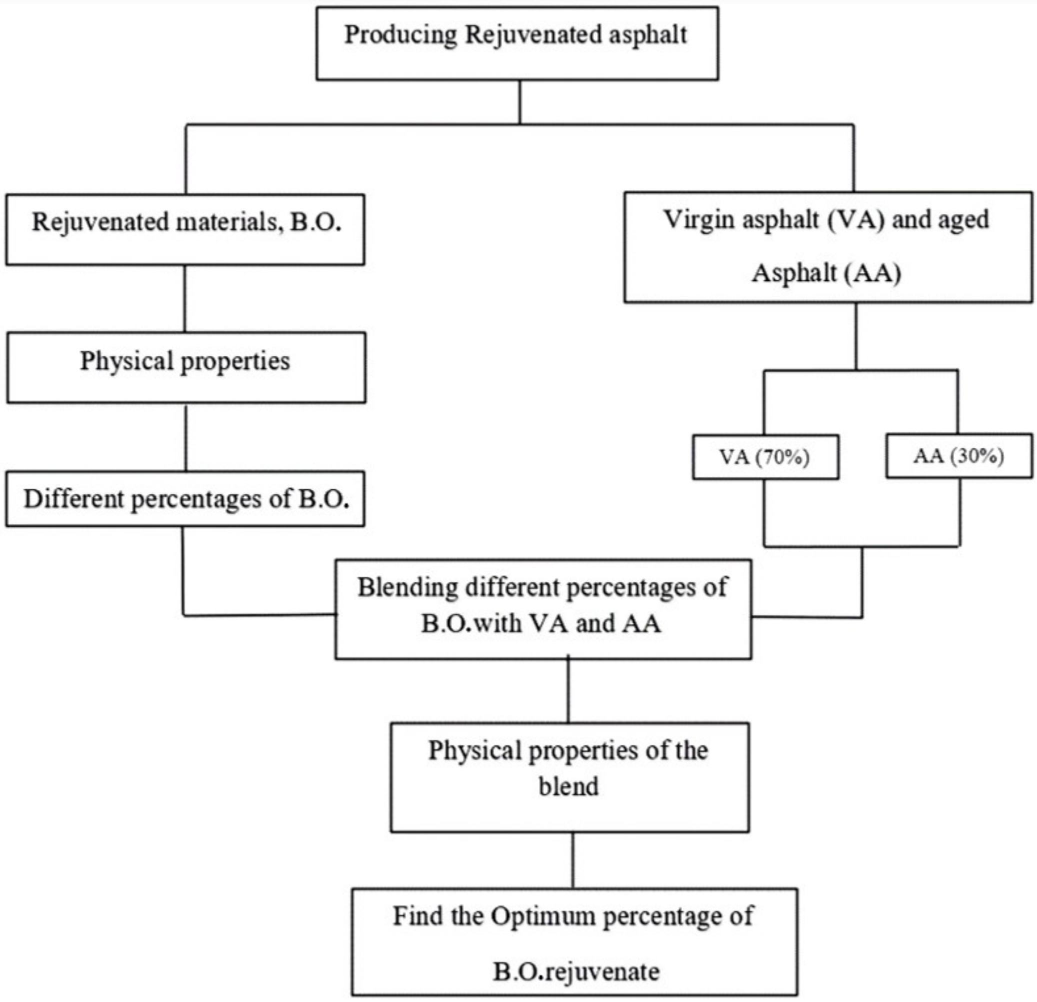

Figure 1. Research methodology.

2. Materials and Methods

2.1. Materials

Asphalt binder

Asphalt binder is the most widely used material for different types of paving in road construction [22]. In this study, 40–50 asphalt grade produced from AL-Daura refinery (Baghdad, Iraq) was used. The basic characteristics of this asphalt binder are shown in Table 1.

Table 1. Physical properties of the VA binder.

Physical properties	Value	Unit	Test condition	SCRB specification (2003)	ASTM standard
Penetration	43	1/10 mm	25 °C, 100 gm, 5 sec	40–50	D5
Ductility	145	cm	25 °C, 5 cm/min	> 100 cm	D113
Softening point	54	°C	Ring & ball	–	D36
Specific gravity	1.03	(25 °C/25 °C)	–	–	D70
Rotational viscosity	573	CP	135 °C	–	D4402
	143	CP	165		

Bio-oil rejuvenator

The bio-oil rejuvenator used in this study is a green liquid composed of several oils extracted from biomass (corn oil, tall oil, sunflower oil, soybean oil, rapeseed oil and vegetable oil), produced by SRIPATH Technology (LLC/ReLIXER). Physical and chemical properties are listed in Table 2.

Table 2. Physical and chemical properties of the bio-oil.

Property	Typical value	
Moisture, Vacuum oven	2 %	
Flash point	> 204 °C	> 400 °F
Density	0.9 kg/liter	7.5 lb/gal
Viscosity at 24 °C (75 °F)	0.05 Pa.s	50 cp
Insoluble	1 %	
Iodine value	115	

Reclaimed asphalt

The RAP used in this study was brought from one of the main roads in the city of Mosul, which connects the Al-Sukkar neighborhood intersection with the third bridge. This paving represents the binder asphalt layer and was created five years before its removal.

The aged asphalt was extracted from RAP using methylene chloride (CH_2Cl_2) as a solvent, according to the extraction test [23] and is shown in Fig. 2. The solvent methylene chloride was then separated from the aged asphalt using a rotary evaporator according to [24], as shown in Fig. 3. Research revealed that the centrifuge method was a reasonably safe and effective cold extraction technique [25]. Physical tests were conducted on the aged extracted asphalt, and the results are listed in Table 3.

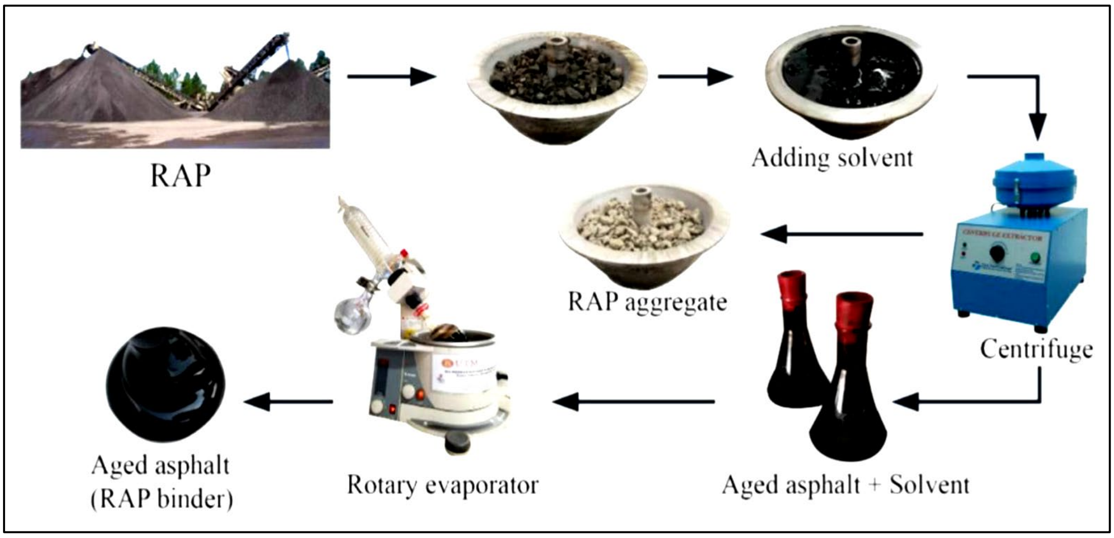

Figure 2. The process of extracting aged asphalt.

Figure 3. Rotary evaporator device.

Table 3. Physical properties of the aged asphalt binder.

Physical Properties	Value	Unit	Test Condition	SCRB Specification 2003	ASTM
Penetration	19.7	1/10 mm	25 °C, 100 gm, 5 sec	40–50	D5
Ductility	21	cm	25 °C, 5 cm/min	> 100 cm	D113
Softening point	67	°C	Ring & ball	–	D36
Rotational viscosity	1433	CP	135 °C	–	D4402
	986.1	CP	165		

2.2. Methods

Mixing bio-oil with VA and RAP

VA and RAP were placed in the oven at a mixing temperature of 150 °C for 60 min. Then, the samples of 30 % RAP with 70 % VA were placed at 150 °C in a shear mixer, and bio-oil was added in different proportions to VA and RAP and mixed at a rotational speed of 1000 rpm for 20 min [26], as shown in Fig. 4.

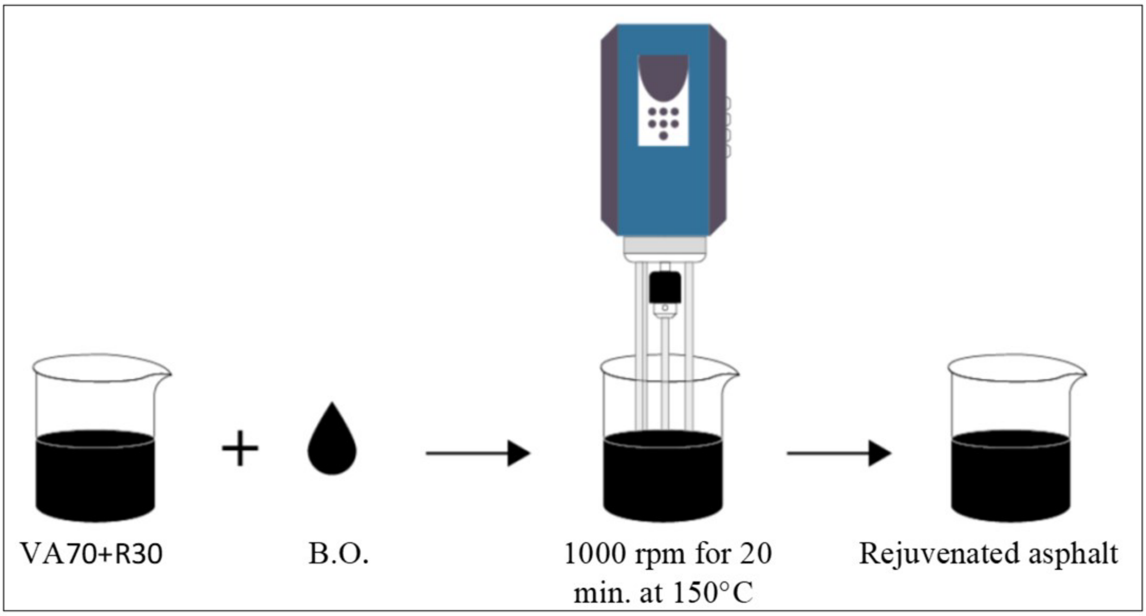

Figure 4. Preparing rejuvenated asphalt using high shear mixer.

Penetration, softening point, ductility and rotational viscosity tests

The penetration test was conducted according to [27] on different samples of VA and RAP (70 % of VA with 30 % of RAP), and several percentages of bio-oil (1 %, 2 %, 3 % and 4 %). The penetration test indicates the uniformity and resistance to deformation of the asphalt at 25 °C.

The softening points of different types of asphalt samples were examined according to [28]. The softening point test measures the temperature sensitivity of the binder when the temperature is increased at a heating rate of 5 °C/min.

The ductility test was performed on different asphalt samples according to [29]. This test is used to determine the elongation characteristics of asphalt binders, which must not be less than 100 cm for the asphalt to be considered successful and in compliance with the specifications.

Viscosity, which is the flow resistance that greatly affects the pumpability, mixability and workability of the binder, was measured using a rotational viscosity test that was performed on a variety of asphalt samples according to [30]. In this test, a cylindrical spindle with a specific diameter and effective length rotates inside a container filled with asphalt binder at a limited speed according to the specifications. The viscosity of the samples was measured at 135 °C and 165 °C.

3. Results and Discussion

Penetration

Fig. 5 shows the penetration results at different percentages of bio-oil. The results indicate that higher the percentage of bio-oil in the mixture leads to greater the penetration values due to the low viscosity of the bio-oil, which reduces the viscosity of the mixture and thus increases penetration [31, 32]. As shown in Fig. 5, the penetration value of 2 % is close to the penetration value of VA and falls within the limits of 40–50 grade specification.

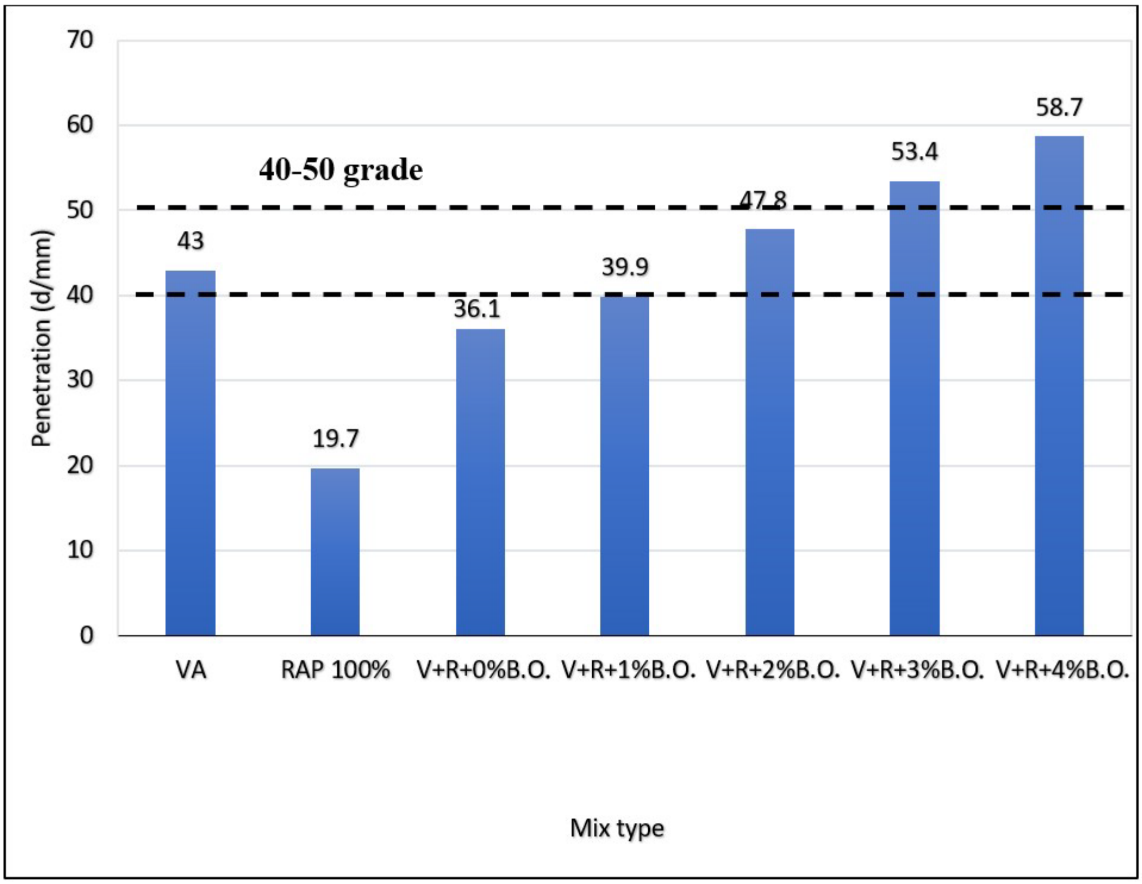

Figure 5. Penetration at different percentages of bio-oil (B.O.).

Softening point

Fig. 6 shows the softening point results at different percentages of bio-oil. The results indicate that the softening point of RAP was measured at 67 °C, a high value resulting from asphalt hardening with age. The softening point decreases consistently with increasing bio-oil content due to the increased sensitivity of the binder to temperature, when adding greater amount of bio-oil chemicals in bitumen, which reduces its softening point [33, 34]. Fig. 6 shows that the softening point value at 1 % is close to the softening point value for VA. It may be close to the optimal value of bio-oil that achieves regeneration of aged asphalt.

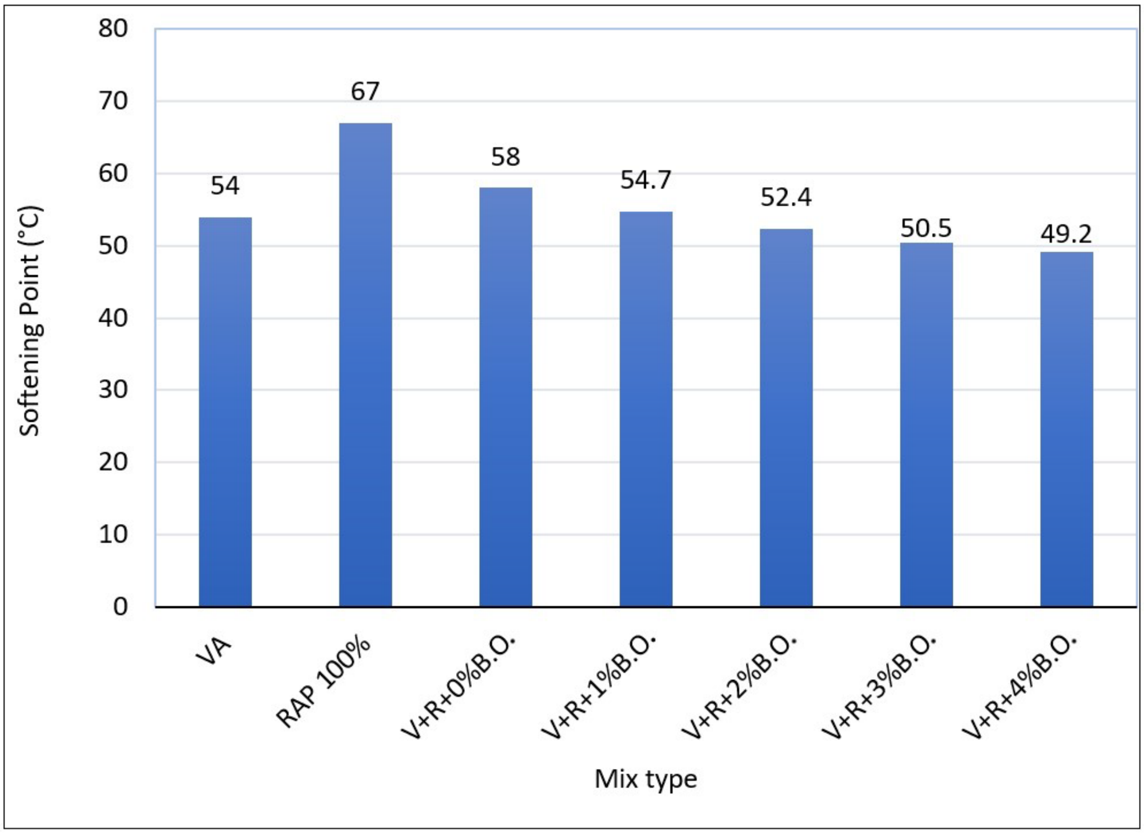

Figure 6. Softening point at different percentages of bio-oil (B.O.).

Ductility

Fig. 7 shows that the ductility value for RAP is 21 cm, which is less than the standard minimum of 100 cm. With the increase in the percentage of bio-oil in the bitumen, the ductility of the binder increases, thus improving the elongation properties of the aged binders and reducing the possibility of asphalt cracking at 25 °C. However, the ductility value begins to decrease, when the bio-oil content is more than 3 % due to reduced viscosity and increased sensitivity to temperature [33–35]. Notably, at 1 % bio-oil content, ductility exceeds 100 cm, meeting specifications and effectively rejuvenating the mixture.

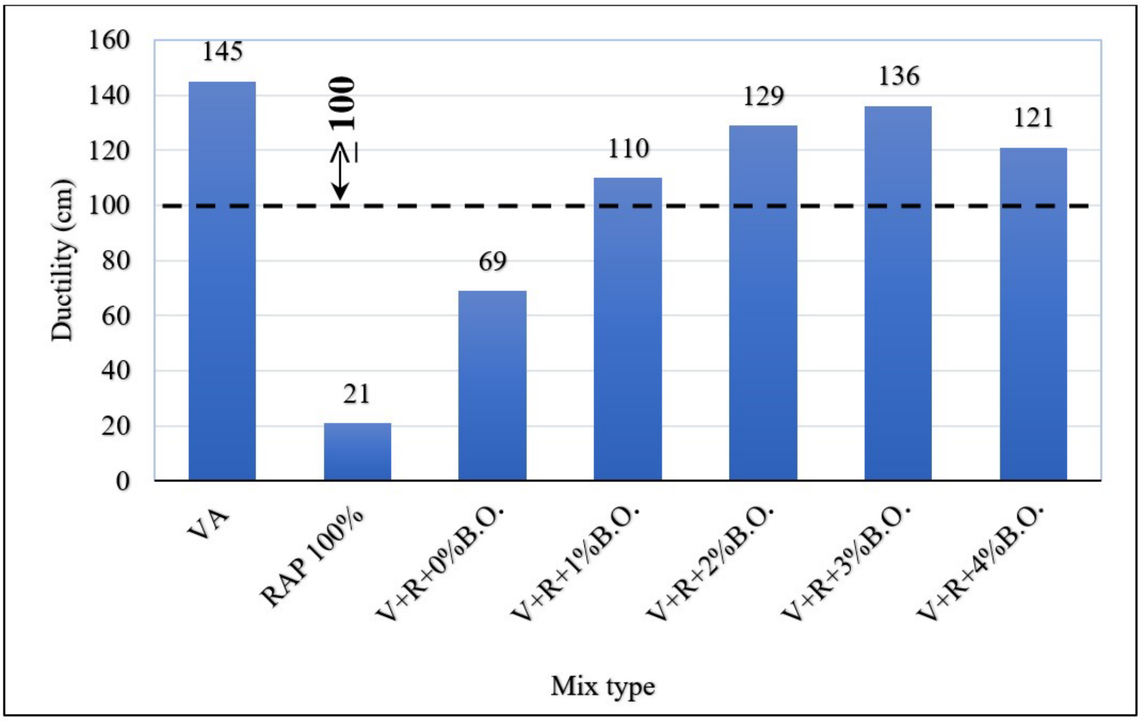

Figure 7. Ductility at different percentages of bio-oil (B.O.).

Rotational viscosity

Fig. 8 shows the results of the rotational viscosity test at different percentages of bio-oil. Compared to VA, RAP samples showed much higher viscosity. This viscosity increase in aged asphalt primarily results from changes in the asphaltene-to-maltene ratio during aging, which alters the internal structure of the asphalt [36]. This supports the results of the softening point and penetration tests. When 70 % VA with 30 % RAP was added, the mixture showed a reduction in the viscosity with further decreases observed at higher bio-oil percentages. Adding a large amount of bio-oil to the asphalt mixture may lead to a decrease in service performance, as the binder with low viscosity will be more susceptible to corrosion at the service temperature of the road, while the binder with high viscosity will be more susceptible to thermal cracking [37].

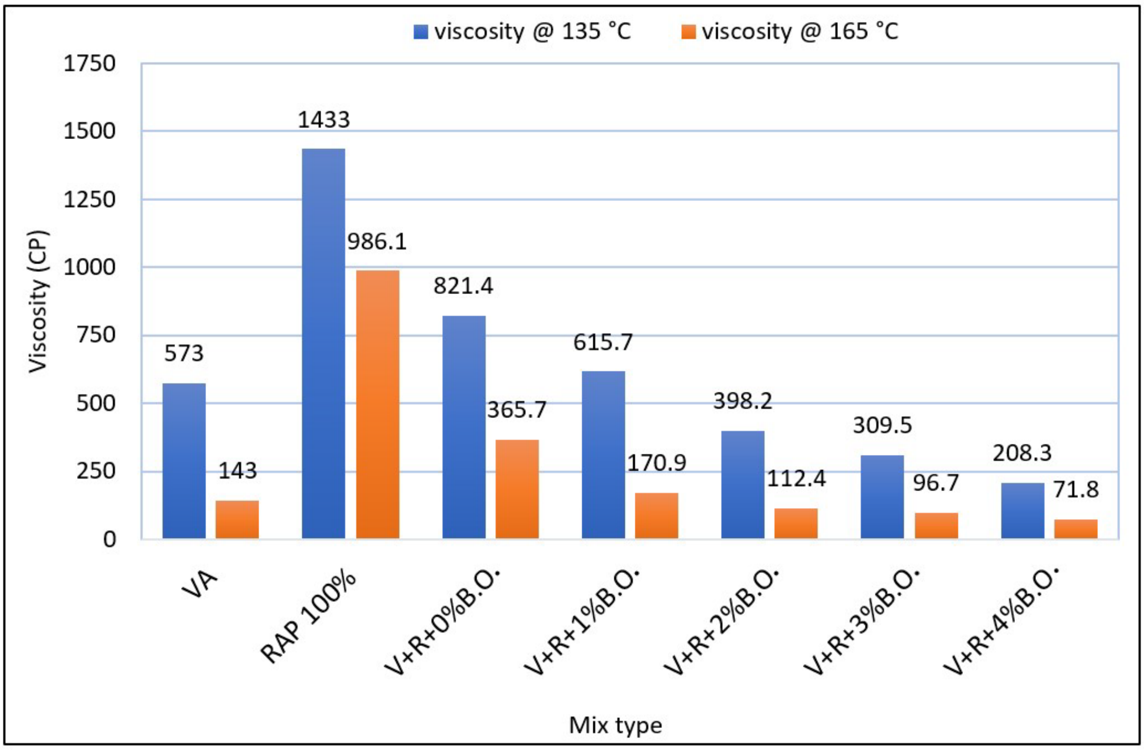

Figure 8. Rotational viscosity at different percentages of bio-oil (B.O.).

Finding the optimal ratio of bio-oil

To find the optimal percentage of bio-oil for rejuvenating aged asphalt to VA property, we compared penetration and softening point values (Figs. 10 and 11).

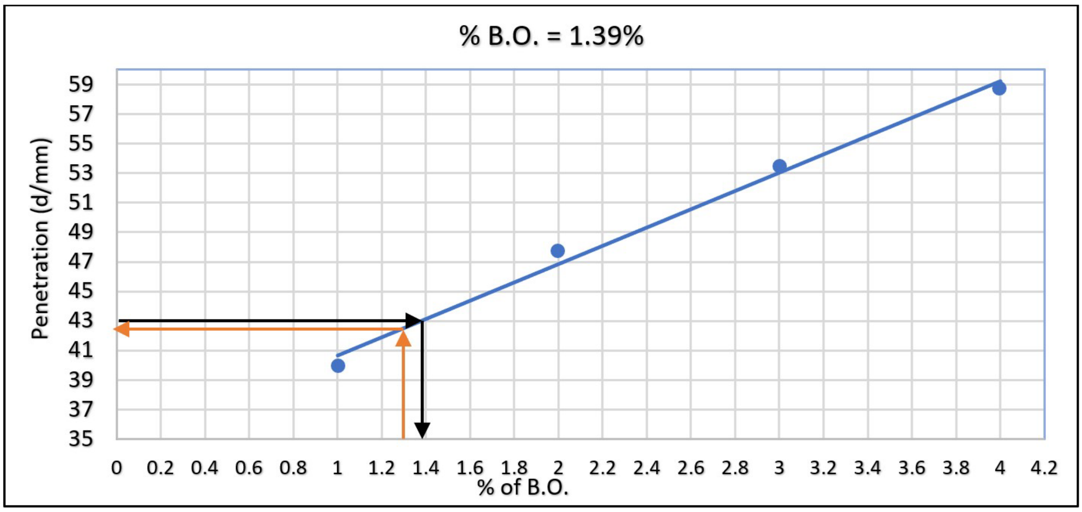

Figure 10. Penetration at different percentages of bio-oil (B.O.).

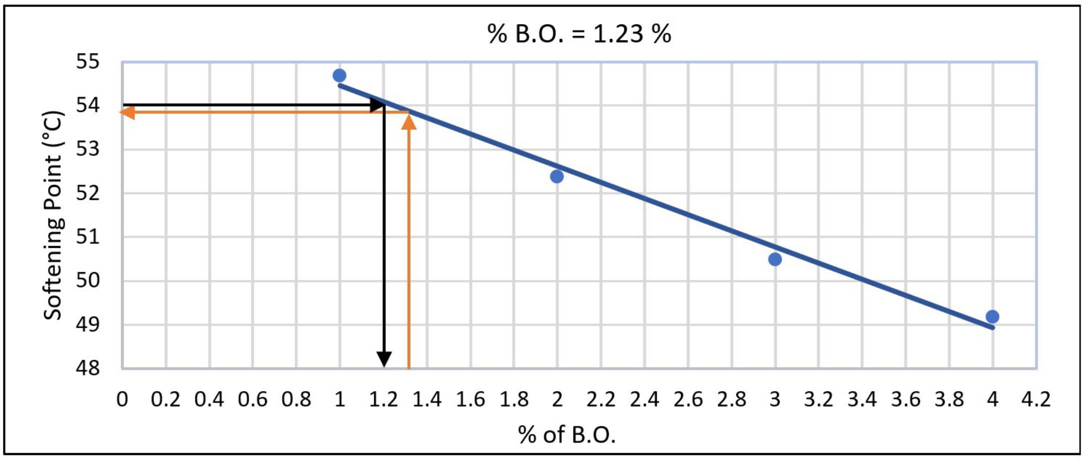

Figure 11. Softening point at different percentages of bio-oil (B.O.).

The optimal bio-oil percentages were 1.39 % for penetration and 1.23 % for softening point, yielding an average of 1.31 %. This value was then applied to all test plots (Figs. 12 and 13) and corresponding physical properties (Table 4).

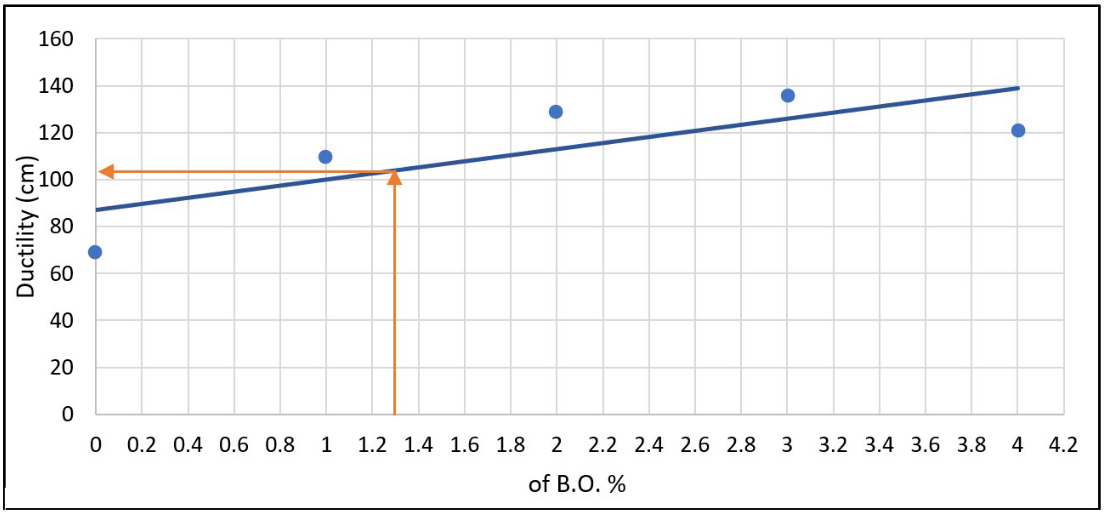

Figure 12. Results of the ductility for the optimal bio-oil percentage.

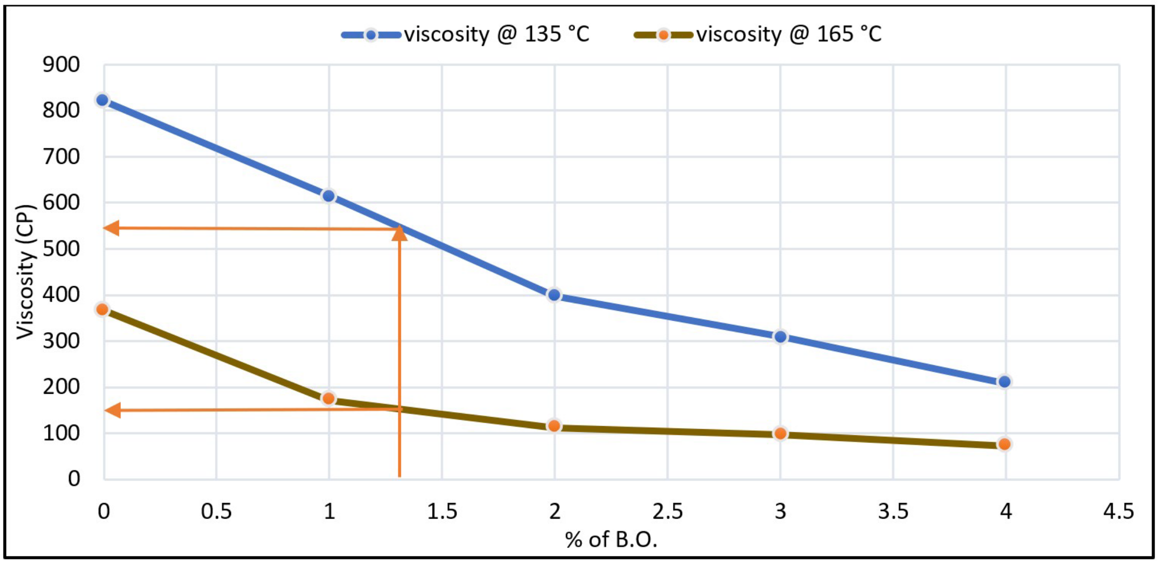

Figure 13. Results of the rotational viscosity for the optimal bio-oil percentage.

Table 4. Physical properties at the optimal bio-oil value.

Physical property	Bio-oil value
Penetration, d/mm	42.8
Softening point, °C	53.9
Ductility, cm	105
Rotational viscosity, CP	550
	150

Adding 1.31 % bio-oil to the mixture consisting of 70 % VA and 30 % RAP increases the penetration and ductility of the asphalt binder by 15.6 % and 34 %, respectively. It reduces the softening point by 7 % and viscosity at 135 °C and 165 °C by 33 % and 58 %, respectively. These results demonstrate that bio-oil addition effectively softens the asphalt mixture and enhances binder performance characteristics.

4. Conclusions and recommendations

This study investigated the physical properties of asphalt binder (70 % VA and 30 % RAP) modified with different percentages of bio-oil. Based on the results, the following conclusions can be drawn:

- The penetration and ductility values of RAP asphalt decrease by 54.2 % and 85.6 %, respectively, compared to VA. Meanwhile, its softening point increases by 24 %, and viscosity values rise by 150 % and 590 % at 135 °C and 165 °C, respectively. These changes result from the increased viscosity of aged asphalt, loss of binding properties, temperature variations and high traffic loads that cause hardening and brittleness, leading to road cracking and surface deterioration.
- Adding 1.31 % bio-oil to VA and RAP mixture increases penetration and ductility by 15.6 % and 34 %, respectively. It reduces the softening point by 7 % and viscosity at 135 °C and 165 °C by 33 % and 58 %, respectively. These improvements demonstrate that bio-oil effectively restores aged asphalt properties, including flexibility, viscosity and temperature tolerance, making it suitable for reuse in road construction.

These findings align with previous studies showing improved physical properties of asphalt treated with bio-oil composed of other bio-based materials [38–41].

Future studies should examine the performance of bio-oil rejuvenators in RAP mixtures for asphalt paving applications.

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