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Laboratory Characterization of Asphalt Binders Modified with Waste Engine Oil (WEO) and Crumb Rubber Modifier (CRM)

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ABSTRACT

Bitumen is a standard material for road infrastructure that is black in color, sticky, and thermoplastic in nature. It is well-known for its many applications. Due to rising traffic, global warming, and the constant introduction of new pavement varieties, forecasting road life has become increasingly complex in recent years. At the same time, a significant quantity of vehicle tires and waste engine oil (WEO) from different cars are dumped into the environment as hazardous waste. Additionally, it has been challenging to manage heavy metals and the substantial costs associated with their sustainable treatment. Therefore, this study looks at how Waste Engine Oil (WEO) and Crumb Rubber Modifier (CRM) affect the characteristics of PEN60-70 asphalt binder. The asphalt binder has been subjected to several tests at different temperatures due to the use of various concentrations of CRM and WEO. To reduce the usage of virgin bitumen (VB) and make bitumen a sustainable material, this study investigates modified bitumen using a waste crumb rubber modifier (CRM) combined with WEO. These WEO concentrations (5% and 10%) and CRM concentrations (0%, 4%, 8%, and 12%) were used in the characterization of modified bitumen, and then the characteristics of virgin and modified bitumen were compared. According to the study, adding WEO to CRM-modified binders reduces softening points by increasing penetration, as well as viscosity and workability, while CRM enhances rutting resistance. Nevertheless, the incorporation of WEO has a detrimental effect on the binder's ability to resist rutting. The study's findings also indicate that the use of WEO and CRM can enhance the resilience of asphalt mixtures to low-temperature cracking. According to the study's findings, adding WEO to co-modify CRM binders significantly reduced their softening point and viscosity values, making them easier to work with. Ultimately, the modified asphalt was found to exhibit positive rheological and physical modifications in the bitumen.

1. Introduction

Asphalt is widely utilized as a road surface material due to its desirable properties, including viscoelastic behavior, smooth texture, and ability to adhere to aggregate when combined. Aging affects the hardening process and renders asphalt brittle due to the intricacy of its chemical composition.

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Asphalt fatigues weaken with age due to temperature shrinkage stress, hydrodynamic stress, and other factors [1]. However, refinery development and petroleum product extraction degrade asphalt binders. Moreover, when traffic volumes and dynamic pressures increase, additional structural defects emerge, such as fatigue fractures, rutting, spalling, and even low-temperature thermal cracking [2].

In reaction to changes in temperature and load, asphalt binder viscoelasticity can be either linear or nonlinear [3]. Asphalt binders with a greater viscosity are more resistant to detected faults, such as rutting. Conversely, the glass transition phenomena will impact the stiffness characteristics due to molecular alterations in asphalt at lower temperatures. The susceptibility of aged asphalt binders to fracture under low temperatures and varying dynamic loads is well-documented since the viscosity of these binders tends to rise due to the conversion of saturates into asphaltene [4].
Asphalt modification has been investigated for decades to increase asphalt binders' resistance to diverse loads [5-6]. Several previous investigations have shown that crumb rubber, polymers, and rubber latex can improve the performance of bituminous mixtures used in road pavements. [7- 8].

Researchers are consistently motivated to explore the feasibility of using various waste materials as additives to bitumen in the hot mix asphalt (HMA) sector. Significant motivators for them included the fact that conventional bitumen is very expensive and the rigorous limitations enforced by environmental authorities. [9-11].

Daily, several items composed entirely or partially of plastics are used and then disposed of as waste afterward. The wrong way to eliminate this plastic waste has become a significant problem, especially in cities, due to overuse, clogged sinks, improper disposal, and aesthetic concerns. Plastic may take anywhere from a few days to many years to degrade into a form that nature can utilize, depending on its quality. As a result, plastics are recognized as the most environmentally hazardous waste materials, and they must be recycled rather than disposed of in landfills. [7, 9, 12]. Adding CRM makes the asphalt more flexible and less likely to fracture and rut when subjected to heavy loads and sweltering heat. The road surface's higher resilience is partly due to the increased flexibility of the asphalt, which also adds to the road's longer lifespan [13]. Adding CRM to asphalt binder may improve the material's overall quality. This is accomplished through numerous enhancements, including increased adaptability, longevity, and resilience against rutting, fracture, and deformation when subjected to demanding loading conditions. Furthermore, the integration of CRM can improve the cohesive characteristics of the asphalt binder [14]. CRM granular is a well-known asphalt modification in the market (15), and it has been shown to improve road surface performance (16).

In addition, the illicit disposal of waste lubricants presented an additional obstacle for investigators considering their recycling in the HMA industry. Vegetable oil waste has become a significant environmental contaminant due to its potential to pollute rivers and land resources. [9]. A co-modifier can significantly enhance thermal fracture resistance by minimizing the increase in stiffness at lower temperatures [17]. Asphalt binder can be revitalized by adding oil compounds, thereby improving its characteristics and reducing reliance on high solubility and permeability rates [18]. Low temperatures can cause engine oil, a byproduct of the refining process, to lose some of its viscosity and stiffness [19]. Recent research has shown that oil-based additives can enhance the adhesion between aggregates and asphalt, leading to a more durable road surface [20-21]. The effects of employing WEO as a co-modifier with different primary modifiers at various temperatures require more study. However, the use of waste engine oil has a significant impact on asphalt binder shear load, adhesion, and glass transition [22].

This research aims to evaluate the properties of asphalt binders treated with CRM in combination with waste engine oil as a co-modifier. This study investigated the impact of CRM and residual waste engine oil concentrations on the penetration, softening point, and viscosity of asphalt binders. Asphalt binders with different CRM and waste engine oil concentrations were investigated for rheology and cracking during short- and long-term ageing in RTFO [23] and PAV [24] Tests. The rotating viscometer (RV) tested better asphalt binders at high temperatures and compared CRM and waste engine oil contents.

The original and short-term aged states after RTFO were tested for rutting resistance using a dynamic shear rheometer (DSR) and compared based on modifier and co-modifier content. Modified asphalt binder fatigue cracking was tracked over time. DSR evaluated fatigue cracking at 25°C.

2. Experimental Program

2.1 Materials

The original binder used in the study had a penetration grade of 60/70 and was intended to be modified with CRM and WEO. The characteristics of the base binder are presented in Table 1. The granular sieve analysis of the CRM modifier is shown in Table 2. WEO was a black and brown oily liquid used in this study. It was retrieved directly from a garage and used without any special treatment. The WEO used had a specific gravity of 0.89, a viscosity of 52 mPa · s, and a water content of 0.34%. Because CRM improves asphalt binder viscosity, WEO is supposed to diminish it at low temperatures.

Table 1. The characteristics of base asphalt binder PEN 60/70.

Aging States	Test Properties	Result
Unaged	Penetration (0.1 mm)	66
	Softening Point (°C)	52
	Viscosity at 135 °C (mPa•s)	415
	G*/sin δ at 70 °C (kPa)	1.22
RTFO Aged Residual	G*/sin δ at 70 °C (kPa)	2.5
RTFO + PAV Aged Residual	G*sin δ at 25 ◦C (kPa)	4600

Table 2. CRM gradation was employed in this study.

Sieve No. (mm)	% Passing	% Cumulative Passing
30 (600)	100	100
40 (425)	91	91
50 (300)	69.8	60.8
80 (180)	65.4	26.2
100 (150)	91.7	17.9
200 (75)	82.1	0

2.2 Asphalt Binder Modification Using CRM-WEO

The basic binders were directly combined with CRM and WEO to make asphalt binder samples. The mixing temperature was set at 170°C, with a tolerance of 5°C. After reaching the desired temperature at 700 revolutions per minute, WEO was added and blended for 10 minutes. It was carefully managed to avoid boiling the binders and losing their original properties, damaging the mixing process and causing the components to congeal. WEO was used at 5% and 10% of the basic binder sample weight. The addition of CRM to the WEO asphalt binder was carried out at elevated temperatures due to the enhanced penetration properties exhibited by WEO. The CRM was introduced into the mixing process after 10 minutes, with three distinct concentrations of 4%, 8%, and 12% relative to the weight of the sample. After adding the CRM, 30 minutes of blending were sufficient to prepare the samples.

The samples were artificially aged in both the short-term and long-term. The short-term aging process required 85 minutes in a rolling thin film oven (RTFO) at 163^{O}C. After that, the sample underwent a 20-hour thermal treatment in a pressure-aging vessel (PAV) at 100^{O}C and 2.1 MPa of pressure. After artificially aging the samples, the experimental design flowchart was used to assess asphalt binders modified with CRM-WEO.

2.3 Tests of Basic Properties

The study evaluated the physical parameters of WEO and CRM-rejuvenated asphalts using ASTM-D5 [25], D36 [26], and D4402 [27] tests, including penetration at 25°C, softening point, and rotational viscosity at 135 and 165°C. Two samples of each modified asphalt binder composition were tested for rotating viscosity at temperatures ranging from 135°C to 165°C. To evaluate asphalt mixture workability, a cylindrical spindle number 27 with a rotation speed of 20 rpm was used. To gather data reliably, a 20-minute test period was set for each sample.

The rheological properties of asphalt binders were measured and determined using the complex shear modulus (G*) and sine of the phase angle (δ) at 70°C for each sample and then finding G*/sinδ. [28]. G* and sinδ were measured, and G*sinδ calculated at 25°C. To calculate an average, three samples of WEO and CRM were examined.

3. Results And Discussion

3.1 Penetration Test Result

The penetration test findings demonstrated how WEO impacted the bitumen's stiffness with CRM, showing that penetration decreased as the CRM percentages increased. The reduction in penetration is attributed to an increase in bitumen hardness resulting from the addition of CRM, which can be attributed to a change in phase in the binder due to the addition of CRM, leading to increased internal resistance. A large volume of oil softens the binder by reducing the hardness of the bitumen and the dose of small CRM. The 5% WEO binder penetration values with 4%, 8%, and 12% CRM are 105 mm, 97 mm, and 83 mm, respectively. While the penetration values of the 10% WEO binder with 4%, 8%, and 12% CRM are 175mm, 152mm, and 131mm, respectively. It was discovered that the binder containing 10% WEO had the maximum penetration results due to the high quantity of WEO. The penetration result is shown in Figure 1. These findings are consistent with prior research [29-30].

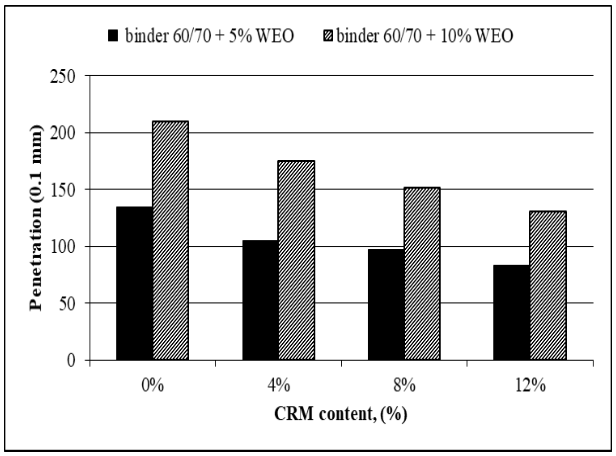

Figure 1. The Penetration values of CRM-WEO modified asphalt binder.

3.2 Softening Point Results

Figure 2 shows that the asphalt binder's softening point and penetration improve with CRM, allowing it to be utilized at higher temperatures. The CRM-WEO bitumen matrix demonstrates the absorption of light viscous components of bitumen by CRM, reducing radical content. The anti-oxidant and anti-ozone properties of the CRM-WEO modified binder were improved by adding the CRM anti-oxidant and anti-ozone agent. Because of these two factors, the CRM-WEO modified binder had a greater softening point and better anti-oxidative capability [31-32].

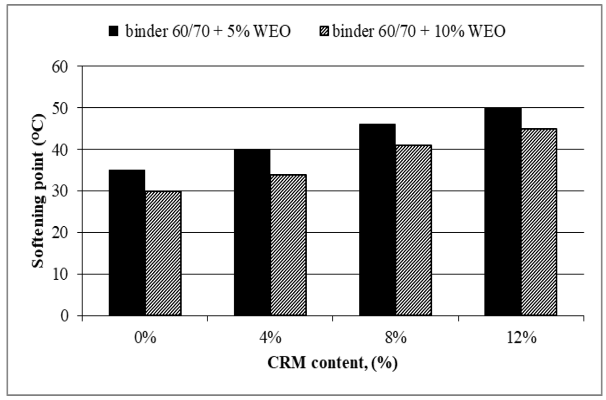

Figure 2. The softening point values of CRM-WEO modified asphalt binder.

3.3 Rotational Viscosity

Understanding binder viscosity is crucial because it affects the ability of coated aggregates to be heated and combined, as well as their capacity to be compacted into a new pavement [33]. Figures 3 and 4 depict the results of the typical RV test for 5% and 10% WEO-modified asphalt binder containing 4%, 8%, and 12% CRM at 135 and 165°C, respectively. At the specified temperature, figure 3 depicts the viscosity of asphalt-modified binder with 5% WEO and 4%, 8%, and 12% CRM. At a temperature of 135°C, the viscosity values were recorded as 597, 1045, 1300, and 1700 mPa.s for 0%, 4%, 8%, and 12% CRM at the identical temperature. Figure 4 demonstrates the viscosity measurements of binders modified with 10% WEO and 0%, 4%, 8%, and 12% CRM, which were 466, 725, 930, and 1000 mPa.s, respectively. Raising the WEO content from 5% to 10% at the same temperature resulted in 22, 31, 29, and 41% reductions for binders containing 0, 4%, 8%, and 12% CRM, respectively. By increasing the temperature to 165°C, the viscosity of all CRM contents decreased due to an increase in WEO from 5% to 10%. Modified asphalt binder with 10% WEO containing 0%, 4%, 8%, and 12% CRM had 24%, 28%, 20%, and 31% reduced viscosity than 5% WEO.

The WEO and CRM viscosity measurements were statistically compared at a specified temperature range. Changes in WEO content and CRM were utilized to determine the significance of temperature variations. The results indicate that used WEO has a high level of penetrability and the potential to reorganize the molecular chain of asphaltene, thereby increasing its workability. The molecular structure and intermolecular interactions present within the network of asphaltene molecules largely influence the rheological characteristics of an asphalt binder. The CRM-modified asphalt binder penetrates the asphaltene network when WEO is present, resulting in improved flexibility and reduced viscosity. The viscosity decrease is necessary to achieve Superpave specifications [33], as seen in Figures 3 and 4. All modified asphalt binders had viscosities under 3000 mPa.s. These characteristics are functional for WEO with a wide variety of modifiers.

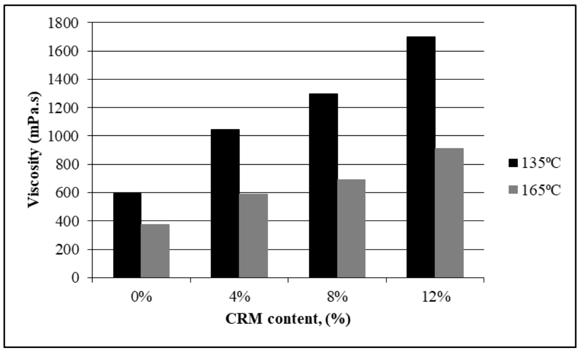

Figure 3. The relationship between the CRM concentration and the viscosity of asphalt binder containing 5% WEO.

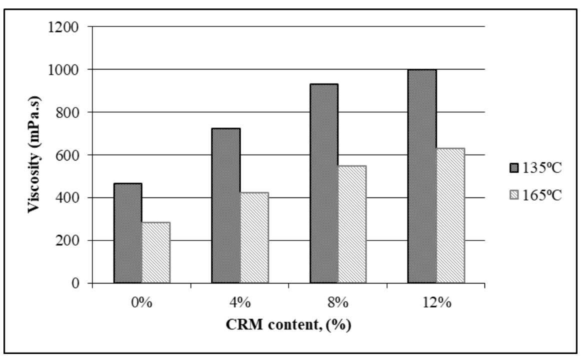

Figure 4. Asphalt binder viscosity values as a function of CRM content, using 10% WEO.

3.4. Rutting Properties

Larger levels of G*/sinδ, as specified in the Superpave Specifications, can provide greater rutting resistance and efficacy. G*/sinδ values were recorded at 70°C in the original state and the short-term aging state (RTFO). The DSR findings for modified asphalt binders in their original form are shown in Figure 5. The G*/sinδ values of 5% and 10% WEO-containing modified asphalt binders showed that CRM increased their resistivity, even though WEO considerably reduces their viscosity and rutting resistivity. The CRM promotes rutting resistance, while WEO enhances the workability of modified asphalt binders. Figure 5 shows that adding CRM to a modified asphalt binder with 5% WEO raised G*/sinδ values by 194%, 305%, and 465% at 4%, 8%, and 12%.

When 4%, 8%, and 12% CRM were added, the G*/sin δ values of the modified asphalt binder containing 10% WEO increased by 188%, 208%, and 534%, respectively. Adding WEO to asphalt binder modified with CRM can alter the molecular properties, thereby influencing its rutting behavior. The rutting characteristics of asphalt binders are contingent upon their interactions with the matrix and their capacity to uphold structure and strength when subjected to a load. The amount of WEO added to asphalt binders can influence their viscosity, stiffness, and durability by altering their molecular structure and interactions. Waste engine oil can potentially interfere with the intermolecular interactions present among asphalt binder molecules, reducing the viscosity of the binder. As a result, the reduction in viscosity may result in a loss in the binder's capacity to withstand rutting.

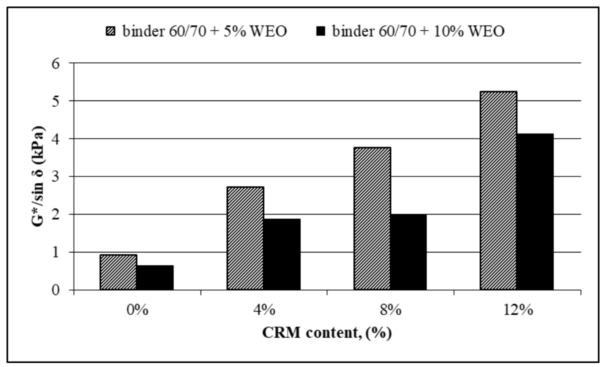

Figure 5. The relation between the G*/sinδ of WEO- asphalt binder and the amount of CRM at 70°C.

Figure 6 displays the G*/sinδ values for modified asphalt binders aged over a short-term aging with 5% and 10% WEO and 0%, 4%, 8%, and 12% CRM. The G*/sinδ values increased 56%, 69%, and 168% upon adding 4%, 8%, and 12% CRM to the modified asphalt binder containing 5% WEO, respectively. The modified asphalt binder with 10% WEO increased G*/sinδ values of 12%, 88%, and 149%, respectively, when 4%, 8%, and 12% CRM were added. Figure 6 demonstrates that adding CRM influences the increase in rutting resistance, whereas WEO enhances the workability and management of asphalt binders.

Generally, the rutting behavior of the binder is significantly influenced by the chemical interactions between WEO and asphalt binder molecules.

Understanding these interactions is crucial for predicting the field conditions of modified asphalt binders and selecting suitable additives to enhance their properties.

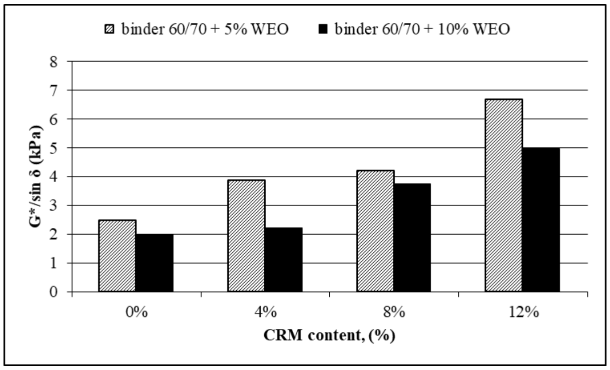

Figure 6. The G*/sin δ value of WEO-modified, short-term aged asphalt binder versus CRM concentration at 70°C.

3.5. Fatigue Cracking

The DSR test, measuring G*sinδ, assessed fatigue cracking in aged modified asphalt binders. G indicates stiffness, while δ reflects viscosity and elasticity. At 25°C, both modified binders were evaluated in 5% and 10% WEO containing 0%, 4%, 8%, and 12% CRM. The G*sinδ of all binders is depicted in Figure 7. The modified asphalt binder, which comprised 5% WEO and different levels of CRM (4%, 8%, and 12%), had G*sinδ values that were reduced by 20%, 54%, and 74%, respectively. The G*sinδ values were decreased by 14%, 55%, and 77% for the CRM ratios of 4%, 8%, and 12%, respectively, in a modified asphalt binder with 10% WEO. Asphalt pavement suffers from fatigue fracture as a result of the binder being loaded and unloaded repeatedly under traffic. This eventually results in pavement failure. Used WEO may degrade asphaltene molecules' intermolecular connections, making them more brittle and fatigue-prone. The high penetration rate of residual WEO rearranges the asphaltene molecular network, resulting in a decrease in G*sinδ, which increases fatigue fracture resistance. Even though adding WEO to asphalt binders makes them less resistant to rutting, adding CRM to asphalt binders makes them much more resistant to rutting. Including WEO in the CRM binder has resulted in a drop in the G*sinδ values. Furthermore, the content of 5% WEO with varying ratios of CRM (4%, 8%, and 12%) exhibited corresponding reductions of 20%, 54%, and 74%. By contrast, the 10% WEO-modified asphalt binder reduced G*sinδ by 14%, 55%, and 77%, respectively.

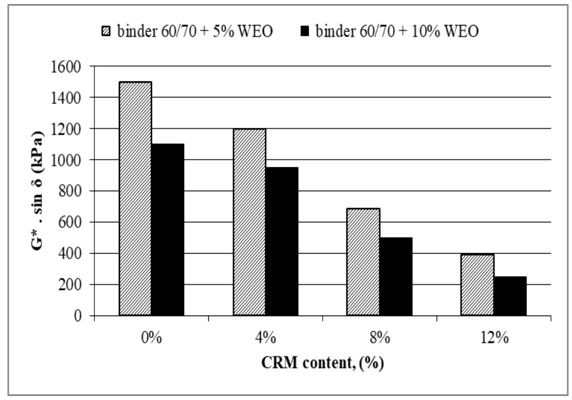

Figure 7. At 25 °C, G*sinδ of RTFO+PAV aged binder with WEO as a function of CRM content.

4. Conclusion

Based on the results of the suggested lab test analysis, the following are the most critical comments and conclusions:

1. As CRM% increases, the modified asphalt binder's softening point increases while penetration decreases.
2. Adding CRM to asphalt binders increases viscosity, but adding WEO decreases it. Due to the effect of WEO on asphaltene molecules, modified asphalt binders containing 10% WEO are less viscous than those containing 5% WEO. The presence of WEO leads to an elevation in molecular elasticity, thereby decreasing viscosity. The binder's performance at high temperatures and flow properties improve as the amount of WEO contained increases. The interaction between WEO and asphaltene molecules yields a stable, low-viscosity system that enhances the rheological properties of the modified asphalt binder.
3. The DSR test showed that WEO coupled with 5% and 10% oil enhances asphalt binder rutting resistance more than CRM alone. The findings indicate an enhancement in the performance at elevated temperatures, accompanied by a reduction in the likelihood of rutting. This is because the asphaltene molecules in the binder have been rearranged by the WEO, making it more elastic and less viscous. The probability of rutting decreases as the system becomes more stable and operates more efficiently overall.
4. According to the fatigue test results, adding CRM and WEO enhanced the flexibility of the asphalt binder and reduced the chance of

cracking. This was caused by the rearrangement of bitumen molecules by WEO, which made the binder more flexible. The increased level of flexibility is crucial in determining the asphalt binder's overall performance and durability.

5. It's essential to achieve the right balance between the two materials since too much of either can cause rutting, thermal cracking, and a decline in the asphalt softening point.

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