СРПСКО ДРУШТВО ЗА ПУТЕВЕ 1934

Пут и саобраћај
Journal of Road and Traffic Engineering

Journal homepage: www.putisaobracaj.rs

Effect of Chemical Composition on Rheological Properties of Asphalt Binders Modified with Rap Binders and Rejuvenator

Enobong Okon Inyang[a], Idorenyin Ndarake Usanga[b], Kufre Primus Okon[a], Sunday Asuquo Saturday[a], Edidiong Okon Mkpa[a]

[a] *Department of Civil Engineering, School of Engineering Akwa Ibom State Polytechnic, Ikot Osurua, Ikot Ekpene, Akwa Ibom State, Nigeria*
[b] *Department of Civil Engineering, Akwa Ibom State University, Ikot Akpaden, Akwa Ibom State, Nigeria*

ARTICLE INFO

DOI: 10.31075/PIS.70.03.03
Professional paper
Received: 14.07.2024.
Accepted: 28.07.2024.
Corresponding author:
enobong.okon@akwaibompoly.edu.ng

ORCID ID
Enobong O. Inyang:0009-0001-5751-020X
Idorenyin Ndarake Usanga: N.A.
Kufre Primus Okon: N.A.
Sunday Asuquo Saturday: N.A.
E. O. Mkpa: N.A.

Keywords
Reclaimed Asphalt Pavement (RAP)
Diesel engine waste oil (DEWO)
Modified binder (MB)

ABSTRACT

Conventional rejuvenating agents such as virgin binders, polymers and so on, poses environmental, technical, and economic challenges. The objective of this study is to investigate the interaction between chemical components and rheological behavior of hot mix asphalt modified with RAP binder and diesel engine waste oil (DEWO) as rejuvenator. 7.2% DEWO was added to the RAP binder to achieve the modified binder (MB), and the effects of the rejuvenator through the MB were evaluated at varying percentages (0 to 100% by weight of the virgin binder) using Dynamic Shear Rheometer (DSR) under short and long-term aging at high and intermediate temperatures, as well as low temperatures using Bending Beam Rheometer (BBR). Saturates, aromatics, resins, and asphaltenes (SARA)-separation, Indirect tensile stiffness modulus test (ITSM), and fatigue life test were also employed to investigate the interaction between chemical components and rheological properties of binder. Results indicated that incorporating 50% modified RAP binder significantly enhanced the performance of the asphalt mixtures, it was also discovered that 100% of RAP content meets standard specifications when modified with oil rejuvenators. This research suggests that large quantities of diesel engine waste oil can be diverted from landfills and employed as useful resource in asphalt production.

1. Introduction

The wearing courses of road pavements have limited-service life periods, hence, frequent maintenance and rehabilitation M&R operations are necessary on the part of road authorities to guarantee adequate safety and comfort conditions for road users (Jiang, 2018.). These yearly operations carried out on the road networks result in the production of huge quantities of reclaimed asphalt pavement RAP. Therefore, RAP should be more and more envisaged as a secondary raw material for production of hot mix asphalt HMA. Considerable amounts of Reclaimed Asphalt binder are produced from the RAP every year. RAP binder is a 100% recyclable and useful material fit to be re-introduced into another cycle of HMA with little or no downgrading of its functionality (P. C. Boriack, 2014). In general, RAP binder rejuvenation introduces some positive changes in the rheological and chemical behavior of bituminous mixtures.

In recent years, the road construction industry has confronted several challenges, including rising costs of conventional materials, a progressive decline in natural resource availability, and significant environmental damage. These issues have considerably impeded the development of road pavement infrastructure, particularly in developing countries. As a result, pavement engineers have shifted their focus towards using recycled alternative materials derived from industrial waste (Kumbargeri, 2016). These materials, which include rejuvenators, offer a promising solution. This approach aims to reduce the substantial costs associated with infrastructure construction while addressing environmental and resource sustainability concerns.

Rejuvenators are characterized by their chemical composition and density (Behnood, 2019). This asphalt component can enhance the stability and density of the mixtures, lower the mixture temperature, reduce moisture susceptibility, and minimize voids in asphalt mixes when combined with asphalt binder (Laukkanen, 2015). Owing to the beneficial properties of rejuvenators in asphalt mixtures, pavement engineers and researchers have been inspired to investigate the potential of various industrial waste oils and vegetable oils as rejuvenators in hot mix asphalt (HMA). Among the waste oils being considered are waste motor oil (Joni HH, 2021), waste cooking oil (Asli), crumb rubber (Fakhri, 2016), waste vegetable oil (Cavalli, 2018), organic oil (Joni H. H, 2019), tail oil, waste engine oil (Huang, 2014). Findings have shown that modifying reclaimed asphalt bitumen with waste engine oils enhances both stability and stiffness, as well as the stability modulus, compared to the virgin mix.

Diesel engine waste oil DEWO is the spent oil from diesel engines after lubricating the engines for a useful specified period. It is a product from crude oil in the distillation window between 200 °C and 350 °C. It consists of approximately 75% aliphatic hydrocarbons ($C_{10}H_{20}$–$C_{15}H_{28}$) and about 25% aromatic hydrocarbons (e.g. benzene, styrene). DEWO is highly compatible with the chemistry of bitumen which contains a complex mixture of aliphatic compounds, cyclic alkanes, aromatic hydrocarbons, PAHs and heterocyclic compounds containing nitrogen, oxygen and sulfur atoms, and metals (e.g. iron, nickel, and vanadium) (CD., 2011). The DEWO is usually emptied from the diesel engine when they oil is less viscos and can no longer lubricate the engines as expected. There is undoubtedly increasing volume of waste diesel engine oil produced on daily bases from power plants, heavy duty equipment, etc. which can be used for large scale HMA production.

Although waste oils are most considered in studies on RAP rejuvenation; Shams M. (2020) studied two different aged asphalt binders modified by two different rejuvenators. He noticed that the mechanical properties of the modified binder were in between those of the virgin and aged binders. Moreover, aging and rejuvenation caused rheological changes to the binder, and the rejuvenator rarely returned the microstructures of the aged binder back to that of the virgin binder. They concluded that physical and rheological changes of the binder due to aging and modification are related to saturates, aromatics, resins, and asphaltene (SARA)-fractions changes.

Asli et al (2012) studied the physical properties of rejuvenated RAP binders at different temperatures (−20°C to 80°C) with dynamic shear rheometer (DSR) and differential scanning calorimeter (DSC) tests. Their study results showed dissimilar softening effects of rejuvenator and virgin asphalt binder on RAP binders. Furthermore, they found the same improvement in the flow property of the RAP binder due to adding vegetable oil base and maltene base rejuvenators.

Zaumanis et al (2014) conducted a comprehensive study focusing on the influence of six types of regenerators on Marshall stability and indirect tensile strength (ITS) in reclaimed asphalt mixtures. Their research involved varying proportions of virgin and old materials and different regeneration components, including used oil, used oil with crumb rubber, soft asphalt cement, and asphalt cement with sulfur.

Mamun et al (2018), explored the impact of WEO and waste vegetable oil (WVO) on the performance of recycled bitumen concrete mixes. Their research encompassed a wide range of RAP ratios, from 10 to 80%, regenerated with WEO and WVO. The results revealed significant improvements in Marshall stability for the recovered blends, demonstrating the effectiveness of rejuvenation.

Usanga et al., (2024) in a study prepared two hot asphalt mixes, one mix consisted of new aggregate and new asphalt bitumen, and the second one included new aggregate mixed with aged asphalt binder modified with waste oil, respectively. Six compacted samples were in a water bath experiment at 60ºC for each mix. It has been noticed from experiments that the modified mix had enhanced the Marshall stability over the "Control Mix". It has been proven that using modified RAP bitumen strengthens the HMA and makes it more solid.

Taylor et al (2014) in their research, focused on the influence of four types of rejuvenators which involve varying proportions of these rejuvenating agent which included cooking oils, crumb rubber etc. In his research, Asli et al (2012) also contributed by investigating the impact of varying RAP proportions ranging from 10-60% modified with waste cooking oil. The result recorded improvements in Marshall stability and Indirect tensile strength test.

The research done by Joni et al. (2021), extended asphalt studies to RAP proportions ranging from 10-80% using different rejuvenating oils. Their findings underscored high moisture damage control hence, establishing a significant advancement in sustainability. In another research, asphalt mixtures containing 25% RAP rejuvenated with condemn engine oil was examined. The result showed that even with the low bitumen content, the durability of the mixture was improved.

These findings suggest that waste oils can effectively modify RAP in asphalt mixtures, but these studies have not thoroughly analyzed the interaction of both the chemical components and the rheological properties of the modified asphalt mix. This is especially important considering the increasing periodic production of both RAP from M&R activities which needs to be recycled and DEWO from diesel engine maintenance which may constitute negative environmental impact like contaminating water bodies and landfills if indiscriminately disposed.

Therefore, this study aims to investigate the interaction between chemical components and rheological properties of hot mix asphalt modified with RAP binder and diesel engine waste oil (DEWO) as rejuvenator.

2. Materials

2.1. Virgin Bitumen

Bitumen with a 60/70 penetration grade was obtained from the Bulletin asphalt batching plant in Uyo, Nigeria. This grade is extensively utilized in bituminous mixtures in Nigeria because of its adaptability to a broad range of temperatures. The key physical properties of this bitumen, tested with three (3) samples each, are shown in Table 1.

Table 1. Physical properties of bitumen

Test	Standard Adopted	Value	Standard Requirement
Penetration at 25 °C (0.1 mm)	ASTM D5	66	60-70
Softening point (°C)	ASTM D36	49	min 46
Brookfield rotational viscosity at 135⁰C (MPa.s)	ASTM D4402	520	< 3000 mPa.s
Flash Point (°C)	ASTM D92	252	min 230
Specific gravity (g/cm³)	ASTM-D70	1.02	1.01 – 1.06

2.2. RAP Binder

RAP in this study was obtained from a road rehabilitation project site in Okobo, Nigeria. The extraction process of the RAP binder was as described in ASTM D2172 (2017b), and the recovery process was achieved using the rotary evaporator and Toluene as solvent in accordance with specifications in ASTM D5404 (2017a). its characterization is as given in Table 2.

Table 2. Physical properties of RAP binder

Test	Standard Adopted	Value
Penetration at 25 °C (0.1 mm)	ASTM D5	33
Ductility at 25°C(cm)	ASTM D113	54
Elastic recovery at 25°C (%)	ASTM D6084	17
Brookfield rotational viscosity at 135⁰C (MPa.s)	ASTM D4402	2283
Softening Point R&B (°C)	ASTM D936	56
Fraass breaking point (%)	EN12593	-6

2.3. Rejuvenator

An oil-rejuvenator was used to restore the properties of the RAP binder. The diesel engine waste oil DEWO in this study was collected from the power plant of a brewery in Uyo, Nigeria. Three percentages of RAP content (25%, 50%, 75%) were used to study the effect of rejuvenator on low medium, and high RAP contents. Based on the procedure recommended by Zaumanis (Zaumanis et al., 2014), the optimum dosage of the rejuvenator was defined as 7.2% by weight of RAP binder. The oil was sieved through #200 sieve in order to extract any particulate matter before it was then subjected to tests as described in Table 3.

Table 3. Physical properties of DEWO

Test	Standard Adopted	Value	Standard Requirement
Penetration at 25 °C (0.1 mm)	ASTM D5	46	40-50
Softening point (°C)	ASTM D36	41	----
Brookfield rotational viscosity at 135⁰C (MPa.s)	ASTMD4402	447	Min 400
Flash Point (°C)	ASTM D92	262	min 232
Specific gravity (g/cm³)	ASTM-D70	1.01	1.01 – 1.06

3. Method

3.1 Preparation of Binder

7.2% dosage of the rejuvenator by weight of the RAP binder was initially added to the extracted RAP binder. To ensure a uniform mixture, it was blended together for 30min at 1500C using a laboratory mixer of 1300rpm. The prepared samples were then set aside to cool at room temperature before preparing 3 specimens from each modified binder MB. To evaluate the effect of the rejuvenator on the RAP binder RB, another sample containing 100% MB was also prepared. Finally, 3 control specimens were prepared from the virgin binder VB Pen 60/70. The classification notation of the samples is illustrated in Table 4.

Table 4. Classification of samples based on RAP content

Mix Ratio	Sample	Notation
Virgin binder	100 VB	M0
RAP binder	100 MB	M25
75% VB + 25% RB	75/25 MB	M50
50% VB + 50% RB	50/50 MB	M75
25% VB + 75% RB	25/75 MB	M100

3.2. Dynamic Shear Rheometer DSR

The rheological properties of the binder blends were assessed using a Dynamic Shear Rheometer (DSR) to determine their performance at elevated temperatures. According to the procedures specified in AASHTO T 315, tests were conducted at multiple temperatures (42°C, 48°C, 56°C, and 65°C) to replicate the 0conditions typically encountered in Nigeria. This evaluation is essential for understanding how asphalt mixtures behave under high temperatures, which is critical for assessing deformation performance. By examining the rheological characteristics at elevated temperatures, the impact of different blends of binder on properties such as stiffness, rutting resistance, and flow behavior can be observed. During the test, both the upper and lower plates of the DSR were preheated to the target temperature to ensure proper specimen adhesion.

The specimens were then placed between the plates, and the testing frequency was set to 10 radians per second, as per the test standard. The DSR software was used to measure the maximum applied stress (σ) and the corresponding maximum strain (τ), from which the complex shear modulus (G*) was calculated using Equation 1.

$$G^* = \frac{\sigma_{\max}}{\tau_{\max}} \quad (1)$$

where σ denotes the maximum stress and τ signifies the maximum strain. The phase angle (δ) was determined by analyzing the time delay between the peaks of σ_max and τ_max. To assess the binder resistance to rutting, the rutting factor, represented as G*/Sin(δ), was calculated. This factor serves as a measure of the binder capacity to resist permanent deformation. A higher rutting factor indicates improved elasticity and greater resistance to rutting. Binder was assessed in three conditions: unaged, short-term aged using the Rolling Thin Film Oven (RTFO), and long-term aged using the Pressure Aging Vessel (PAV). For an unaged binder, the minimum value of G*/Sin(δ) is 1.0 kPa, while for an RTFO-aged binder, the minimum value is 2.2 kPa. The RTFO-aged binder was tested at the highest temperature using a 25 mm steel base plate with a 1 mm gap.

3.3. Bending Beam Rheometer BBR

The bending beam rheometer (BBR) was used to measure the low-temperature creep stiffness and logarithmic creep rate of the asphalt binder. In this test, a beam of asphalt binder 125 mm long, 12.5 mm wide, and 6.25 mm thick is formed by pouring binder into a mold and allowing it to cool. This beam is placed in a low-temperature (-18°C, -12°C, and -6°C) bath, during testing, which was accomplished within 60± 5 minutes of placing the beam in the bath, the beam is placed on two simple supports having a span of 100 mm. A constant load of approximately 1,000 mN, maintained for 240 seconds, was applied to the center of the simply supported beam.

For a low-temperature classification, the stiffness (S) must be less than 300 mPa, and the creep rate (m-Value) must be greater than 0.30 within a 60-second loading period. This test provided a detailed analysis of the performance of binder blends at low temperatures, providing valuable insights into their ability to withstand thermal cracking under varying temperature conditions.

3.4. Indirect tensile stiffness modulus test (ITSM)

This test is usually used to study the stress-strain properties of asphalt mixtures under dynamic loading. It can be regarded as an index to evaluate crack resistance. In this study, Hydraulic Compression Testing Machine (ISO VG 32 + 68) model with linear variable differential transformer (LVDT) was used to conduct the test in accordance to ASTM D8225-19 (ASTM D 8225-19, 2019). Before the tests, asphalt mixture cylindrical specimens with dimensions of 150 mm in diameter and 62 mm in height compacted 75 times on each side, according to Marshall procedure were kept in the environmental chamber of 20 °C for at least 5 h. The specimen was only removed from the chamber when the test began. All the test process is completed in a short time in order to ensure the temperature of specimen does not change obviously. Three parallel specimens were used for the test of each content. The loading rate of 1 mm/min was selected and the vertical deformation on the top surface of specimen and the load were recorded during the test. The tensile strength and tensile failure strain were calculated by following Equation 2.

$$S_m = F \times (\mu + 0.27)/(h \times Z) \quad (2)$$

where Sm represent Indirect tensile stiffness modulus; F is the maximum loading, μ is Poisson’s ratio = 0.35 at 20 ◦C, h is the specimen height, Z is the horizontal deformation.

3.5 Fatigue Test

Fatigue cracking is a major concern for asphalt pavements in service. The resistance of hot mix asphalt (HMA) to fatigue damage depends mainly on the properties of the materials used in the mix. To avoid early fatigue, it is crucial to investigate the fatigue behavior of DEWO-modified asphalt mixes. This study utilized a four-point bending test (4PB) to measure the fatigue crack resistance of DEWO-modified asphalt mixtures. The test was carried out using a digitally controlled, servo-pneumatic beam fatigue apparatus from Industrial Process Controls (IPC), Inc., in accordance with AASHTO T321 (AASHTO T321, 2014) standards.

First, beam specimens of dimensions 420 x 150 x 50 mm were prepared using a rolling wheel compactor and the compacted specimens were cut into dimensions of 420 x 50 x 50 mm before testing. Fatigue life (Nf) is defined as the number of cycles needed to reach a 50% reduction in the mixture's initial stiffness. Brown and Needham observed that strain levels in pavement structures are generally below 200 microstrain, depending on factors such as layer thickness, subgrade, mixture type, and load. The fatigue tests were performed at a temperature of 20°C and a frequency of 10 Hz, with a strain level of 150 microstrain, using a sinusoidal waveform in a controlled strain mode. This methodology allows for an accurate assessment of the fatigue resistance of DEWO-modified asphalt mixtures, ensuring that the material's durability and performance under cyclic loading are thoroughly evaluated.

3.6. Sara Separation Test

Results from analysis of saturates, aromatics, resins, and asphaltenes (SARA) are valuable for understanding the aging process of bitumen and have been associated with mechanisms of roadway weathering and decay. In this research, the SARA separation test was carried out to evaluate the influence of varying percentages of RAP content on an asphalt binder modified with a rejuvenator, in accordance with ASTM D4124 (ASTM., 2001). Flash chromatography with Evaporative Light Scattering Detection (ELSD) was found to be an efficient means of both separating the SARA components and quantifying them. In addition, the automatic solvent switching during a run allowed resolution of the SARA components. Individual components of the fraction were calculated using the expression

$$\%Weight(SARAfractions) = \frac{WF \times 100}{(1-FV) \times BU} \quad (3)$$

Where,
WF= $Weight\ of\ Fraction\ (mg)$
FV= $Fraction\ Volatile)$
BU= $Amount\ of$ bitumen $Used\ (mg)$

4. Results and Discussion

4.1. Dynamic Shear Rheometer

To assess the high-temperature performance of samples, the rheological tests were performed by using an Anton Paar DSR rheometer with 25 mm parallel plates and a 1 mm gap between the plates. The rheological characteristics of both virgin bitumen and modified bitumen were analyzed in this study. Figure 1 presents the rutting factor at various temperatures (40°C, 48°C, 56°C, and 68°C) for unaged bitumen.

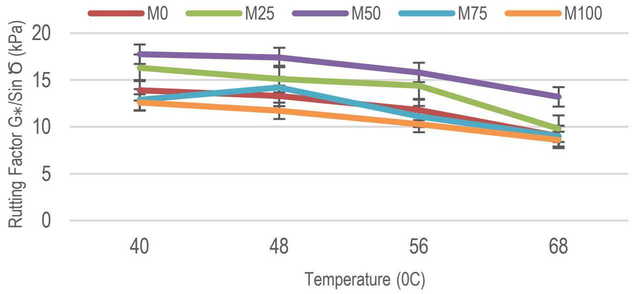

Figure 1. Rutting factor of binder at unaged condition

The rutting factor, denoted as G*/Sin(δ), primarily reflects stiffness properties. The addition of MB enhanced the rutting resistance of the modified bitumen. Test results at 680C shows that there is a higher accumulated strain at lower RAP content. Specifically, at 50% RB modification, the rutting factor increased by 38% compared to 100% VB. However, with 100% MB, the rutting factor decreased below that of VB.

This suggests that MB can notably improve rutting resistance at high temperatures when partially replacing VB due to its viscos properties, which enhance workability and bonding within the bitumen matrix.

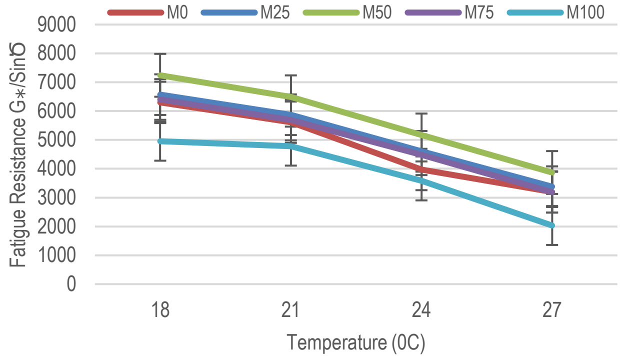

Figure 2. Rutting factor of binder at RTFOT-aged condition

The rutting factor of binder under RTFOT-aged conditions is presented in Figure 2. Similar to unaged conditions, RTFOT-aged bitumen with 50% MB exhibited a higher G*/Sin(δ) value compared to 100% VB. This indicates that adding MB to VB can withstand higher temperatures and oxidation rates associated with asphalt concrete production, transportation, and compaction due to MB's mineralogical composition. Following the long-term aging test, RTFO residues were utilized in PAV, resulting in different values of fatigue resistance of bitumen at various temperatures.

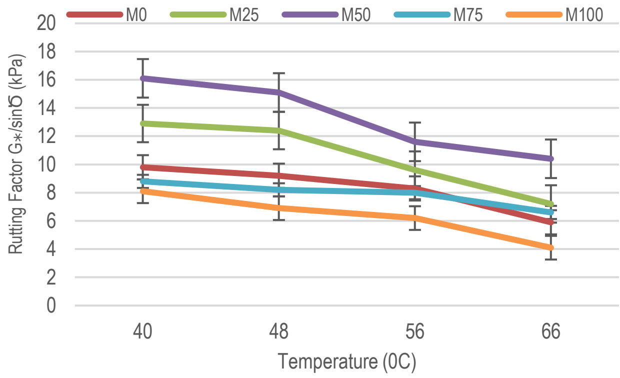

Figure 3. Fatigue resistance of RTFOT-PAV aged bitumen binder

Figure 3 shows the fatigue resistance of RTFOT-PAV aged bitumen. Essentially, G*Sin(δ) characterizes the fatigue behavior of asphalt binder after long-term performance. The results in Figure 3 show that fatigue resistance is lower in virgin binder alone but increases with modified binder addition. This aligns with the findings of D'Angelo et al (D'Angelo, 2007). The fatigue resistance of binder with 50% modified binder using DEWO was higher than that of 100% VB. However, when MB content reached 100%, fatigue resistance was lower than that of conventional VB. This suggests that adding MB to VB improves binder stiffness properties under aged conditions due to thermal stability (Elkashef, 2018) and the presence of aromatics in DEWO, which slows oxidation rates.

However, complete replacement of VB with MB at 7.2% DEWO addition leads to excessively viscos binder (Usanga, Okafor, & Ikeagwuani, Investigation of the Performance of Hot Mix Asphalt Enhanced with Calcined Marl Dust Used as Fillers, 2023), which makes compaction difficult, and susceptible to cracks.

4.2. Bending Beam Rheometer

The stiffness (S) and creep rate (m) of binder under low-temperature conditions are illustrated in Figures 4 and 5.

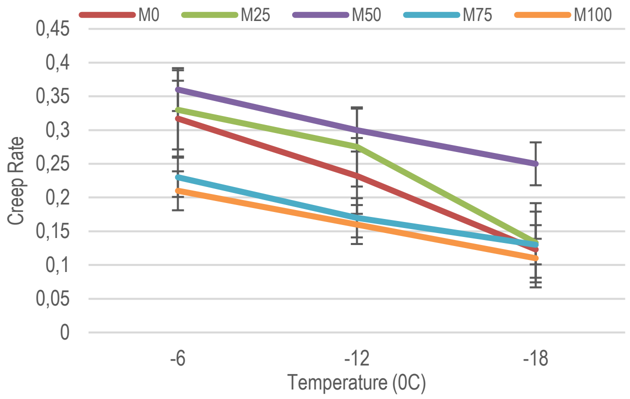

Figure 4. Creep rate m- temperature relationship of binder

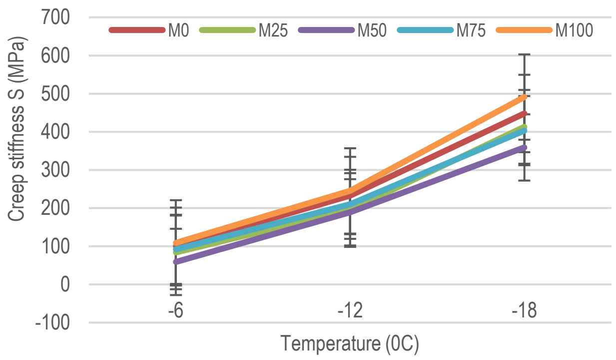

Figure 5. Creep stiffness S- temperature relationship of binder

A lower creep stiffness value and a higher creep rate suggest a more resilient binder with increased resistance to cracking and reduced stress relaxation properties. As per AASHTO M320 guidelines (AASHTO M320, 2010), the S value should be below 300 MPa, while the m value should exceed 0.3.

The incorporation of MB into VB notably enhances its stiffness at low temperatures as demonstrated in Figure 5. Particularly, a blend comprising 50% MB and 50% VB shows lower stiffness compared to 100% VB. However, complete substitution of VB with MB leads to a highly cohesive mixture of MB. Similarly, in Figure 4, representing the creep rate, an opposite trend in creep stiffness is observed. This suggests that incorporating MB at a moderate level can enhance the relaxation properties of asphalt concrete at low temperatures.

4.3. Indirect Tensile Stiffness Modulus Test

The ITSM test was conducted at 20 ℃ to evaluate the stiffness modulus of the PSAF-modified mixtures. Typically, modified asphalt mixtures demonstrate notably higher stiffness modulus than unmodified ones, as documented in various studies.

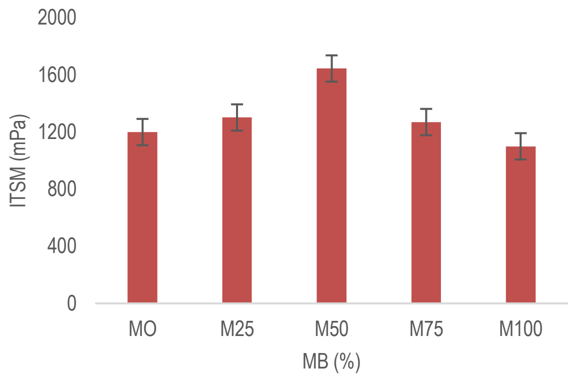

Figure 6. ITSM results

Analysis of the ITSM test results, depicted in Figure 6, indicates that the blend consisting of 50% VB and 50% MB shows elevated stiffness values compared to other combinations. These results indicate that incorporating 25%, 50%, and 75% MB concentrations increases the ITSM values by 19%, 29.3%, and 4.8%, respectively, compared to the control.

However, with 100% replacement of VB by MB, the stiffness decreases below the control mixture's value. This enhancement can be attributed to potential chemical bonding and improved adhesion between MB and the VB, leading to a more durable mix due to its viscos properties. Additionally, the low viscosity of the MB improves the workability and aids in compacting the asphalt mix.

Zhang et al. (2018) suggests that RAP binders modified with rejuvenators contribute to higher stiffness and better interaction with bitumen due to their tendency for uniform distribution in asphalt mixes. ITSM values were averaged across three specimens for each mixture to ensure test consistency. These findings imply that asphalt mixtures containing 50% MB are likely to demonstrate improved crack resistance. These outcomes are consistent with the findings of Singh et al (Singh, 2018).

4.4. Results of Fatigue Life Test

The fatigue test results are depicted in Figure 7, showing that the mixture containing 50% MB exhibits the highest fatigue life, significantly influencing fatigue behavior compared to both the control and other PSAF concentrations.

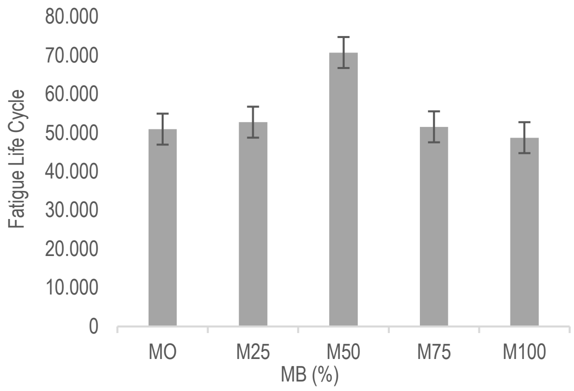

Figure 7. Fatigue life results

There was a notable 31.8% increase in the fatigue life of the 50% MB mixture compared to the control VB mixture, attributed to valuable enhancements in the cohesive properties of the asphalt mixture. However, at complete replacement of VB with MB, the fatigue life slightly reduced by 2.5%. This improvement in fatigue life of the modified asphalt mixes is attributed to increased adhesive force between the asphalt binder. It is observed that the chemical composition of the DEWO plays a role in asphalt binder distribution in the mix, hence, enhancing adhesion within the modified binder (Mogawer, 2015).

4.5 Sara Separation Result

The fractional composition of the binders revealed that RAP binder contained less amount of saturate and aromatic contents and large percentages of resin and asphaltene contents, the addition of RAP altered the fractional composition of the virgin binders based on RAP percentages.

Saturates are colorless oily liquids, while aromatics form a yellow to red oily fluid at room temperature according to Eberhardsteiner et al. (Eberhardsteiner, 2015) . These components account for the viscosity and plasticizing properties of the binder. Asphaltenes and resins are black solid at room temperature, contributing to the adhesion, plasticity, and ductility of binder. There is a recommendation for SARA fractions ranges thus; asphaltenes 5%–25%, resins 20%–35%, aromatics 30%–45%, and saturates 5%–15% (Eberhardsteiner, 2015).

Figure 10 reveals the SARA composition of RAP binder to include 12% saturates, 35% aromatics, 28% resins, and 25% asphaltenes, while these percentages are 11, 49, 24, and 16% for base binder (Pen 60-70). The results also indicate a different pattern in the change of SARA-fractions because of increasing RAP content. By adding 25% RAP, saturate content was almost constant, aromatic content decreased by 8%, and the resin and asphaltene content increased by 4% and 13%, respectively.

When RAP content was increased from 25%to50% it caused additional 5% decrease in saturates, 8% decrease in aromatic and 8% increase in resins with 16% increase in asphaltenes as shown in Figure 8.

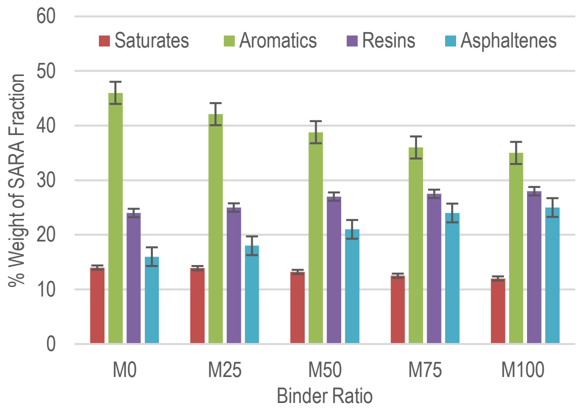

Figure 8. SARA Fraction Result

For 100% of RAP content the fractional composition of samples did not experience extreme change by the addition of higher RAP contents. It means that the rejuvenation process of the extracted binder was a physical interaction and could not change its chemical structure. Some researchers investigated the effect of rejuvenators in recycled asphalt binders by some microstructural and rheological tests and reported the same findings (Chen, 2018; Yu, 2014).

4.6 Correlation of Rheological Properties of Binder and Chemical Components

To evaluate the relationship between the chemical composition and rheological properties of RAP binder in this study, two indices, Gastel Index (IG), and Asphaltene Index (IA) shall be considered. IG is used in measuring the colloidal stability of the binder (Lesueur, 2009), it is expressed as

$$I_G = \frac{S_{at} + A_{sph}}{R + A_r} \tag{4}$$

where,

Asph = Asphaltene content
Sat = Saturate content
R = Resin content
Ar = Aromatic content.

A decrease in IG represents an increase in the colloidal stability of the binder. The range of values for IG is between 0.22 to 0.5, higher values represent harder binder while lower values represent possibility of temperature susceptibility.

The asphaltene index IA is expressed thus,

$$I_A = \frac{R + A_{sph}}{S_{at} + A_r}$$

Figure 8 shows consistent increase in asphaltenes and resins as the MB increases in proportion against the aromatic and saturates. This trend is responsible for the low temperature cracking and rutting resistance and it agrees with the study by (Wang, 2019). The improvement of high temperature performance was also attributed to the increase in asphaltene and resin components. It was also noticed that the increase in asphaltene and resin was responsible for the decrease in creep rate (m) and increase in creep stiffness (s).

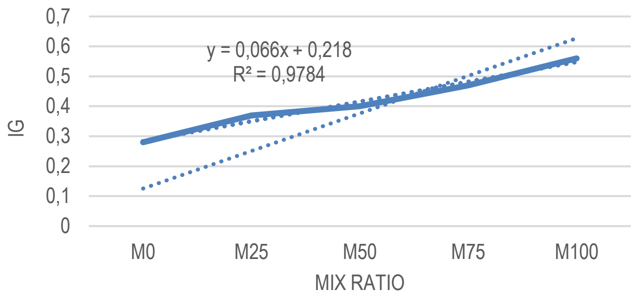

Figure 9. Gastel Index relationship with mix proportion

To further evaluate the correlation between the chemical component and rheological properties of the binder, the relationship between the mix proportions and the indices were statistically fitted and their R2 of 0.9784 and 0.9308 were considered significant and a good fit as shown in figures 9&10.

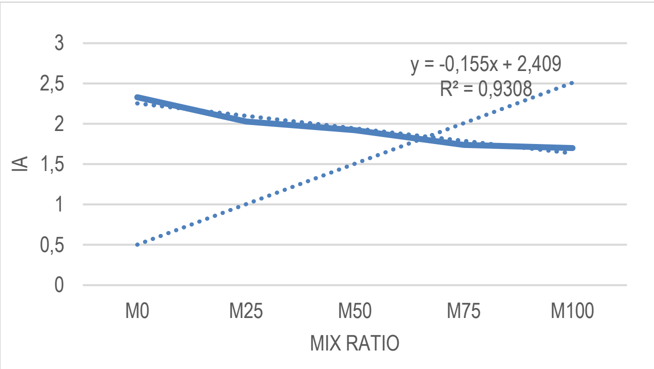

Figure 10. Asphaltene Index relationship with mix proportion

5. Conclusions

This research was carried out to investigate the influence of oil-rejuvenator on the chemical composition of RAP binders and evaluate the rheological properties of varying proportions of RAP contents. The following conclusions were reached; Oil-rejuvenation causes a significant improvement on the rheological properties of the RAP binder even up to 100% RAP content.

There is a significant correlation between the rheological properties and the chemical composition of the binder. The percentage proportion of the RAP binder significantly influences the chemical composition of the binder.

Rheological properties such as the m-value and s-value are directly affected by the asphaltene contents which is related to the chemical composition of the binder. Increased RAP content resulted in improved rut resistance which is related to increase in the asphaltene content. The high and low temperature performances of the binder improved with application of the oil-rejuvenator due to the presence of aromatics in DEWO, which slows oxidation rates. The relationship between the Asphaltene Index IA and the mix proportions of the binder shows more statistical reliability than the relationship between the Gastel Index IG and the mix proportion, hence, the Asphaltene Index can be used more independently for evaluating the influence of rheological properties on chemical composition.

The main objective of this research which was evaluating the influence of oil-rejuvenation on the chemical composition and its correlation with rheological properties of the binder has been established but there is need for advance studies in the field to confirm this research. This study is limited to SARA chemical component, other components should be researched on as it affects the rheological properties of asphalts. Finally, this study is practically useful in selection of rejuvenator for modification of RAP.

References

[1] AASHTO M320. (2010). Standard specification for performance-graded asphalt binder. Washington, D.C: AASHTO.

[2] AASHTO T321. (2014). Standard Method of Test for Determining the Fatigue Life of Compacted Hot-Mix Asphalt (HMA) Subjected to Repeated Flexural Bending. Washington DC: AASHTO.

[3] Asli, H. E. (2012.). “Investigation on physical properties of waste cooking oil-rejuvenated bitumen binder.”.” Constr. Build. Mater., 37, 398–405. https://doi.org/10.1016/j.conbuildmat.2012.07.042.

[4] ASTM D 70. (2003). American society for testing and materials, Standard test method for density of semi solid bituminous materials (Pycnometer method). Pennsylvania, USA.

[5] ASTM D 8225-19. (2019). Standard Test Method for Determination of Cracking Tolerance Index of Asphalt mixtures using Indirect Tensile Stiffness Modulus. West Conshohocken PA, USA: ASTM.

[6] ASTM D 92. (2020). American society for testing and materials, Standard test method for determination of flash point using a Prensky-martens closed-up apparatus. Pennsylvania, USA.

[7] ASTM D36. (2006). American Society for Testing and Materials, Standard test methods for softening point of bitumen (Fing and ball apparatus). Pennsylvania, USA.

[8] ASTM D4402. (2022). American society for testing and materials, Standard test method for viscosity determination of asphalt at elevated temperatures using rotational viscometer. Pennsylvania, USA.

[9] ASTM D5. (2006). American Society for Testing and Materials, Standard test methods for penetration of bituminous materials. Pennsylvania, USA.

[10] ASTM. (2001). Standard test methods for separation of asphalt into four fractions. ASTM D4124. West Conshohocken: PA: ASTM.

[11] Behnood, A. (2019). Application of rejuvenators to improve the rheological and mechanical properties of asphalt binders and mixtures: A review.". 231 Behnood, A. 2019. "Application of rejuvenators to improve the rheological and mechan171–182. https://doi.org/10.1016/j.jclepro .2019.05.209), 171–182.

[12] Cavalli, M. C., M. Zaumanis, E. Mazza, M. N (2018). "Aging effect on rheology and cracking behaviour of reclaimed binder with bio-based rejuvenators." J. Cleaner Prod. 189(Jul), 88-97.

[13] CD., D. (2011). Investigation of using waste engine oil blended with reclaimed asphalt materials to improve pavement recyclability. Michigan: Department of Civil Engineering, Michigan Technological University.

[14] Chen, A. G. Chen, (2018). "Research on the aging and rejuvenation mechanisms of asphalt using atomic force microscopy."." Constr. Build. Mater. 167(Apr), 177-184.

[15] D'Angelo,J., D'Angelo,J.,R. Kluttz,R.N. Dongre,K. S., (2017) "Revision of the Superpavehigh temperature binder specification: The multiple stress creep recovery test (with discussion). " J. Assoc. Asphalt Paving Technol. 76, 123-162.

[16] Eberhardsteiner, L. J. (2015). "Influence of asphaltene content on mechanical bitumen behavior: Experimental investigation and micromechanical modeling." . " Mater. Struct., 48(10), 3099-3112.

[17] Elkashef, M. (2018). "Thermalstabilityand evolved gas analysis of rejuvenated reclaimed asphalt pavement (RAP) bitumen using thermogravimetric analysis-Fourier transform infrared (Tg–FTIR)."." J. Therm. Anal. Calorim. 131(2), 865-871.

[18] Fakhri, M. (2016). "Evaluation of warm mix asphalt mixtures containing reclaimed asphalt pavement and crumb rubber. J. Cleaner Prod. 165(Nov.), 1125–1132. https://doi.org/10.1016/j.jclepro.2017.07 .079.

[19] He, H. E. (2018). "Effect of the softer binder on the performance of repeated RAP binder. Constr. Build. Mater. 178(Jul), 280-287.

[20] Huang, S., Q. Qin, W. R. Grimes, A. (2014) "Influence of rejuvenators on the physical properties of RAP binders.". J. Test. Eval. 43(3), 594-603.

[21] Jiang, H. Z. (2018., (Aug)). "Experimental assessment on engineering properties of aged bitumen incorporating a developed rejuvenator." Constr. Build.Mater., 179(https://doi.org/10.1016/j.conbuildmat.2018.05.2), 1–10.

[22] Joni H. H, A.-R. R.-z. (2019). Rejuvenation of aged asphalt binder extracted from reclaimed asphalt pavement using waste vegetable and engine oils. Constr Mater., 10(Oct), 1-10.

[23] Joni HH, Al-Rubaee RH, Shams MK. (2021) Assessment of durability properties of reclaimed asphalt pavement using two rejuvenators: Waste engine oil and asphalt cement (60–70) penetration grade. IOP Conf Ser Mater Sci Eng.;13(1):1–13.

[24] Kumbargeri, Y. S. (2016). "Understanding aging behaviour of conventional asphalt binders used in India. India.: Transp. Res. Procedia. 17 (Jan): 282–290. https://doi.org/10.1016/j.trpro.2016 .11.094.

[25] Laukkanen, O. V. (2015). "Low-temperature rheology of bitumen and its relationship with chemical and thermal properties. Aalto Univ.:"M.S. thesis, School of Engineering, Aalto Univ.

[26] Lesueur, D. (2009). "The colloidal structure of bitumen: Consequences on the rheology and on the mechanisms of bitumen modification." Adv. Colloid Interface Sci., 145(1-2), 42-82.

[27] Mamun A. W. (2018). Evaluation of waste engine oil rejuvenated asphalt concrete mixtures with high RAP content. Adv Mater Sci Eng., 8(2018), 1-8.

[28] MK., S. (2020). Influence of using different rrjuvenators on recycled hot mix asphalt properties. M.s.c. Thesis, Department of Civil Engineering, University of Technology; .

[29] Mogawer, W. S., A. Austerman, R. Roque, S. U(2015). "Ageing and rejuvenators: Evaluating their impact on high RAP mixtures fatigue cracking characteristics using advanced mechanistic models and testing methods.". Road Mater and pavement, 6(2), 1-28.

[30] P. C. Boriack, S. W. (2014). Laboratory evaluation of asphalt concrete mixtures containing high contents of reclaimed asphalt pavement (RAP) and binder. Charlottesville, VA: Virginia: FHWA/VCTIR 15-R8.

[31] Singh, D. a. (2018). "Influence of RAP sources and proportions on fracture and low temperature cracking performance of polymer modified binder."." Constr. Build. Mater., 120(Sep), 10-18.

[32] Tran, N. A. (2014). "Effect of rejuvenator on performance properties of HMA mixtures with high RAP content." Asphalt Pavements., 201(https://doi.org/10.1201/b17219), 1661-1870.

[33] Usanga, I., Okafor, F., & Ikeagwuani, C. (2023). Investigation of the Performance of Hot Mix Asphalt Enhanced with Calcined Marl Dust Used as Fillers. International Journal of Pavement Research and Technology, https://doi.org/10.1007/s42947-023-00323-w.

[34] Usanga, I., Okafor, O., & Ikeagwuani, C. (2024). Analysis of performance parameters based on surface free energy to evaluate moisture susceptibility of asphalt mixtures modified with calcined marl dust. International Journal of Pavement Engineering, 25(1), DOI: 10.1080/10298436.2023.2301453.

[35] Wang, T. J. (2019). "Effects of SARA fractions on low temperature properties of asphalt binders.". Road Mater. Pavement Des. 1–18, 1-8.

[36] Wang, Y. D. (2019). "Development of a performance-volumetric relationship for asphalt mixtures." Transp. Res. Rec. 2673(6), 416-430.

[37] Yu, X. M. (2014). "Rheological, microscopic, and chemical characterization of the rejuvenating effect on asphalt binders."." Fuel. 135(Nov), 162-171.

[38] Zaumanis M, M. R. (2014). Za Evaluation of different recycling agentsforrestoringagedasphaltbinderandperformanceof100% recycled asphalt. Mater Struct Constr. 14(8), 1-14.