ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/IJISRT24JUL1744

Impact of Waste Vegetable Oil (WVO) on the Chemical and Rheological Properties of Crumb Rubber Modified Bitumen (CRMB)

J. B. Mudasiru[1*], S.O. Odunfa[1], O.S. Abiola[1] and O.S. Sojinu[2]
[1]Department of Civil Engineering, Federal University of Agriculture Abeokuta, Abeokuta, Nigeria
[2]Department of Chemistry, Federal University of Agriculture Abeokuta, Abeokuta, Nigeria

Corresponding Author: J. B. Mudasiru[1*]

Abstract:- The utilization of waste vegetable oil (WVO) in bitumen has been a subject of research for an extended period, yet its application in crumb rubber-modified bitumen (CRMB) has not been thoroughly documented. In this study, blends incorporating varying proportions of WVO (5-20% wt) and crumb rubber (CR) were formulated, and the physical, chemical, and rheological properties of the WVO-CRMB blend were systematically examined. Essential physical tests, encompassing penetration, specific gravity, softening point, flash point, and viscosity, were conducted, along with chemical analyses (FTIR), including SARA composition. Rheological assessments were performed using Dynamic Shear Rheometer (DSR) and Bending Beam Rheometer (BBR). The findings revealed an upswing in penetration, increasing from 48.2 at 20% CR content to 67.61 with a 10% addition of WVO to 20% CR bitumen, coupled with a decline in softening point from 62.35°C to 37.51°C. Additionally, SARA composition tests indicated that WVO led to a reduction in asphaltene content and the colloidal stability index of CRMB, decreasing from 0.71 at 20% CR content to 0.55 with a 20% addition of WVO to 20% CR bitumen. Rheological analyses demonstrated enhanced rutting and fatigue resistance, particularly in high-temperature deformation resistance. The rutting (G*/sinσ) and fatigue (G*.sinσ) parameters exhibited improvement from 2.33 at 20% CR to 2.91 with a 20% addition of WVO to 20% CR bitumen at an elevated temperature of 76°C. These advancements in physical, chemical, and rheological properties suggest that incorporating WVO into CRMB enhances the overall performance of the bitumen. This modification holds promise for alleviating pavement distress and enhancing the overall performance and longevity of highway pavements.

Keywords:- *Bitumen, Bitumen Modification, Crumb Rubber, Crumb Rubber Modified Bitumen, Waste Vegetable Oil*

I. INTRODUCTION

Asphalt technology has witnessed transformative advancements with the introduction of Crumb Rubber Modified Bitumen (CRMB), a sustainable alternative that incorporates recycled rubber to enhance pavement performance. However, despite its notable benefits, CRMB is not exempt from challenges, prompting a closer examination of its shortcomings and avenues for improvement [1]. CRMB, known for its enhanced durability, improved resistance to rutting and cracking, and positive environmental impact through rubber recycling, is not without its limitations. The complex interaction between crumb rubber and bitumen can lead to challenges such as reduced workability during mixing and compaction, uneven dispersion of rubber particles, and concerns related to the high viscosity of the modified binder [2]. Additionally, issues with adhesion between the modified binder and aggregate surfaces may impact the overall performance of the asphalt mix [3]. WVO has been found to enhance the penetration of asphalt cement, leading to a softer asphalt mixture. This property makes it a promising rejuvenator for recycled asphalt pavement or used asphalt, as highlighted in several studies [4][5][6][7]. However, its potential in conjunction with virgin asphalt has not been thoroughly explored. The concept of this research is to study waste vegetable oil's fluxing effect on virgin bitumen modified by crumb rubber via the wet process for asphalt concrete.

WVO, sourced from culinary processes, offers a sustainable alternative that not only addresses the shortcomings of CRMB but also contributes to the repurposing of organic waste.

In the study by Zargar et al. [8], it was discovered that incorporating 3-4% waste cooking oil (WCO) by weight of the binder can enhance the penetration value, closely resembling that of virgin bitumen. Similarly, Asli et al. [9] explored the physical properties of WCO as a rejuvenator in conjunction with reclaimed asphalt pavement (RAP) materials. Their research revealed that introducing up to 5% WCO as a rejuvenating agent in the mixture had no detrimental effects on the performance of pavement mixtures. Conversely, Ji et al. [10] extended the WCO percentage to 8% to bolster the rutting resistance of aged binders under

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/IJISRT24JUL1744

elevated temperatures. The study investigated the use of vegetable oils, specifically soybean oil and waste cooking oil (WCO), as rejuvenators for aged asphalt binders. The findings showed that the addition of 6-8% vegetable oil content in the rejuvenator was effective in recovering the properties of aged asphalt binders, particularly in terms of improving their rutting resistance under elevated temperatures. Wen et al. [11] conducted a comprehensive study on WCO-based binders, highlighting their capacity to enhance low-temperature resistance and reduce moisture susceptibility. However, the study noted that the introduction of WCO-based binders resulted in diminished resistance to fatigue cracking, rutting, and stiffness. In contrast, Maharaj et al. [12] reported a contrasting outcome, observing significant enhancements in fatigue cracking resistance with the incorporation of WCO into the mixture. This study concluded that the addition of WCO contributed to an overall improvement in the fatigue resistance of the asphalt mixture. The addition of crumb rubber (CR) to asphalt binders has been a common practice to improve the performance of asphalt pavements. CR can enhance the rheological properties of the binder, leading to improved resistance to rutting, fatigue cracking, and thermal cracking [13]. However, the complex interaction between CR and bitumen can also lead to several challenges. One of the key issues with CR-modified asphalt is the reduced workability during mixing and compaction. The high viscosity of the CR-modified binder can make it difficult to achieve proper dispersion of the rubber particles, leading to uneven distribution within the mixture. This can impact the overall performance of the asphalt pavement, as the inconsistent distribution of CR can result in variable mechanical properties across the surface [14].

The rejuvenating effect of WVO is attributed to its ability to dilute the high-polarity sulfoxide base of the aged asphalt, improving the molecular weight distribution. This can help overcome the issues related to the high viscosity and uneven dispersion of CR-modified binders, leading to better workability and more consistent performance of the asphalt mixture [15]. However, there has been little research work on the use of WVO as a fluxing agent in CRMB. This paper, therefore, explores the integration of Waste Vegetable Oil (WVO) as a potential solution to mitigate the drawbacks associated with CRMB.

II. MATERIALS AND METHODS

A. Materials

- *Virgin Bitumen*

The asphalt binder used was obtained from Lagos State Public Works Commission (LSPWC) in Lagos State, Nigeria. The virgin bitumen of 60/70 grade serves as the base bitumen; the physical properties are presented in Table 2.

- *Waste Vegetable Oil (WVO)*

WVO was obtained from eateries and road-side pastry and confectionery makers around the Lagos metropolis. WVO was used as a fluxing agent during the wet process of the bitumen modification. The virgin bitumen was modified with WVO at varying percentages ranging from 5% to 20%.

- *Crumb Rubber (CR)*

The crumb rubber used was obtained from Lagos State Public Works Corporation (LSPWC) yard at Imota, Ikorodu, Lagos State, Nigeria. Crumb rubber was used to modify the bitumen via the wet process at varying percentages ranging from 5 to 20%.

B. Methodology

Table 1 below summarizes the laboratory tests conducted throughout the research proceedings. All tests are conducted according to the ASTM specifications.The bitumen was heated to 160 degrees Celsius while crumb rubber was added at 10, 15, and 20% by weight of the bitumen. The specimen was mixed at 1200 rpm by a shear mixer for approximately 60 minutes.

Physical, chemical and rheological tests were carried on the bitumen samples. The physical test, which is the specific gravity test, penetration, viscosity, softening point, flash point were conducted according to ASTM D70, ASTM D5, ASTM D2170, ASTM D36-06 and ASTM D92.

The chemical tests which include SARA (saturates, aromatics, resins and asphaltene) composition and colloidal stability were conducted according to ASTM D6703.

The rheological properties of modified bitumen was done through Dynamic shear rheometer -DSR (ASTM D7175) and Bending beam rheometer-BBR (ASTM D6648).

III. RESULTS AND DISCUSSION

A. Physical Properties

The ASTM specification and fundamental physical tests results such as specific gravity, penetration, viscosity, softening point, and flash point on WVO, base bitumen, CRMB and WVO-modified CR bitumen samples, as well as the physiochemical test such as pH, refractive index, pour and cloud point on WVO are presented in Tables 2 to 4.

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/IJISRT24JUL1744

Table 1: Materials and Laboratory Tests Conducted

Materials	Laboratory Test
Waste Vegetable Oil (WVO)	pH Refractive index Pour point Cloud point
Virgin bitumen, CR-blended bitumen, CR and WVO blended bitumen composite.	Specific Gravity Penetration Viscosity Softening Point Flash Point Colloidal Stability Complex modulus Rutting and fatigue parameter via Dynamic shear rheometer (DSR) Bending beam rheometer (BBR)

Table 2: Physical Test Result on Unused Vegetable Oil (UVO) and Waste Vegetable Oil (WVO)

Parameters	WVO Value	UVO Value
Physical State	Liquid	Liquid
Specific gravity @40oC	0.9407	0.898
Kinematic viscosity @40oC (cP)	5.70	5.20
Moisture content (%)	0.02	-
Flash point (oC)	187	161

Table 3: Preliminary Test Results of Bitumen Used

Properties	Values	Standard Specification (ASTM)		Remarks
		Min	Max	
Specific Gravity at 25 °C	1.03	1.01	1.06	Satisfactory
Penetration at 25 °C, 100g, 5s	63.85	60	70	Bitumen 60/70
Viscosity at 1350C (Cst)	396.82	250	-	Satisfactory
Viscosity at 1650C (Cst)	134.51			
Softening Point (0C)	55	46	56	Satisfactory
Flashpoint (0C)	292	232	-	Satisfactory

Table 4: Physiochemical Test Result on Waste Vegetable Oil (WVO)

Parameters	Composition
pH	5.61
Refractive index	1.34
Pour point (oC)	5..0
Cloud point (oC)	-3.0

➢ *Effect on Penetration*

The specification for roads in Nigeria is Pen 60/70 [16], which is suitable for tropical regions and heavy traffic, which is the case with Nigeria. The impact of CR and WVO on the penetration of the bitumen can be seen clearly in Figure 1.

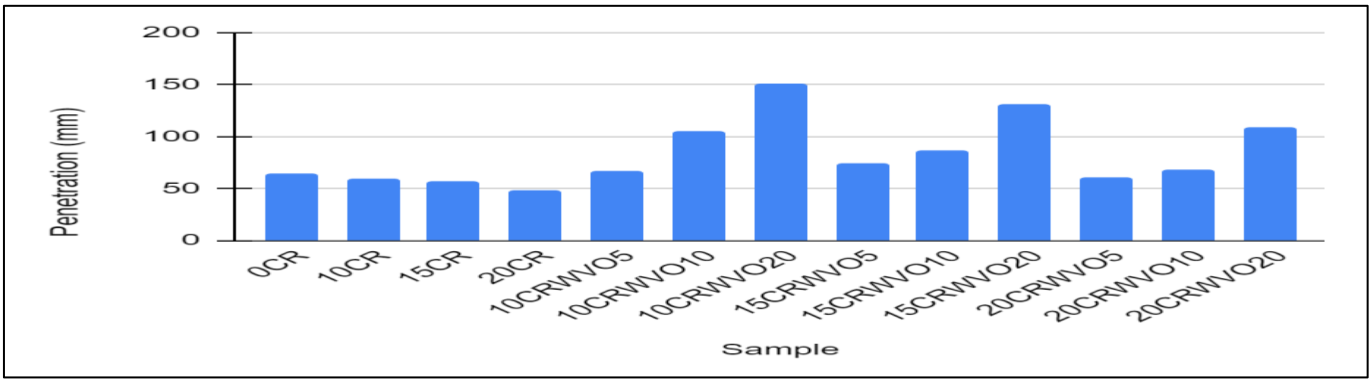

Fig 1: Penetration Test Results for Base and Modified Bitumen

This figure the CR content increases from 0CR to 20CR, the penetration value decreases (e.g., from 63.85 mm to 48.20 mm), indicating that crumb rubber makes the bitumen harder. This finding aligns with previous studies that show crumb rubber increases the stiffness of bitumen due to its elastomeric properties, as also expressed by the findings of Manoharan et al. [17], Khaleel et al. [18] and [19]. An increase was observed with the addition of WVO on CR-modified bitumen. The penetration value increased for 10CR, 15CR and 20CR with addition of 5, 10, and 15 WVO by 155.2, 129.0 and 108.3%, respectively. However, 10CR05, 20CR05 & 20CR10 fall within the penetration value of the original bitumen and are achieved with 5 & 10% WVO. This improvement can be attributed to crumb rubber's ability to enhance the bitumen's stiffness. However, with the addition of WVO, fluxing was observed as the presence of WVO increased the penetration, making it softer [20]. The more the content of WVO, the more fluxing occurred.

➢ *Effect on Softening Point*

The ASTM D36-00 code limit for softening point is between 46°C and 56°C. This test determines the actual temperature at which the bitumen is needed to heat up for mixing purposes. The softening point indicates the mean temperature at which bitumen begins to soften. The modification results, as presented in Figure. 2, show that 10CRWVO5 was the only sample within the accepted limits.

In contrast, other samples except for the control sample fell above or below the accepted limits. Adding CR increased the softening point, suggesting improved thermal stability. This is similar to the results obtained by Khaleel et al., Navarro et al. and Mashan et al. [18][21][22]. This increase is ascribed to the heightened stiffness of the bitumen, stemming from interactions between the rubber and bitumen, which consequently elevate the molecular weight of the bitumen. Asphalt cement with a high softening point is preferred in hot weather regions [23]. Adding WVO reduced the softening point, indicating reduced thermal stability. Similar effects were observed by Yang et al. [24] and Bilema et al.'s work [25]. This reduction is due to the significant effect and ability of WVO to soften binders.

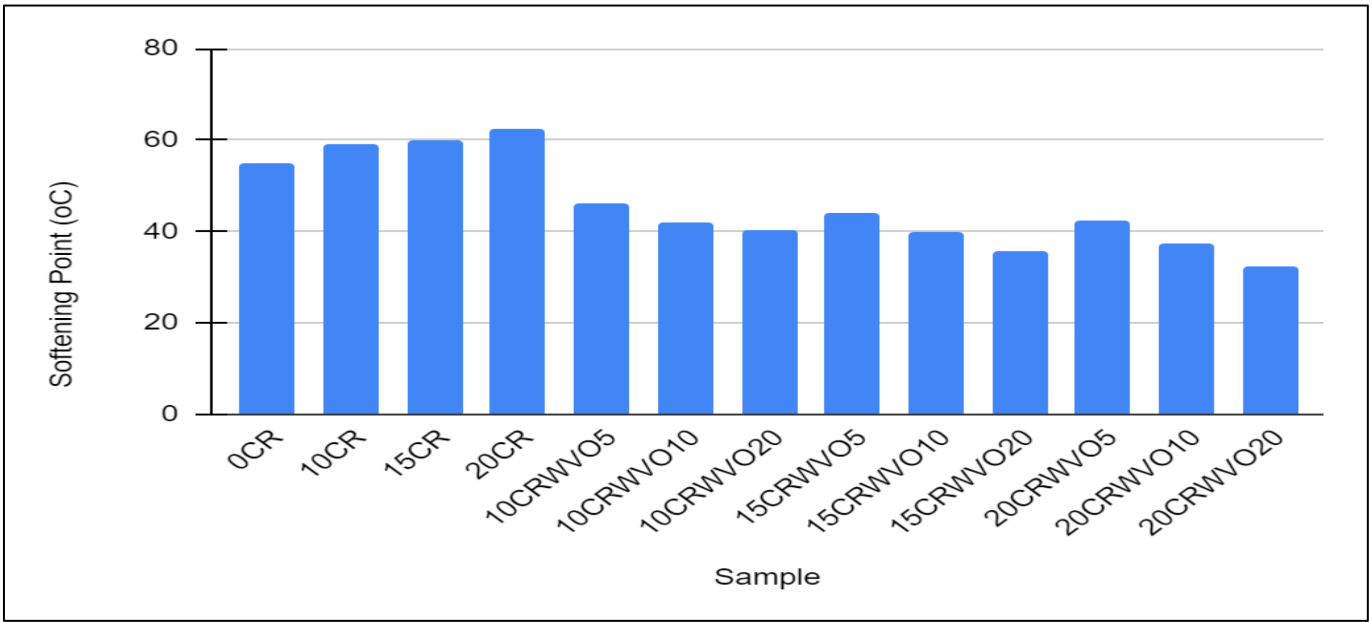

Fig 2: Softening Point Test Results for Base and Modified Bitumen

➢ *Effect on Specific Gravity*

The modification results, as presented in Figure 3, showed that samples 10CR, 15CR, 10CR05, 10CR10, and 10CR20 fell within the accepted standard, while others, except the control sample, fell above the accepted limits. An increase in the addition of CR increased specific gravity. Adding WVO increased the specific gravity; however, continuous increments in WVO resulted in a gradual reduction in specific gravity, aligning with observations from Fini et al.[26] where bio-oils reduced the overall density of modified bitumen.

➢ *Effect on Flashing Point*

A minimum of 232°C is the ASTM limit for flashpoint. The results, as presented in Figure 4, showed that all samples satisfy this criterion. The flash point increases with CR content, indicating enhanced safety during handling and processing. This increase in flash point with rubber addition has been documented by Goh et al.[27], but decreases with WVO addition, which might raise concerns regarding safety. Similar reductions in flash point with bio-oil additives were noted by Xiao et al. [28].

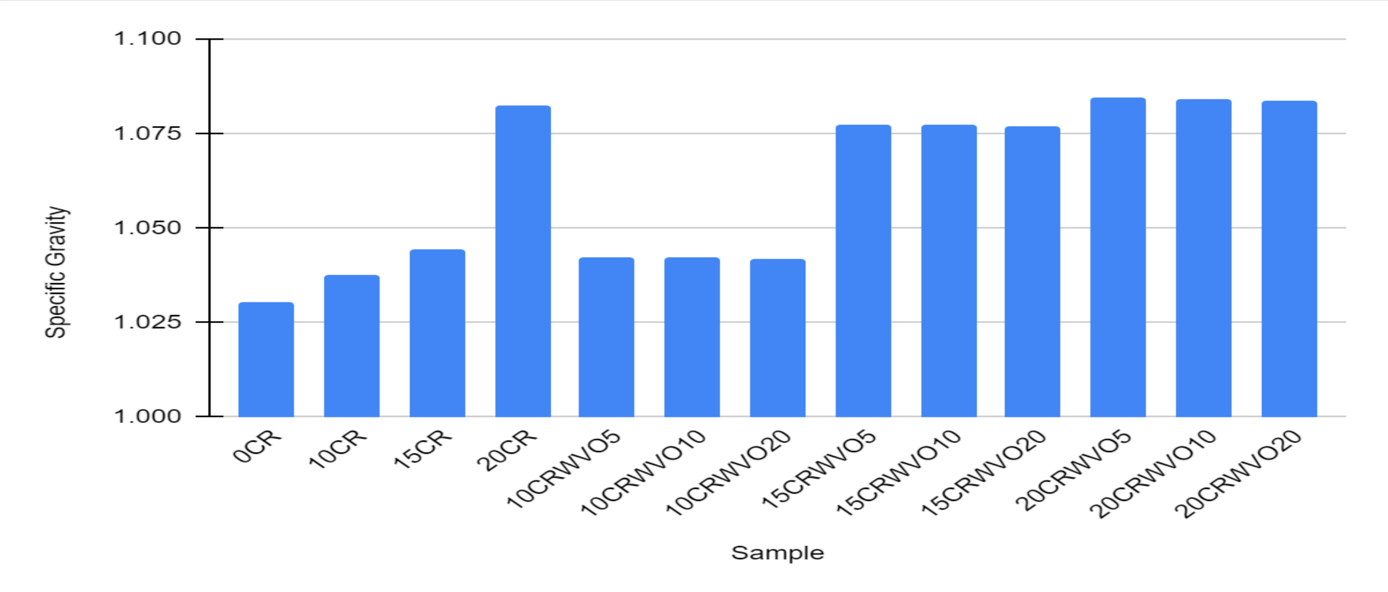

Fig 3: Specific Gravity Test Results for Base and Modified Bitumen

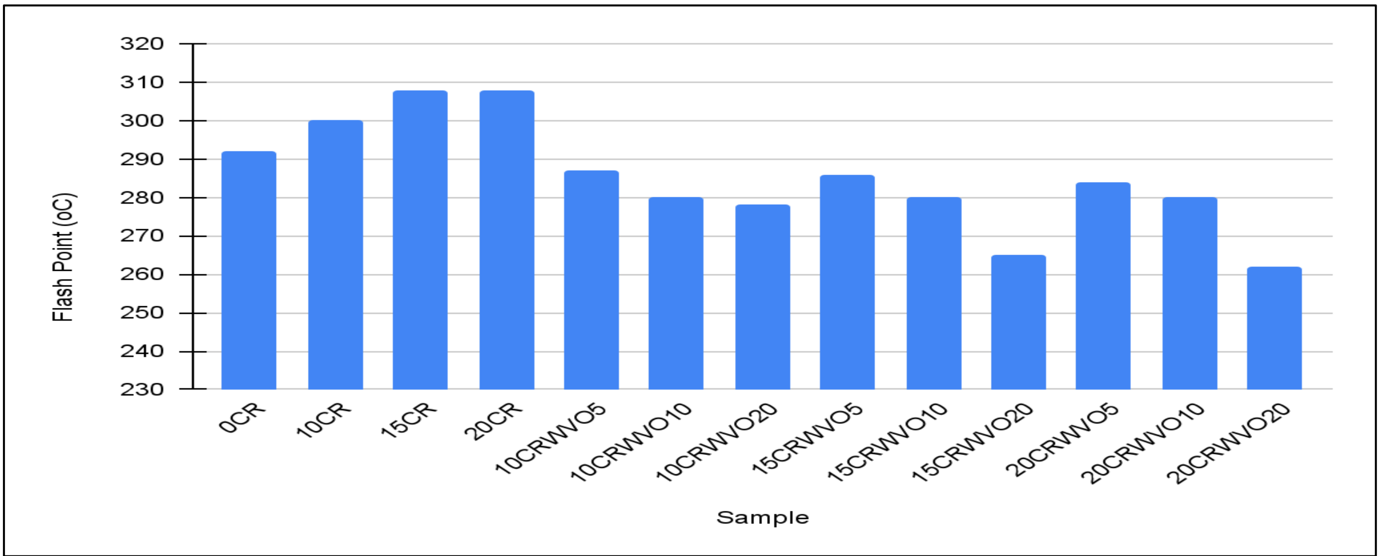

Fig 4: Flash Point Test Results for Base and Modified Bitumen

➢ *Effect on Viscosity*

A minimum of 250cSt is the ASTM limit for viscosity at 135°C. This value determines the range of temperatures suitable for mixing and compaction works for a given asphalt mix. When the viscosity value increases, resistance against rutting, mixing, and compaction temperature increases. The results in Figure 5 show that all samples satisfy this criterion. The result showed a 42% and 46% increase for 15% and 20% of crumb rubber. Viscosity increases with CR, reflecting higher resistance to flow and improved stiffness. This trend aligns with studies by Shu and Huang [29], which reported increased viscosity in crumb rubber-modified bitumen. WVO reduces viscosity, thereby enhancing workability and flow. Similar findings were observed by He et al. [30], where vegetable oil additives reduced the viscosity of bitumen, making it easier to handle and apply. This is also consistent with results obtained by Khaleel [18]. The increase ratio as researched by Khaleel stated 33% and 43% for 4% and 6% tyre rubber-modified bitumen samples respectively. The addition of waste vegetable oil further increased viscosity. This increase is contrary to the findings of Al-Omari et al [31], Wang et al. [32], and Sun et al [33], whose results showed that adding WVO in bitumen decreases the viscosity of the bitumen. The increase in viscosity is also contrary to the findings of Feng et al [34], who used waste cooking oil to activate waste crumb rubber with room temperature immersion method. The increase in viscosity, as obtained, may be due to the interaction of WVO with CRMB components. At high temperatures, WVO can react with asphaltenes, the heaviest and most complex component of bitumen. This reaction can lead to the formation of larger asphaltene aggregates, which can increase the viscosity of the mixture [35][36].

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/IJISRT24JUL1744

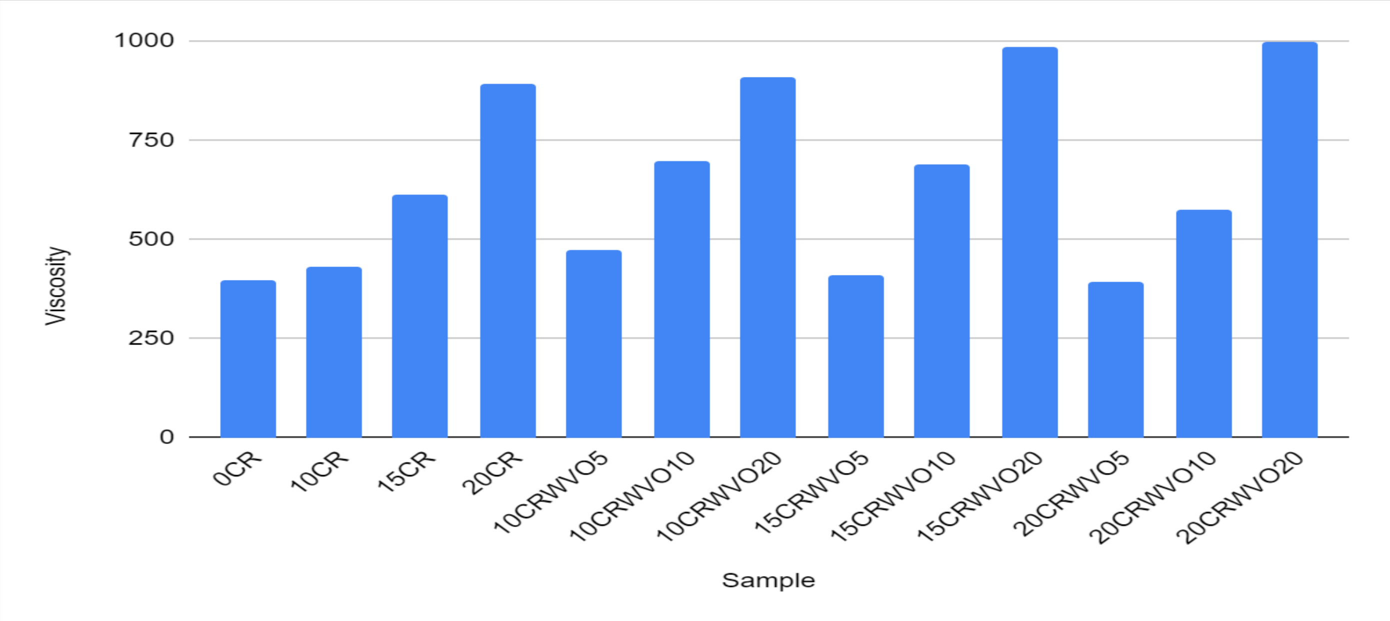

Fig 5: Viscosity at 135^{0}C for Base and Modified Bitumen

The increase in viscosity is not favourable, as a binder with high viscosity necessitates elevated temperatures for laying, compaction, and mixing, resulting in excessive energy consumption [25].

B. Chemical Properties

Bitumen is composite material with an intricate organization that poses challenges to gaining a systematic understanding of the connections between composition, structure, and performance. Asphaltene-rich asphalt boasts enhanced performance, offering increased stiffness (reduced penetration and creep) for improved structural integrity, as well as higher viscosity and thermal resistance for greater durability and longevity [37][38][39].

The result in Figure 6 shows that the addition of crumb rubber (CR) to the base bitumen (0CR) significantly increased the asphaltene content, from 10.65% to 31.57-37.54% for the CR-modified samples. This trend suggests that crumb rubber incorporation leads to a higher concentration of asphaltenes, possibly due to the rubber particles interacting with and stabilizing the heavier fractions of the bitumen. Similar findings were reported by Navarro et al. [21], where crumb rubber increased the asphaltene content in bitumen. This increase in asphaltenes led to a corresponding rise in the colloidal stability index (C.I.), from 0.22 for the base bitumen to 0.71-0.86 for the CR-modified samples. The C.I measures the stability of bitumen colloids; a lower C.I indicates better stability. This increase in C.I indicates reduced stability, which means that crumb rubber can destabilize the colloidal structure of bitumen [21].

As WVO content increases, the asphaltene content decreases (e.g., from 37.54% in 10CR to 28.00% in 10CR20). WVO appears to reduce the concentration of asphaltenes, likely due to its diluting effect on the heavier fractions of bitumen, consistent with the observations by Fini et al. [26]. The addition of waste vegetable oil (WVO) to the CR-modified bitumen samples (10CR, 15CR, 20CR) further influenced the colloidal stability, as presented in Table 5. The addition of WVO decreases the C.I (e.g., from 0.86 in 10CR to 0.65 in 10CR20), improving colloidal stability. This finding is supported by Wang et al.[20], where bio-oil additives improved the stability of bitumen.

Saturates are the lighter fractions in bitumen, influencing viscosity and flow. The saturate content shows a slight increase with CR content (e.g., from 7.12% in 0CR to 10.00% in 20CR). This suggests that crumb rubber may contribute to a more balanced distribution of lighter fractions in bitumen. This aligns with research by Heitzman [40] which reported a slight increase in saturates in crumb rubber-modified bitumen.

The data suggests that there is an optimal balance between the CR and WVO content to achieve the desired colloidal stability. For example, the 10CRWVO5 sample had the highest C.I. of 0.86, indicating the best colloidal stability among the WVO-modified samples. Increasing the WVO content beyond 10% led to a significant decrease in the C.I., potentially making the bitumen less suitable for certain applications [35][41].

The saturate content further increases with the addition of WVO (e.g., from 8.61% in 10CR to 11.30% in 10CR20), indicating that WVO contributes more light fractions to the bitumen, as also noted by Wang et al. [20].

Aromatics are important for the solvency of asphaltenes and contribute to the bitumen's viscoelastic properties. Aromatic content decreases with increased CR (e.g., from 61.57% in 0CR to 27.82% in 10CR), suggesting that crumb rubber reduces the soluble fractions. This decrease aligns with findings by Huang et al. [42], where aromatic content decreased in rubber-modified bitumen.

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/IJISRT24JUL1744

The aromatic content increases with WVO addition (e.g., from 27.82% in 10CR to 33.40% in 10CR20), indicating that WVO helps in maintaining the balance of solvable fractions, which is consistent with findings by Yang et al. [24].

Resins help in the dispersion of asphaltenes, affecting the stability and adhesiveness of bitumen. Resin content increases with CR addition (e.g., from 20.66% in 0CR to 27.37% in 20CR). The increase in resin content with CR is corroborated by Goh et al. [27], which highlights enhanced adhesive properties in crumb rubber-modified bitumen.

WVO addition further increases resin content (e.g., from 26.03% in 10CR to 27.30% in 10CR20), suggesting improved dispersion of asphaltenes, as also noted by Xiao et al. [28].

Table 5: Colloidal Stability Index of Base and Modified Bitumen

Sample	Colloidal Stability index (C.I)
0CR	0.22
10CR	0.86
15CR	0.82
20CR	20CR
10CRWVO5	0.86
10CRWVO10	0.77
10CRWVO20	0.65
15CRWVO5	0.85
15CRWVO10	0.71
15CRWVO20	0.59
20CRWVO5	0.78
20CRWVO10	0.67
20CRWVO20	0.55

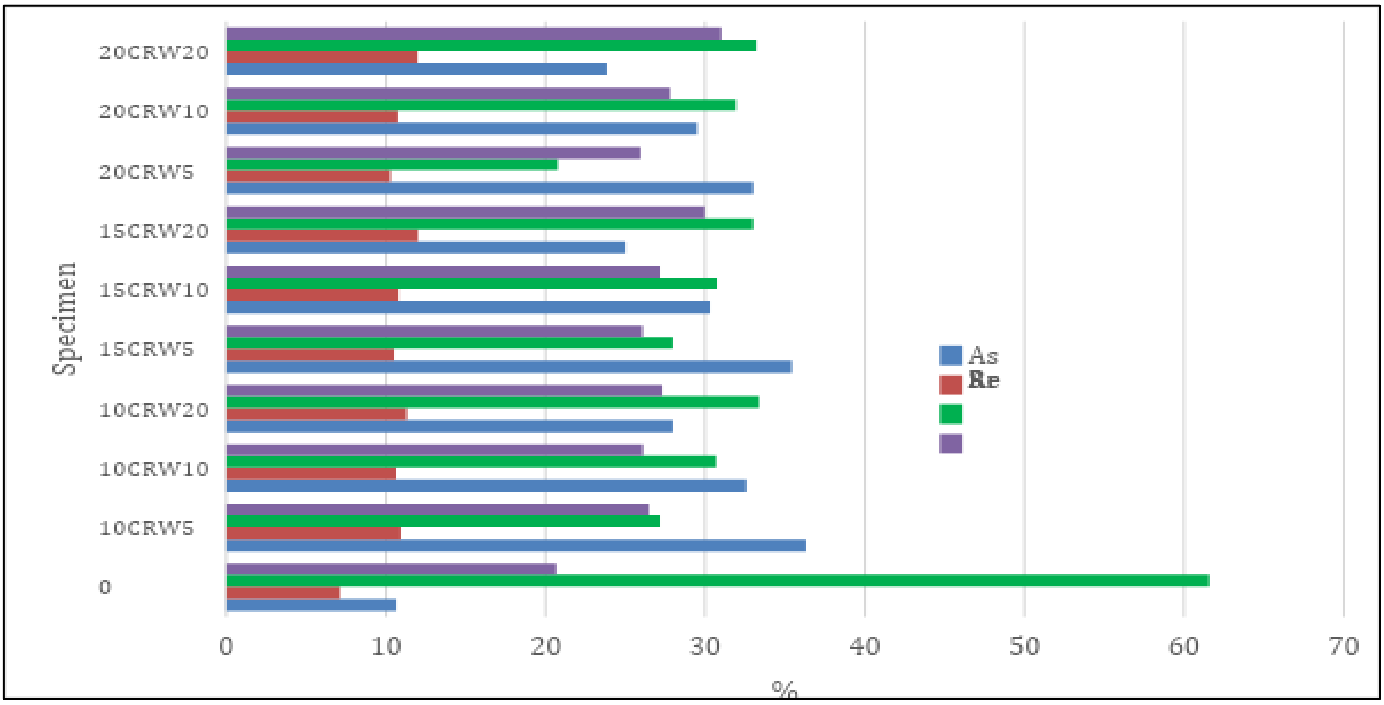

Fig 6: SARA properties for base and modified bitumen

C. Rheological Properties

- *The Rheological Tests Conducted on the Base and Modified Bitumen Samples used Include:*

- Dynamic Shear Rheometer (DSR) test - Complex Shear Modulus, Phase angle, Rutting Parameter, and Fatigue Factor.
- Bending Beam Rheometer (BBR) test - Flexural creep and dynamic creep.

- *Dynamic Shear Rheometer (DSR)*

The DSR test is conducted at intermediate and high temperatures to evaluate the fatigue cracking and rutting resistance of both unmodified and modified bitumen. The test was conducted within a temperature range of 58°C to 76°C, with a strain value of $\gamma = 12\%$ and an angular frequency of $\omega = 1.6$ Hz (equivalent to 10 rad/s), and the bitumen samples were tested with the adoption of a 25 mm diameter plate.

The early life of roadways is plagued by the menace of rutting, a deformation caused by repeated traffic loads. As pavements mature, fatigue cracking, driven by cyclic stresses, takes center stage as the primary concern. The DSR test provides critical insights into these opposing threats through two key outputs: complex shear modulus (G*) and phase angle (δ). G* represents the material's overall resistance to deformation under repeated shearing. It essentially gauges how much the material "fights back" against traffic loads. Phase angle (δ), on the other hand, reflects the material's "viscousness" by measuring the lag between applied stress and resulting strain. By analyzing both G* and δ, engineers can predict the susceptibility of Hot Mix Asphalt (HMA) to both rutting and fatigue cracking, ensuring long-lasting and resilient roadways.

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/IJISRT24JUL1744

The result in Figure 7 shows that the complex moduli of crumb rubber-modified bitumen (CRMB) and WVO-CRMB are both larger than that of control asphalt, except for sample 10CRWVO5, suggesting that incorporating crumb rubber enhances asphalt's resistance to high-temperature deformation.

With the increase in temperature, the complex moduli of both control asphalt and modified asphalt decrease. The higher the complex modulus is, the stronger the shear resistance of asphalt at high temperatures. The initial introduction of WVO decreased the complex modulus due to the lightweight components contained in WVO; the dilution and lubrication of WVO-CRMB tend to reduce the high-temperature deformation resistance.

However, with the increase of WVO, the complex modulus value increased, with the highest value obtained at 20% of WVO.

The complex modulus value of CRMB showed a better result than WVO-CRMB; however, both samples showed a better result than the control sample. This shows that CR and WVO modifications improve bitumen’s resistance to shear stress. Bilema et al. [25] also reported comparable findings. They incorporated CR and waste frying oil (WFO) as a hybrid rejuvenator on the RAP binder, the result obtained showed that binders with 25% and 40% RAP content incorporating the combination of WFO and CR give a G* value of 37.2 and 32.7 kPa at 46 °C, respectively, which was slightly higher than that of virgin bitumen.

The phase angle (δ°) signifies the level of elasticity in the bituminous binder, with values ranging from 0° to 90°. The result in Figure 8 shows an increase in the phase angle of the samples with an increase in temperature, which is consistent with the findings of Maharaj et al. [12] and Bilema et al. [25]. As the phase angle of the samples increases, the elastic component is reduced, making the bitumen more “sticky” at high temperatures, and the ability to resist deformation decreases.

The result shows that adding crumb rubber increased the bitumen's phase angle, which is consistent with the findings of Badri et al [43], whose results showed a phase angle of 77° and 85° for 10% CR at 58°C and 76°C respectively, and 76° and 82° for 12% CR at 58°C and 76°C respectively. However, adding WVO reduced the phase angle, consistent with the result obtained by Bilema et al. [25]. Their results showed that binders with 25% and 40% RAP content incorporating the combination of WFO and CR have the δ° values of 78.5° and 77.9° at 46 °C, respectively, which was lower than that of the virgin bitumen.

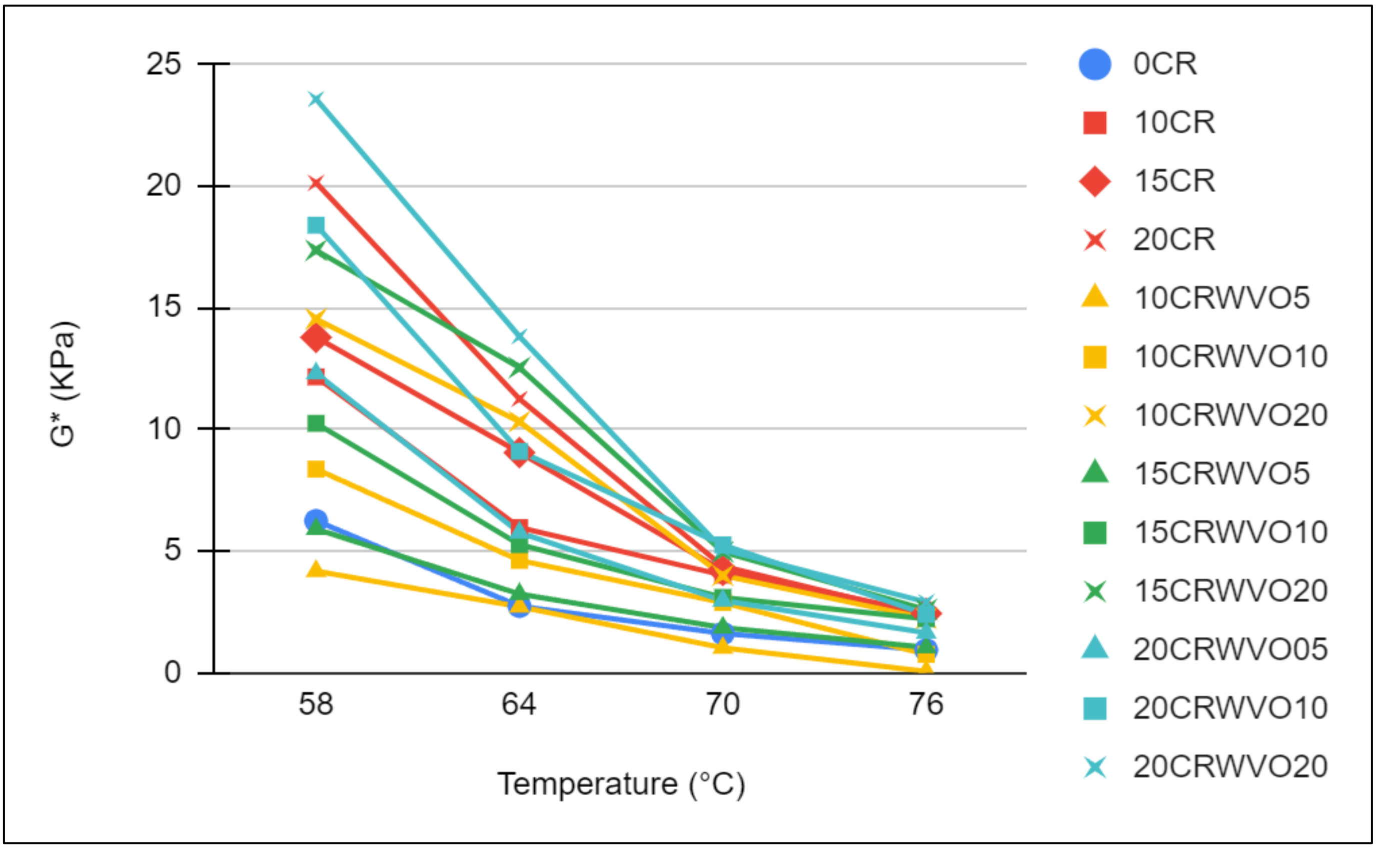

Fig 7: Complex Shear Modulus of Base and Modified Bitumen at Different Temperatures

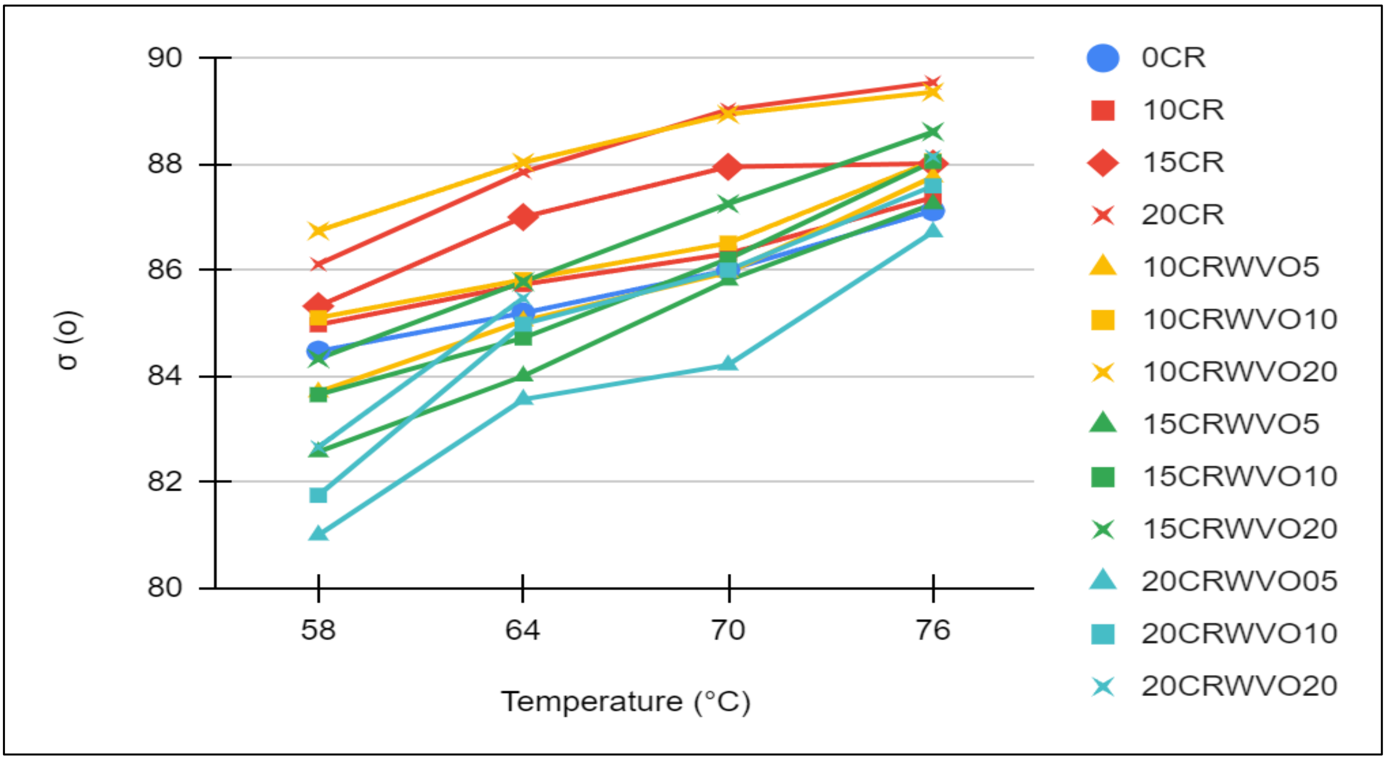

Fig 8: Phase Angle of Base and Modified Bitumen at Different Temperatures

Superpave specifications leverage two key parameters, fatigue resistance (G.sinσ) and rutting resistance (G/sinσ), to assess asphalt binders' performance at high and intermediate temperatures. For rutting resistance, Superpave sets a minimum threshold of 1.0 kPa. Fatigue resistance falls within a broader range of 1.0 kPa to 5000 kPa. High G/sinσ values at high temperatures signify robust rutting resistance, reflecting the binder's ability to withstand deformation under heat [44].

Figures 9 and 10 illustrate the rutting and fatigue parameters for both modified and unmodified bitumen.

As expected, increasing test temperatures lowered the resistance to both rutting and fatigue for all binders. However, higher CR content mitigates this decline, indicating better high-temperature performance.

Figure 9 demonstrates that crumb rubber binders exhibit superior resistance to rutting compared to the control sample. The control sample experienced failure at a high temperature of 76 °C, dropping below 1.0 kPa, marking 76 °C as the "failure" or "critical" temperature. Samples containing crumb rubber outperformed the control sample, with optimal results achieved at 20% crumb rubber content, aligning with findings from Xu et al. [45]. Binders with waste vegetable oil (WVO) content displayed an increasing G*/sinσ value with rising WVO content, reaching an optimum value at 20% WVO content. Rutting resistance values at 76 °C for 10CRWVO20, 15CRWVO20, and 20CRWVO20 were 2.24, 2.60, and 2.91 kPa, respectively, all meeting SuperPave specifications.

A similar trend was observed for the fatigue parameter, as depicted in Figure 10, consistent with the findings of Bilema et al [25] and Sun et al [33]. It can be inferred that the addition of crumb rubber significantly increases the complex shear modulus (G) and rutting parameter (G/sinδ), indicating improved resistance to permanent deformation [46][47]. However, the higher fatigue factor suggests that while CR improves rutting resistance, it may negatively impact fatigue performance [21]. The addition of WVO reduced some of the higher molecular mass chains in the binder, rendering it less stiff and thereby improving rutting and fatigue resistance of bitumen compared to the control sample [48].

➢ *Bending Beam Rheometer (BBR)*

BBR test measures the low-temperature stiffness and relaxation properties of asphalt binders. These criteria reflect the capacity of an asphalt binder to withstand low-temperature cracking, commonly referred to as "thermal crack" or transverse crack, which is a significant pavement distress factor in cold regions. A specified maximum creep stiffness value (300 MPa) is set, as higher creep stiffness values correlate with elevated thermal stresses. Additionally, a minimum m-value (0.300) is established, as a lower m-value indicates a diminished ability to relax stresses.

The results in Figures 11 and 12 showed that the flexural creep stiffness increases with decreasing temperature, which means that the thermal stresses increase. Also, the creep rate decreases, reducing the ability to relax these stresses.

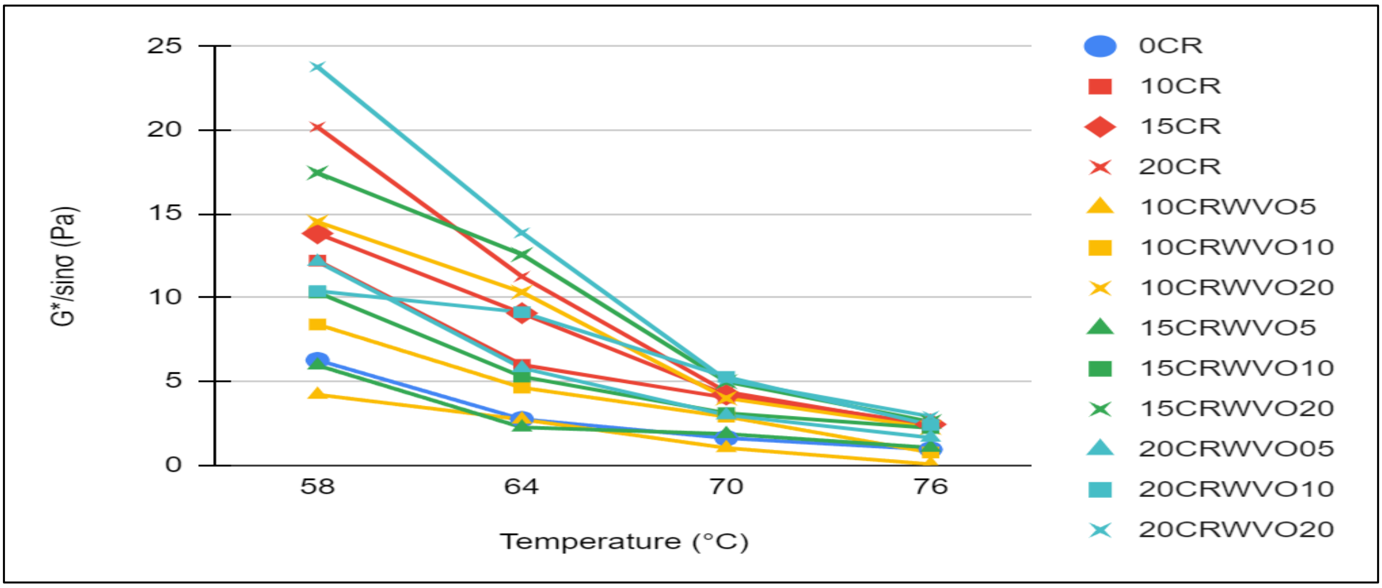

Fig 9: Rutting Parameter G*/sinσ of base and Modified Bitumen

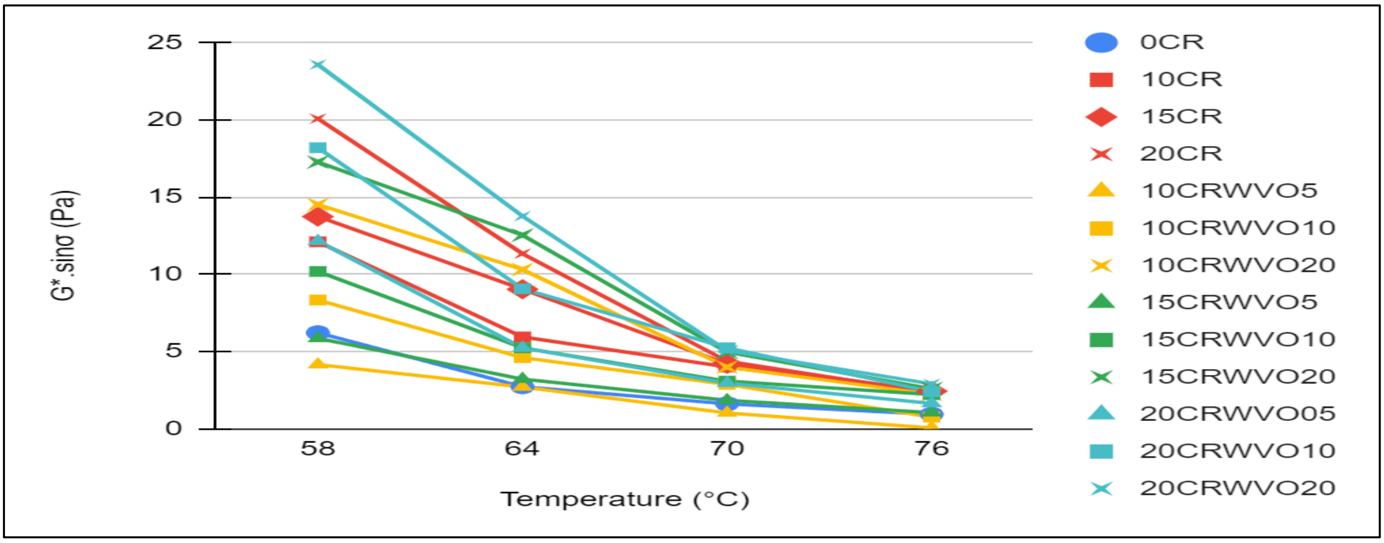

Fig 10: Fatigue Factor G*.sinσ of base and Modified Bitumen

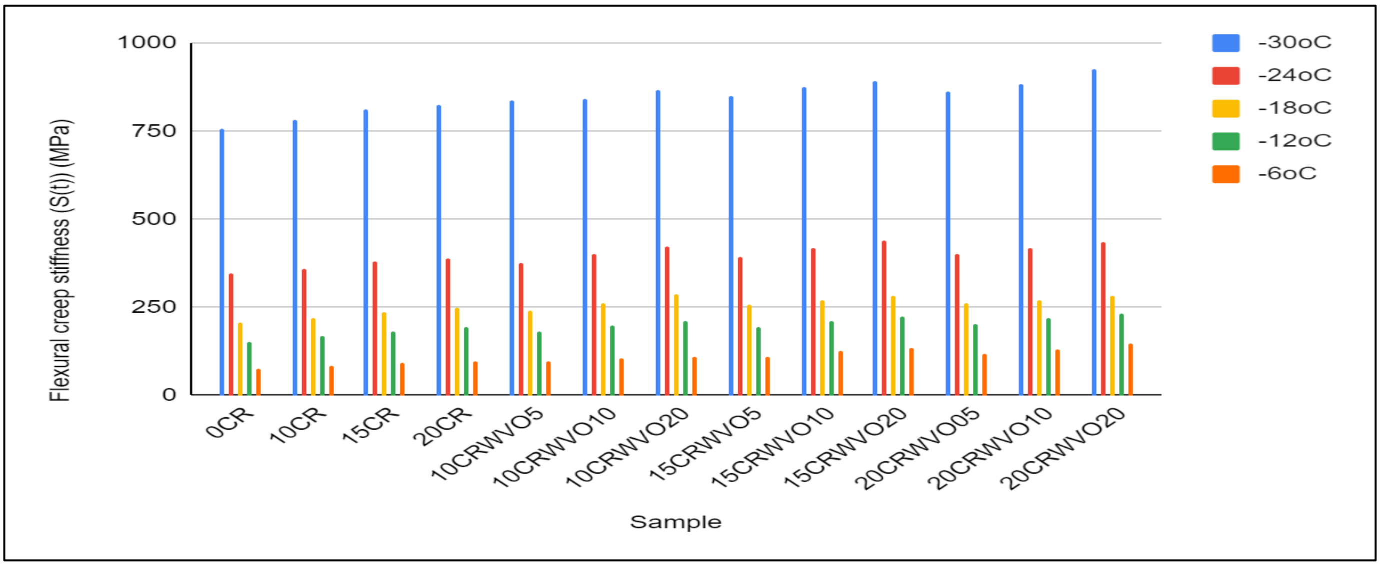

Fig 11: Flexural Creep Stiffness of Base and Modified Bitumen

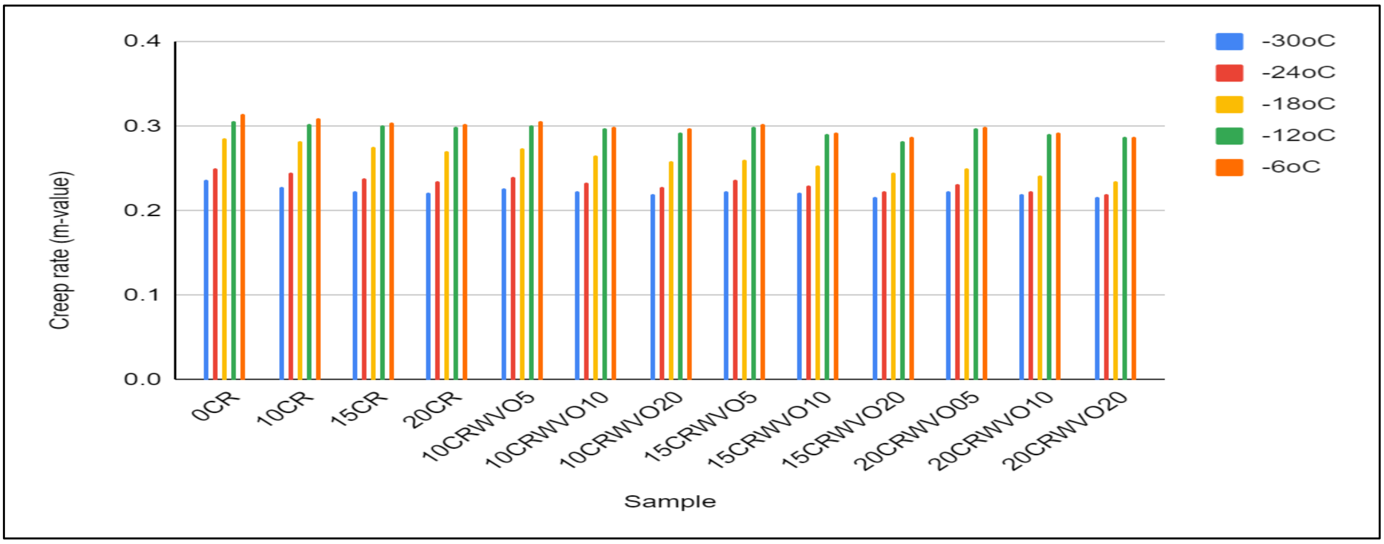

Fig 12: Creep Rate of Base and Modified Bitumen

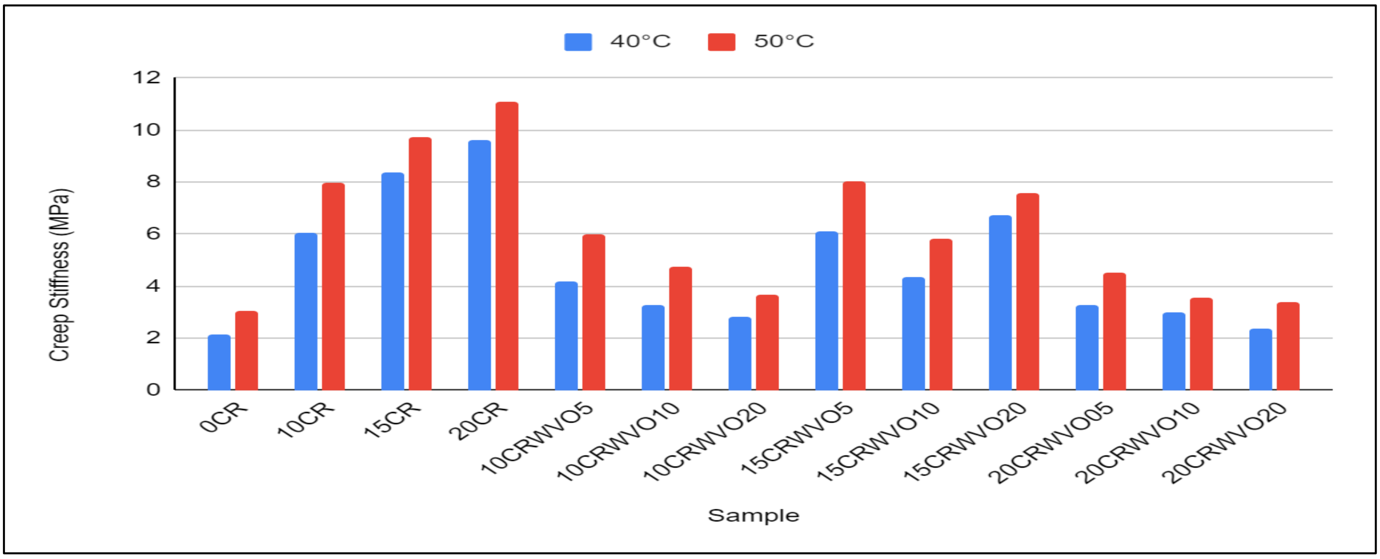

Fig 13: Dynamic Creep Stiffness of Base and Modified Bitumen at 200 kPa

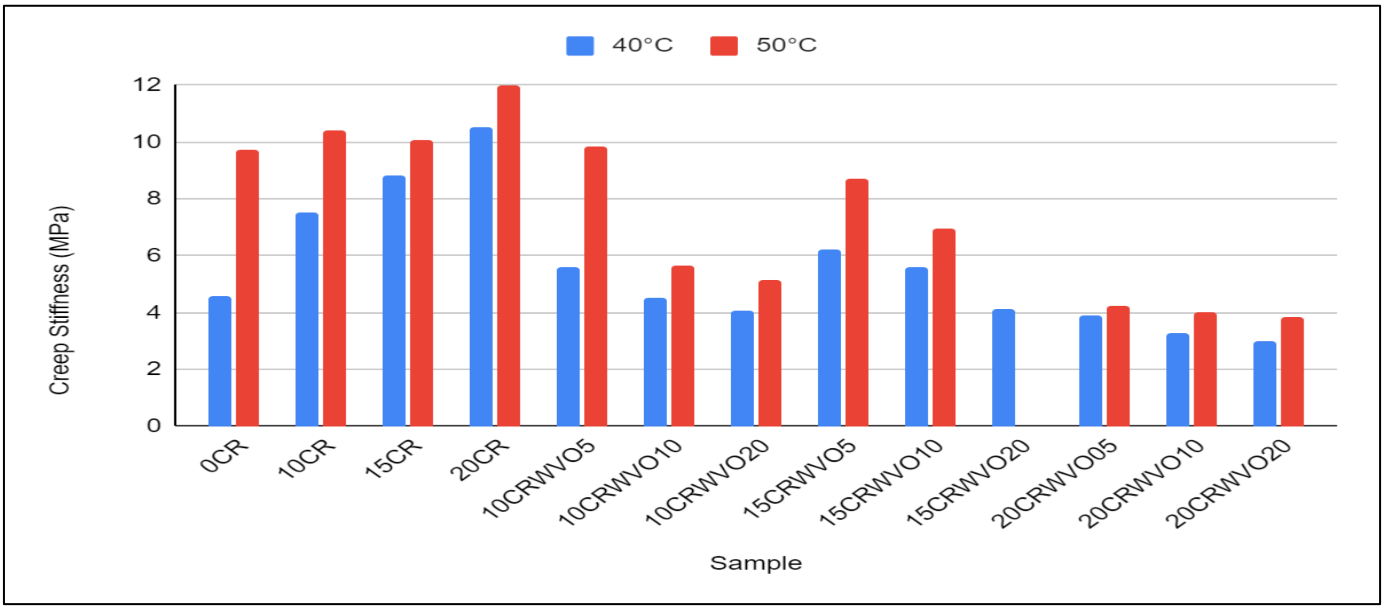

Fig 14: Dynamic Creep Stiffness of Base and Modified Bitumen at 400 kPa

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/IJISRT24JUL1744

The increasing addition of CR increased the flexural creep stiffness and reduced the creep rate, indicating that the addition of crumb rubber increases the stiffness of the bitumen at low temperatures. The addition of WVO modifies the S(t) values for each CR content level. For example, at 10CR10 (10% CR, 10% WVO), the S(t) value is higher compared to 10CR but lower compared to 20CR at the same temperature. The addition of WVO increases the m-value for each CR content level (e.g., from 0.229 for 10CR to 0.226 for 10CR05 at -30°C). This suggests that WVO has a softening effect on the bitumen, making it less stiff and potentially improving its resistance to low-temperature cracking [24][26]. The temperature at which the specification was satisfied is -12°C.

Dynamic creep test investigates the permanent deformation of asphalt mixtures. It is done at varying loads and temperatures and is pertinent to hot climate conditions like Nigeria. The dynamic creep rate as expressed in Figures 13 and 14 showed that the dynamic creep rate increased with temperature and with loading or stress. This trend was observed with an increment in CR but decreased with an increment in WVO.

A higher creep stiffness value indicates a lower resistance potential. The results show that bitumen modified with CR and WVO has a higher resistance to permanent deformation and therefore deforms much lower compared to the control sample.

IV. CONCLUSION

This study investigated the effects of crumb rubber (CR) and waste vegetable oil (WVO) modification on bitumen properties relevant to pavements in Nigeria, a hot climate region with heavy traffic. The findings were evaluated against standard specifications and compared to previous research.

The study used 60/70 grade virgin bitumen as the base bitumen, heated to 160°C. Crumb rubber was added at 10%, 15%, and 20% by weight of the bitumen and mixed for 60 minutes at 1200 rpm. Tests were conducted to determine the specific gravity, penetration, viscosity, softening point, flash point, SARA composition, and FTIR. The rheological properties were assessed using DSR and BBR.

➢ *Based on the Result, the Following Conclusions were Made:*

- Penetration: CR modification increased stiffness (decreased penetration) due to its elastomeric properties. WVO addition had a softening effect. 10CR05 and 20CR05 achieved the desired penetration value within the standard limits by adding only 5% WVO.
- Softening Point: CR increased the softening point, indicating improved thermal stability. WVO reduced the softening point. For hot weather regions, 10CR modification is optimal.
- Specific Gravity: 10CR, 15CR, 10CR05, 10CR10, and 10CR20 fell within the standard limits. Increasing CR content increased specific gravity. WVO increased specific gravity, but further addition led to a decrease.
- Viscosity: All samples met the minimum ASTM viscosity requirement at 135°C. CR increased viscosity. WVO further increased viscosity, potentially due to WVO-CR interactions, which may not be ideal for energy consumption during mixing and compaction.
- Asphaltene Content and Colloidal Stability: CR significantly increased asphaltene content and Colloidal Stability Index (C.I.). WVO content exceeding 10% destabilized the colloidal structure and reduced C.I. 10CRWVO5 exhibited the best colloidal stability among WVO-modified samples due to the optimal balance between CR and WVO content.
- High-Temperature Performance: CR modification improved the complex modulus, indicating better resistance to high-temperature deformation. While WVO initially decreased it, the complex modulus increased with higher WVO content (20%). Overall, both CR and WVO modifications improved bitumen's high-temperature performance.
- Rutting Resistance: CR modification improved rutting resistance (G*/sinδ) compared to the control bitumen. WVO content up to 20% further enhanced rutting resistance. Samples containing 20% crumb rubber (20CR) achieved the optimal rutting resistance at 76°C. Additionally, WVO content up to 20% (10CRWVO20, 15CRWVO20, and 20CRWVO20) met rutting resistance specifications.
- Fatigue Resistance: Similar to rutting resistance, WVO content up to 20% improved fatigue resistance compared to the control sample.
- Low-Temperature Performance: CR and WVO increased low-temperature stiffness (flexural creep stiffness) and reduced the creep rate at temperatures exceeding the specification limit (-12°C). This might require further investigation for colder regions. However, the dynamic creep rate with CR increased with temperature and loading, while WVO showed the opposite trend, suggesting better resistance to permanent deformation.

Overall, crumb rubber modification improved bitumen's stiffness, rutting resistance, and thermal stability, making it a suitable option for pavements in Nigeria. Waste vegetable oil, in limited quantities (up to 10%), can further enhance rutting resistance without compromising colloidal stability, making it a potentially viable and sustainable approach for road construction. However, the increased viscosity due to the WVO-CR interaction might raise energy consumption concerns during construction. Further research is recommended to optimize CR-WVO ratios and assess the long-term performance of these modified binders.

ACKNOWLEDGMENT

We would like to thank the staff and technicians of Reynolds Construction Company for their support.

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/IJISRT24JUL1744

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