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Characteristics of Waste Oil-rejuvenated RAP Bitumen: An Experimental Study

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ABSTRACT

In recent years, Reclaimed Asphalt Pavement (RAP) has become very popular in pavement construction due to its benefits to the economy and the environment. The present study investigates the feasibility of employing Waste Cooking Oil (WCO) and Waste Engine Oil (WEO) as rejuvenators blended with reusable asphalt binder through physical and rheological properties at high and intermediate temperatures. Examined conventional properties of WCO-and WEO-modified bitumen include softening point, penetration, ductility and viscosity. In addition to these rheological properties, they also include Amplitude Sweep, Frequency Sweep, Multiple Stress Creep Recovery (MSCR), Linear Amplitude Sweep (LAS) and High-temperature Performance Grading (HTPG) tests carried out by Dynamic Shear Rheometer (DSR). The experimental outcomes revealed that both WCO and WEO could reduce deformation resistance and improve stiffness, workability and viscous behavior of aged bitumen. Moreover, the addition of waste oils improves the fatigue lives of rejuvenated bitumen and enhance fatigue cracking resistance, but at the cost of rutting resistance. Overall, WCO performs better in restoring stiff binder properties than WEO as per rheological testing.

KEYWORDS: Dynamic shear rheometer (DSR), Reclaimed asphalt pavement (RAP), Rejuvenators, Waste cooking oil (WCO), Waste engine oil (WEO).

INTRODUCTION

Nowadays, using RAP in flexible pavements proves to be cost-effective, environment-friendly and energy-conserving (Yusoff et al., 2019). Every year, more than a hundred million tons of RAP is generated from milling pavements that encompass the main segment of waste materials over the globe (Zahoor et al., 2021). Recycling asphalt pavement reduces the consumption of natural aggregates and the waste of landfills due to the dumping of removed pavement material, which is an effective measure for the sustainable development of any country. A recent study by Qiao et al. (2019) showed that using 40% of RAP in new pavement construction can cut down the initial cost by approximately 18%. However, reprocessing of RAP is associated with a significant problem of bitumen aging, leading to asphalt failures, such as fatigue, moisture damage, thermal cracking, rutting and raveling (Jain et al., 2021). This aging process adversely affects several properties of bitumen, making it more brittle and complex than fresh one and increasing its viscosity. Mixing asphalt binder generated from RAP with fresh bitumen results in a stiffer binder, which influences its workability and makes it more prone to cracking (Ongel and Hugener, 2015). One way to avoid the binder stiffness problem is to reprocess the RAP binder with some recycling agents termed rejuvenators.

The primary role of rejuvenators is to recover various parameters of aged asphalt, such as viscosity, workability, rutting and fatigue cracking resistance by altering its physical and chemical structures. It is perceived that the rheological and physical properties of virgin binder can be attained from aged binder by mixing it with rejuvenators that stabilize asphaltene to maltene ratio (Pan et al., 2018). Nowadays, using

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rejuvenators with RAP is a prime area of research (Singh et al., 2021). Several types of polymers and oils, like aromatic extracts, tall oils, bio-oils and vegetable oils available in the market are used as rejuvenators. However, there is a cost implication of commercially available rejuvenators. As a result, emphasis is being placed on incorporating a sustainable rejuvenator that lowers construction costs and reduces environmental impacts. Waste oils can be used for RAP rejuvenation because of their similar molecular and chemical structures to those of asphalt.

Vegetable oils are among the most widely used kitchen products, recommended not to be reused because of their harmful effects on the environment and human health. The disposal of waste cooking oil (WCO) must be managed and treated correctly. One of the best ways to preserve the environment is reusing these oils in applications other than the food industry. The physical and chemical properties of these oils attracted many researchers (Ahmed and Hossain, 2020; Al-Omari et al., 2018; Cao et al., 2018; Chen et al., 2014; Chen et al., 2014; Mamun and Wahhab, 2020; Taherkhani and Noorian, 2021; Zahoor et al., 2021; Zargar et al., 2012) to explore their usage as a rejuvenating material in asphalt mixtures for regaining the properties of the aged binder. The rejuvenators added must have the potential to sustain their capability to resist rutting, cracking and fatigue. It has been found that WCO can effectively soften the RAP binder and improve its fatigue and thermal-cracking behavior while reducing its rutting resistance (Asli et al., 2012; Azahar et al., 2017; Luo et al., 2017; Xinxin et al., 2018). Considering natural-resource conservation and low energy utilization, the other prospective agent commonly used for recycling RAP material is waste engine oil (WEO). Globally, the number of automobiles powered by internal-combustion engines has expanded considerably. As a result, engine oil requirement and consumption have increased many folds in the recent past. Engine oil is derived from petroleum; it needs to be discarded after a specific use, as it fails to serve the intended purpose of lubrication. From the previous studies (DeDene and You, 2014; Jia et al., 2015; Li et al., 2019; Mamun and Wahhab, 2018), it can be stated that WEO enhances stiffness, fatigue resistance, workability and temperature sensitivity while rutting resistance is compromised.

Further, it can be observed that the inclusion of waste oil leads to softening of the RAP binder. However, advancement in fatigue and rutting resistance is not sure, as softer RAP binders become more liable to rutting and cracking. In conclusion, there is still a lack of a comprehensive study about the probable adverse effects and optimum dosages of WEO and WCO.

Recently, many researchers have been using WEO and WCO in conjunction with aged RAP binder as rejuvenators (Azahar et al., 2016; Ackbarali et al., 2017; Mamun et al., 2020). From their results, it can be concluded that both oils could effectively enhance penetration and ductility and reduce the stiffness and viscosity of aged binder owing to improving the workability of the mix. Further, WEO and WCO may be adopted as substitutes for commercial rejuvenators, as they may bring down the demand for virgin materials.

The current study examines the feasibility of employing waste oils; i.e., WEO and WCO, as rejuvenating additives blended with an aged binder. The primary objective of this study is to examine and compare various physical and rheological characteristics of RAP binders modified with WCO and WEO. This comparison illustrated which oil best serves the purpose of improving the features of an aged binder compared to a virgin one. A comprehensive investigation is performed to understand the impact of waste oils; i.e., WCO and WEO, on the performance characteristics of RAP bitumen using conventional and advanced tests, like linear amplitude sweep (LAS) and multiple stress creep recovery (MSCR) tests. The present study will also focus on determining the optimum content of rejuvenator dosages.

Objectives

(a) To study the impact of WCO and WEO as potential rejuvenating materials on restoring the fundamental physical properties of RAP at varying dosages.

(b) To examine and compare the influence of both rejuvenators on rheological characteristics, like complex shear modulus(G^*), phase angle(δ), performance grading temperature, rutting resistance parameter ($G^*/\sin\delta$) and fatigue resistance parameter ($G^*\sin\delta$) of RAP binder.

MATERIALS

This study uses different materials comprised of reclaimed asphalt binder, reference bitumen viscosity grade -30 (VG-30) and waste oils as rejuvenators.

Reclaimed Asphalt Pavement (RAP)

For this study, RAP material having a field age of approximately ten years was obtained from a dumped site near Braham Sarovar in Kurukshetra. It was a rehabilitation project undertaken by Public Works Department (PWD) on (SH-6) from Pipli to Kurukshetra university road. A large quantity of RAP material was generated during this project. VG-30 grade binder was used in the pavement at the time of construction. Reclaimed binder was extracted using benzene as solvent through centrifuge extractor as per ASTM-D2172 (2017), followed by recovery of binder from solution through Abson recovery method given in ASTM-D1856 (2015). Further, to remove even traces of benzene from solution, RTFO ageing of RAP binder is performed. After performing RTFO ageing, we assume that RAP binder is now ready for further testing.

Reference Bitumen

The VG-30 grade of bitumen is taken as reference bitumen obtained from the Indian Oil Corporation, Limited (IOCL) Panipat refinery for the present study. The various conventional properties of the reference binder are given in Table 1.

Table 1. Properties of virgin bitumen (VG-30) as per IS-73, 2013

Sr. No.	Properties	Obtained Value	Reference Values as per IS-73	Testing Code
1.	Penetration (25°C 100g, 5sec.) (0.1mm)	59	50-70	IS 1203
2.	Softening point (°C)	50	47	IS 1205
3.	Ductility at 25°C (cm)	57	40	IS 1208
4.	Specific gravity	1.01	0.97-1.02	IS 1202
5.	Dynamic viscosity at 60°C (Poises)	3032	2400-3600	IS 1206 (II)
6.	Kinematic viscosity at 135°C (Cst)	408	350 (Min.)	IS 1206 (III)

Waste Oils

In this study, WCO and WEO are used as rejuvenators because of their similar molecular structure as that of bitumen. WCO and WEO were acquired from the hostel mess of National Institute of Technology (NIT) Kurukshetra and a local automobile workshop in Kurukshetra, respectively. To remove the suspended impurities, oils were filtered in the laboratory through a simple filtering process. The basic properties of WCO and WEO are given in Table 2.

Table 2. Properties of WCO and WEO

Sr. No.	Test	WEO	WCO
1.	Flashpoint (°C)	185	251
2.	Specific gravity	0.92	0.97
3.	Kinematic viscosity (Cst)	384	312

Experimental Procedure

Preparation of Rejuvenated Samples

The rejuvenated modified samples were made by blending RAP binder with five dosages of WCO (3%, 6%, 9%, 12% and 13.5%) and WEO (3%, 6%, 9%, 12% and 15%) by weight of binder. For this purpose, the extracted aged binder was heated to a temperature of 115°C for 25 minutes and transferred into beakers. Then, the rejuvenators (in the desired quantity) were added to the beakers, mixed and stirred for at least 5 minutes (Nayak and Sahoo, 2017) or until a homogeneous sample was obtained for further testing.

Conventional Properties

Penetration, softening-point and ductility tests are the basic tests to determine the fundamental properties of a virgin as well as WEO-and WCO-rejuvenated samples in accordance with IS:1203 (1978), IS:1205 (1978) and IS:1208 (1978), respectively. Further, viscosity tests were performed on aged, virgin and rejuvenated samples using a dynamic shear rheometer to determine the internal friction and flow resistance of the asphalt binder. The tests were conducted at 60°C and 135°C temperatures to determine dynamic and kinematic viscosity, respectively, in accordance with

IS:1206-II (1978) and IS:1206-III (1978).

Firstly, to check the consistency of bitumen, a penetration test is performed at 25°C. In this test, a standard needle penetrates a bitumen sample under a load of 100g for a known loading time of 5 seconds, defining a distance in tenths of a millimeter, called penetration value. The more viscous the bitumen, the less distance the needle can penetrate. The higher penetration value of rejuvenated RAP delineates a softer consistency of bitumen.

Softening-point test is a method to check the consistency of asphalt binders by determining the equi-viscous temperature at which a specific degree of softening is attained. Furthermore, ductility is another parameter of bitumen that gives an idea about the adhesive property of bitumen and its capability of stretching under certain conditions.

Rheological Properties

DSR is used to elaborate the viscoelastic behaviour of asphalt binders over a varied range of frequencies and temperatures according to AASHTO-T315 (2010). In the present work, Anton Par Rheometer (MCR-72) was utilized to determine high-temperature and intermediate-temperature properties through parallel-plate geometry of 25 mm and 8 mm with 1-mm and 2-mm gaps, respectively. DSR offers strain information against applied stresses within the material at different frequencies and temperatures. This information determines parameters, like complex shear modulus (G*) and phase angle (δ). G* and δ parameters can be used to find a relationship between fatigue and rutting resistance of the binder and its rheological performance.

Amplitude Sweep Test

The linear viscoelastic region indicates the strain range (without destroying the structure) of the sample within which all other tests are carried out. In this context, amplitude sweep tests were conducted to figure out the asphalt binders' linear viscoelastic limits (LVE). After determining the LVE range, a frequency sweep test was conducted to see how the modified binders behaved at different temperatures and frequencies from rheological considerations.

Frequency Sweep Test

G* and δ are the two basic rheological parameters representing the stiffness properties of bitumen binders. It has to be ensured that the test has been conducted within the LVE limits. The experiment was conducted at a temperature ranging from 30°C to 70°C and at a strain rate of 0.1%. The range of frequency was chosen from 0.1 to 100 rad/sec for this test. The experimental data was plotted as isothermal plots at a temperature of 60°C.

Superpave Rutting Test

G*/sinδ obtained through the superpave rutting test is further used for evaluating the failure criteria of the rejuvenated binders. Temperatures conforming to G*/sinδ values of 1 kPa and 2.2 kPa for virgin binder and short-term aged binders, respectively, are PG temperatures, as per superpave specification AASHTO-T315 (2010). In the present study, tests were conducted with a constant strain rate of 12% and frequency (angular) of 10 rad/sec. The test was initiated at a temperature of 58°C and continued with an increase of 6°C until G*/sinδ value ranges below 1 kPa. The temperature at which the failure occurs is known as the performance-grading (PG) temperature.

Multiple Stress Creep Recovery (MSCR) Test

Although the rutting factor (G*/sinδ) obtained using superpave rutting test indicates the high-temperature performance of the binder, this parameter doesn't account for rejuvenated binders' delayed recovery response. To overcome this limitation, MSCR test was performed, as it can reflect nonlinearity in the rheological response of modified binder as per AASHTO-T350 (2018). Parameters, such as percent recovery (R) and non-recoverable creep compliance (Jnr) found from the MSCR test strongly correlate with the rutting property of modified binder. Using 25-mm spindle and 1-mm gap setting in DSR, Jnr and R are calculated by applying stress levels of 0.1 and 3.2 kPa on modified binders for a consecutive cycle of 1-sec creep and 9-sec recovery. As per the standard procedure, the test was run at a temperature of 64°C. Ten continuous loading and recovery cycles are generated for each stress level.

Superpave Fatigue Parameter Test

According to recommendations of SHRP (Strategic Highway Research Programme), G*sinδ is utilized to measure binder fatigue resistance. It is based on the idea of dissipated-energy perception. This means that reduced energy dissipated per cycle will lead to lower accumulated stress. Therefore, the bitumen binder having lesser G*sinδ has a better fatigue strength. G*sinδ is limited to a maximum of 5000 kPa as recommended by SHRP for good fatigue resistance. This test was performed using DSR with 8-mm diameter and 2-mm gap setting geometry at a temperature of 25°C.

Linear Amplitude Sweep (LAS) Test

Although G*sinδ is attributed to the measurement of fatigue resistance, the test suffers from serious shortcomings, as it does not have a good correlation with asphalt mixture fatigue property. LAS test has been anticipated as a substitute for the evaluation of fatigue cracking as outlined in AASHTO-TP101-14 (2013). Further, the data obtained from the LAS test is used to evaluate the parameters ‘A’ and ‘B’ needed in the binder fatigue equation given as:

$$N_f = A(\gamma_{max})^{-B} \quad \text{(Eq. 1)}$$

where N_f is defined as the number of failure cycles, A and B are model parameters and γ_{max} is the maximum expected binder strain. This test was performed using DSR with an 8-mm diameter and a 2-mm gap setting arrangement at 25°C. The test is performed in two stages. First, α (an undamaged-material property) is calculated using frequency sweep test at the strain rate of 0.1% with frequency variation of 0.2 to 30 Hz. Further, α is used to analyze ‘B’ parameter in the equation (B=2α). Secondly, amplitude sweep test is performed at 10-Hz frequency with linearly increasing load amplitude of 0.1 to 30%. The amplitude is increased by 1%, while the binder is subjected to 10 cycles at each strain value. Viscoelastic continuum damage (VECD) mechanistic analysis technique is used to determine parameter ‘A’.

RESULTS AND DISCUSSION

Physical Tests

Penetration and softening-point tests are the most crucial parameters for determining the physical properties of binders. The results of penetration test conducted on RAP rejuvenated with WCO and WEO are shown in Figure 1(a). RAP had the lowest penetration value among all the samples due to its stiffer and oxidative behavior. The increased penetration of rejuvenated binders reveals that adding WCO and WEO softens the RAP by reducing its consistency, indicating that both rejuvenators significantly impacted the RAP. The identical outcomes were observed by Banerji et al. (2022). Usage of waste oils in the modification of RAP binders followed almost a similar increasing trend, since all of the rejuvenated binders decreased their stiffness as the proportions of WCO and WEO increased.

It is apparent from Figure 1(b) that the ductility value of the RAP increases with the increase in the amount of oils, which states that the inclusion of oils makes rejuvenated binders more ductile. A lower increment is observed in ductility value by adding WEO compared to WCO. This implies that WCO could contribute to making used bitumen more resistant to breaking and better able to withstand high temperatures after it has been utilized. As demonstrated in Figure 1(c), the RAP has the uppermost softening point due to its aged behavior and high melting temperature, which decreases with increasing proportions of WCO and WEO, revealing the higher temperature susceptivity of waste oil-modified binders.

Furthermore, by analyzing the results in Figure 1, it is observed that with the increase in doses of both waste oils, ductility of rejuvenated RAP binder follows an exponential trend, while penetration and softening-point values observe a polynomial pattern.

When both waste oils, were compared, only minor differences were found in softening-point values of rejuvenated samples. Moreover, 13.5% of WCO and 15% of WEO proportions were supposed to be optimal, as with these proportions softening temperature approaches that of virgin binder. To summarize, addition of waste oils in RAP leads to higher penetration and consequently lower softening point, which is a clear indication of viscous behavior of RAP binder. Moreover, higher ductility of rejuvenated RAP binders implies more expansibility.

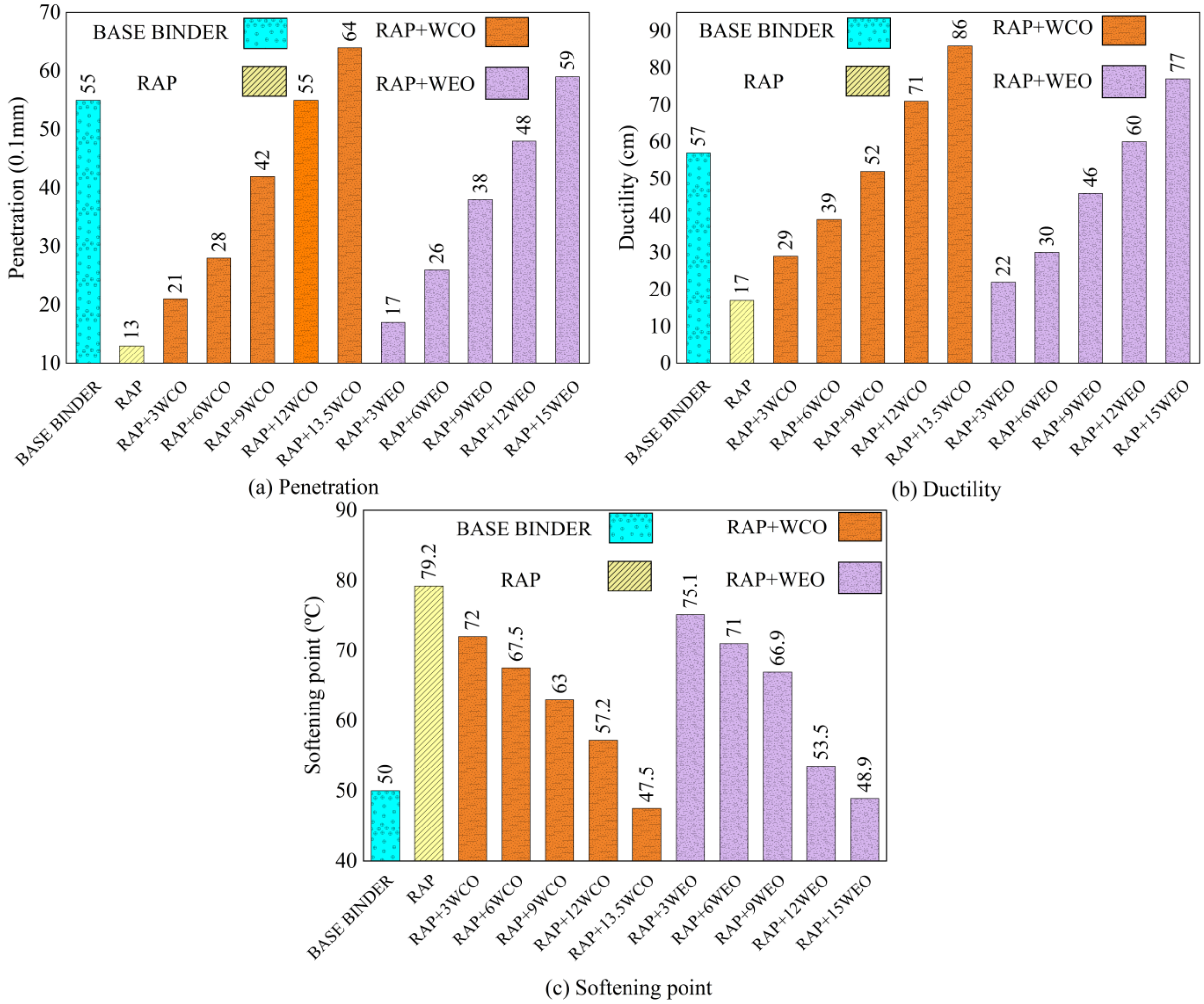

Figure (1): Penetration, ductility and softening-point test results of different binders; (a) penetration, (b) ductility and (c) softening point

Figure 2 depicts the viscosity results of a virgin RAP and different modified binders. The dynamic and kinematic viscosity results at two different temperatures 60 °C and 135 °C for WCO and WEO are shown in Figure 2(a) and 2(b), respectively. It can be seen that RAP binder had the highest viscosity due to its stiff nature. With the accumulation of WCO and WEO at varying proportions, viscosity is found to be declining with both rejuvenators. Dynamic and kinematic viscosity results follow an exponential and a polynomial pattern, respectively, with varying dosages of WCO and WEO. The observed changes in the viscous behavior of rejuvenated RAP are due to the dissolution of asphaltenes in these oils, which balances the asphaltene/maltene ratio near that of virgin binder. The frictional resistance of aged binder can be improved considerably with the addition of both WCO and WEO. Too high viscous RAP binder is unfavorable for mixture performance, as it would not spread evenly on the road due to segregation effects. On the other hand, if viscosity is kept too low, the asphalt road becomes more liable to cracking and rutting. Hence, for the consistent performance of RAP binder, the WEO and WCO dosages should be in the appropriate range. For the present work, the optimum doses of rejuvenators are found to be 13.5% and 15% for WCO and WEO, respectively, as this led to similar viscosity values to that of virgin binder.

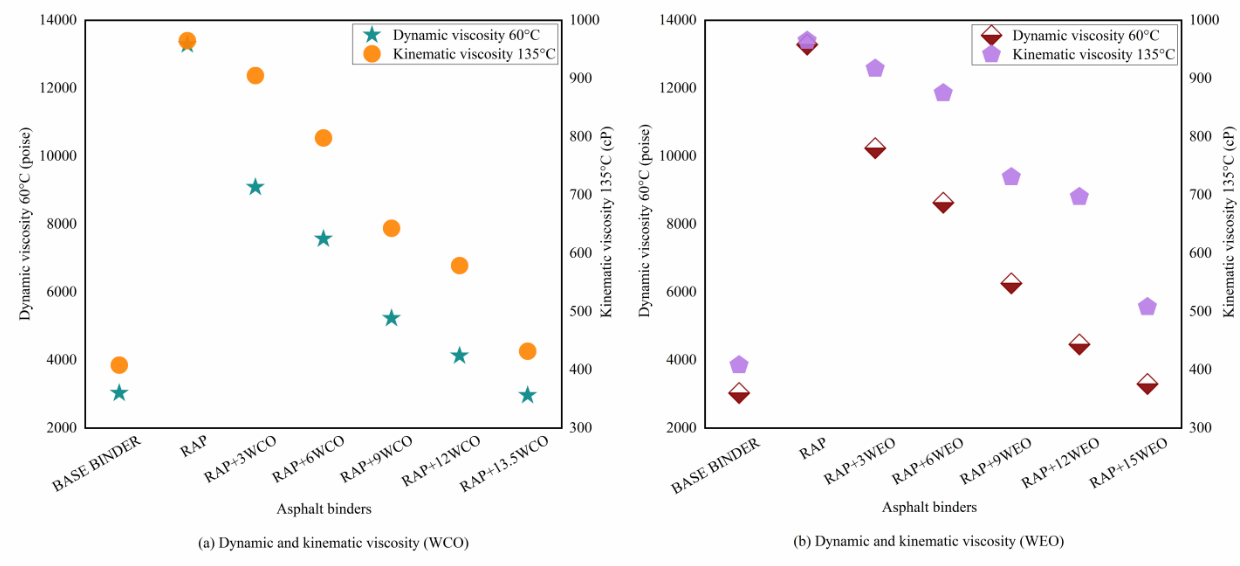

Figure (2): Dynamic and kinematic viscosity test results of different binders; (a) dynamic and kinematic viscosity (WCO) and (b) dynamic and kinematic viscosity (WEO)

Complex Shear Modulus and Phase Angle (Isothermal Plots)

The fraction of maximum shear stress to maximum shear strain is known as the complex-shear modulus (G*). It also measures the material's overall resistance to deformation under shear loading at different frequencies and temperatures. The time lag between shear stress and strain is termed phase angle (δ). Isothermal plots for G* and δ at a temperature of 60ºC with varying frequencies are displayed in Figures 3 and 4, for WCO and WEO-modified binders, respectively. The stiff structure of RAP binder contributes to highest complex-modulus value. Further, G* decreased as the oil contents increased, illustrating that flow deformation resistance of all modified binders kept reducing. The complex-shear modulus has the lowest G* values for 13.5% of WCO and 15% of WEO, analogous to the reference binder, which implies that both the rejuvenating agents have the capability to reinstate the stiffness property of the RAP binder.

Asphalt binder having smaller δ performs better in terms of elastic recovery, as it replicates its viscous response. It can be seen from Figures 3 and 4 that RAP bitumen has a lower value of δ than the virgin binder. The phase angle of RAP bitumen displays a growing pattern as the proportion of WCO and WEO increases, indicating the more viscous behavior of the rejuvenated samples compared with the aged binder. Adding 13.5% WCO and 15% WEO blended with aged samples resulted in δ close to that of virgin bitumen at all frequencies. Therefore, the addition of waste oils decreases the overall deformation resistance and viscosity, making RAP binder stiffer and recover better its original characteristics after being deformed by load.

Superpave Rutting Parameter Test

G*/sinδ imparts a crucial role in determining the rutting resistance of bitumen binders at high temperatures. The values of rutting parameter of virgin, RAP and rejuvenated samples are displayed in Figure 5. As expected, the RAP binder had the highest value of (G*/sinδ) because of its stiff nature due to aging. It is found that the accumulation of both rejuvenators restores the asphaltenes to maltenes ratio by changing the RAP structure (i.e., by rising the aromatic and resin contents of maltenes and reducing asphaltenes), which leads to the reduction of rutting parameter (Sun et al., 2016) of aged binders. Thus, it can be deduced that the more the waste oils added to RAP binder the less the capability of rejuvenated binders against rutting.

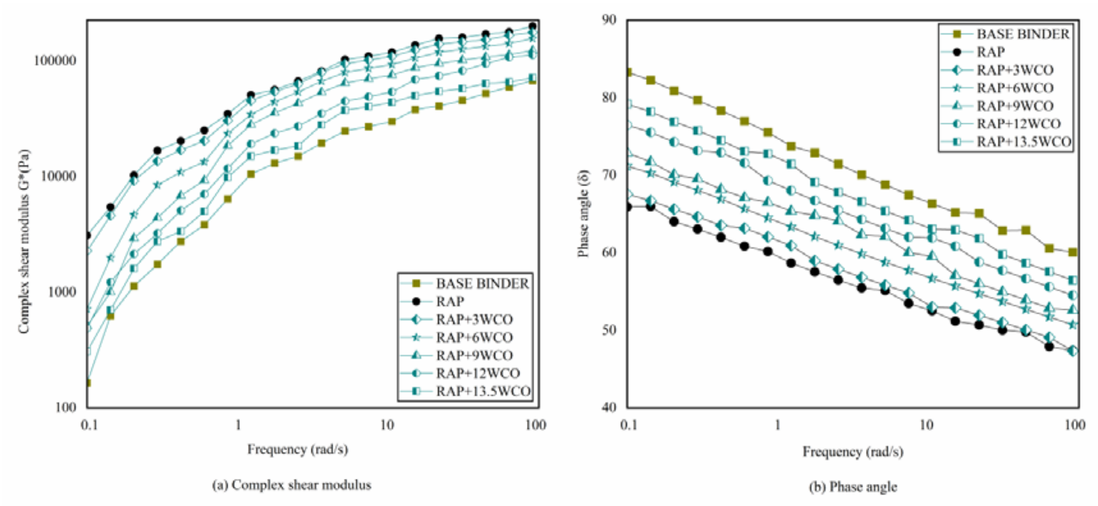

Figure (3): Complex-shear modulus and phase-angle test results of WCO-rejuvenated binders; (a) complex-shear modulus and (b) phase angle

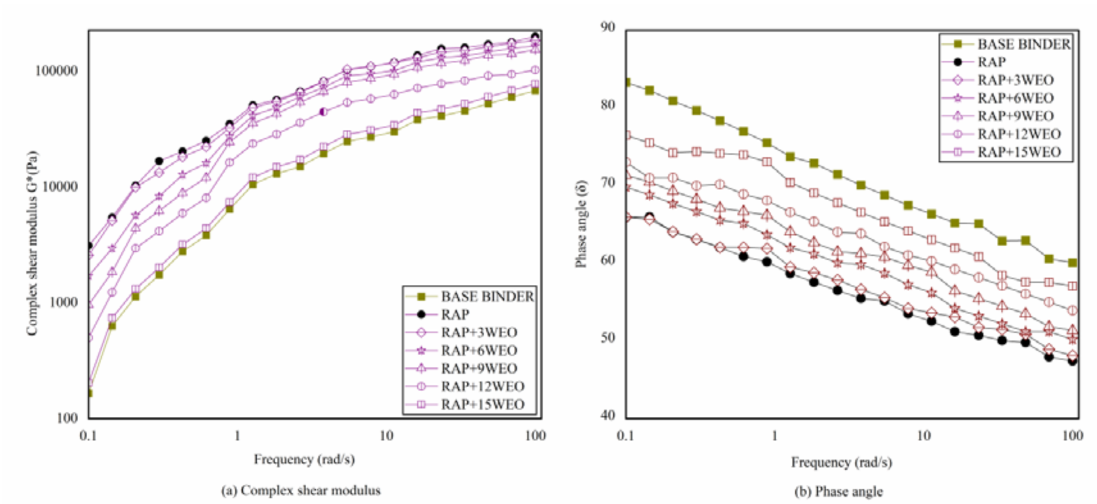

Figure (4): Complex shear-modulus and phase-angle test results of WEO-rejuvenated binders; (a) complex-shear modulus and (b) phase angle

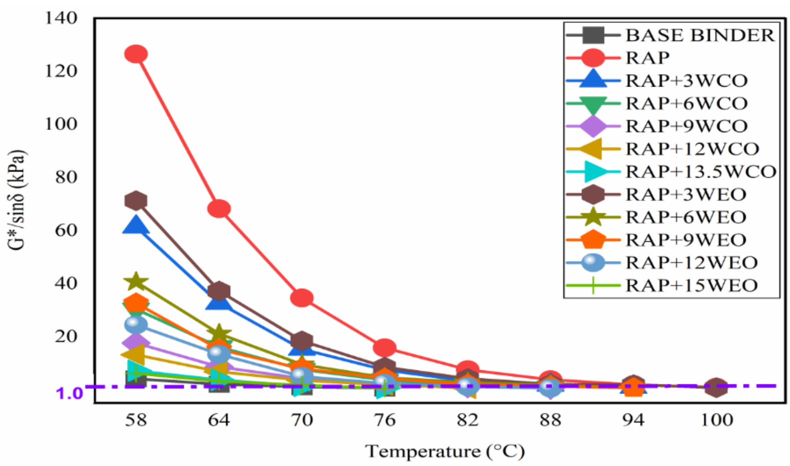

Figure (5): Superpave rutting parameter results

Performance Grading (PG) Temperature

Further, to evaluate the PG temperature, G*/sinδ must be less than 1.0 kPa for fresh binders and less than 2.2 kPa for RTFO aged binders. Based on this, the values of performance grade temperature found for different binders are represented in Figure 6. It can be seen that RAP binder has the highest value of PG temperature and virgin binder has lowest value of PG temperature. The PG temperature of RAP binder shows an appreciable reduction after the addition of waste oils. This might be due to the lesser viscosity of waste oils. By adding 15% WEO and 13.5% WCO, the PG temperature of the modified bitumen approaches that of virgin bitumen.

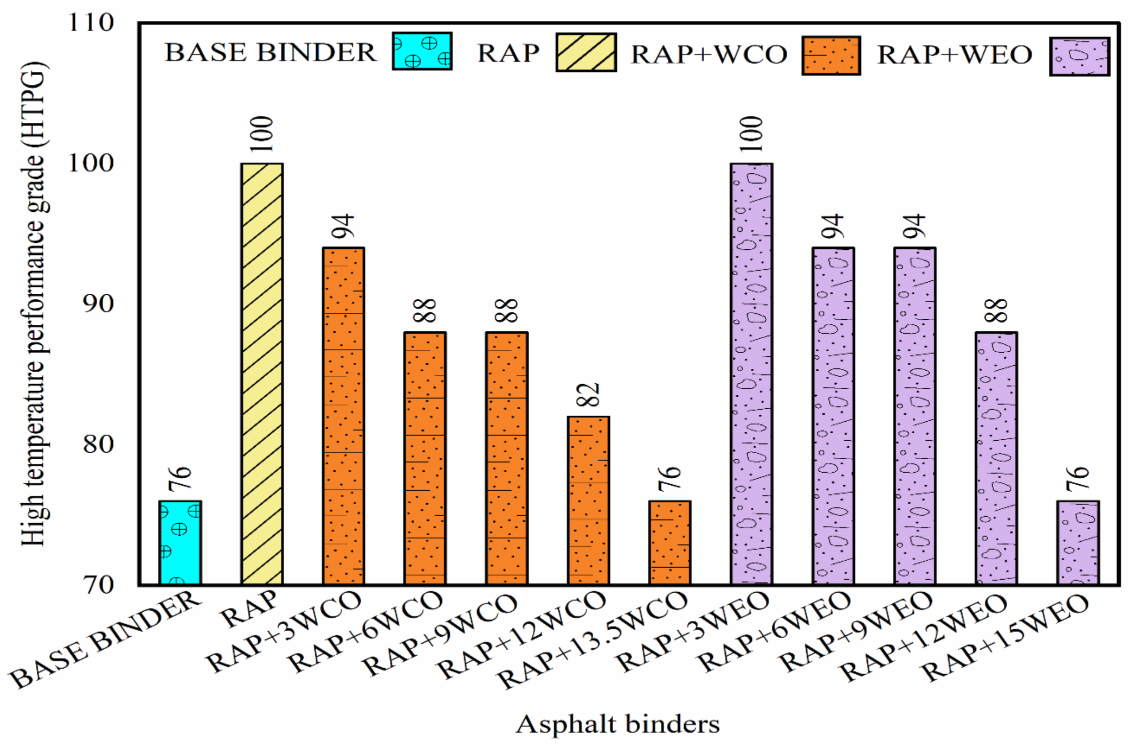

Figure (6): Performance-grading temperatures of different binders

Multiple Stress Creep Recovery (MSCR) Test

The process of a steady increase in strain over time under the application of constant stress is known as creep (Xiao et al., 2012). To access the elastic response of RAP, MSCR test was performed to calculate Jnr and %recovery (R) at stress levels of 0.1 and 3.2 kPa (Singh et al., 2018). It can be observed from Figures 7 and 8 for WCO-and WEO-modified binders, respectively, that the RAP binder has the lowermost Jnr and uppermost R (%) values owing to its hardness. Furthermore, Jnr increased and R% decreased with an increment in the dosages of WCO and WEO, which is ascribed to the softening of the aged binder due to the incorporation of rejuvenators. A substantial increase in Jnr value clearly indicates that the addition of waste oils will degrade the rutting performance (Al-Omari et al., 2018). Generally, higher R% specifies that oil-based rejuvenators enhance asphalt elasticity, which is also advantageous for rutting resistance. On the contrary, the lower recovery rate of rejuvenated binders in Figures 7 and 8 dictates that waste oils make RAP softer and more liable to rutting. RAP binders rejuvenated with WCO had more Jnr and less recovery in comparison with WEO-rejuvenated binders, indicating that WCO is considered to make RAP binders more pliable. A similar trend was observed at 0.1-kPa and 3.2-kPa stress levels.

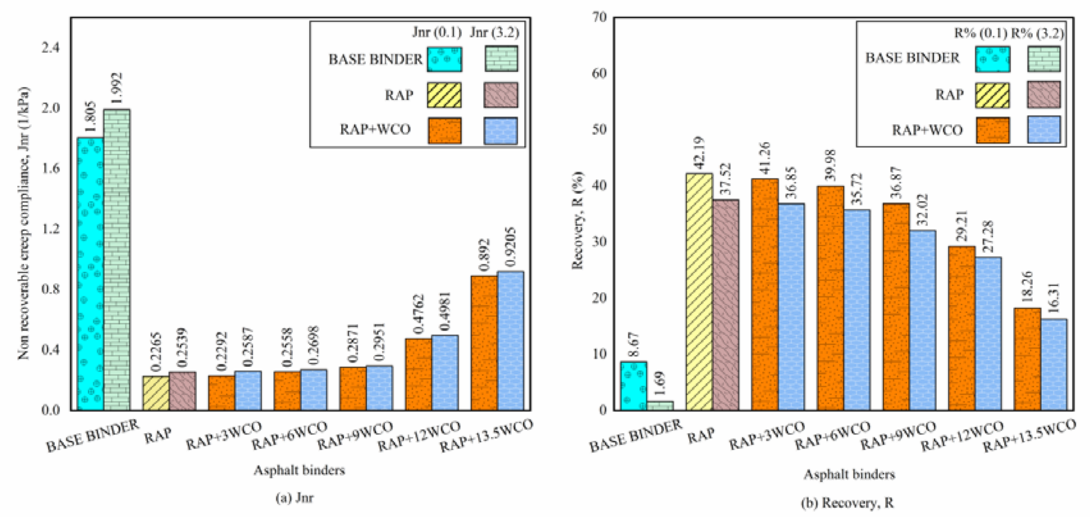

Figure (7): Jnr and recovery test results of WCO-rejuvenated binders; (a) Jnr and (b) recovery

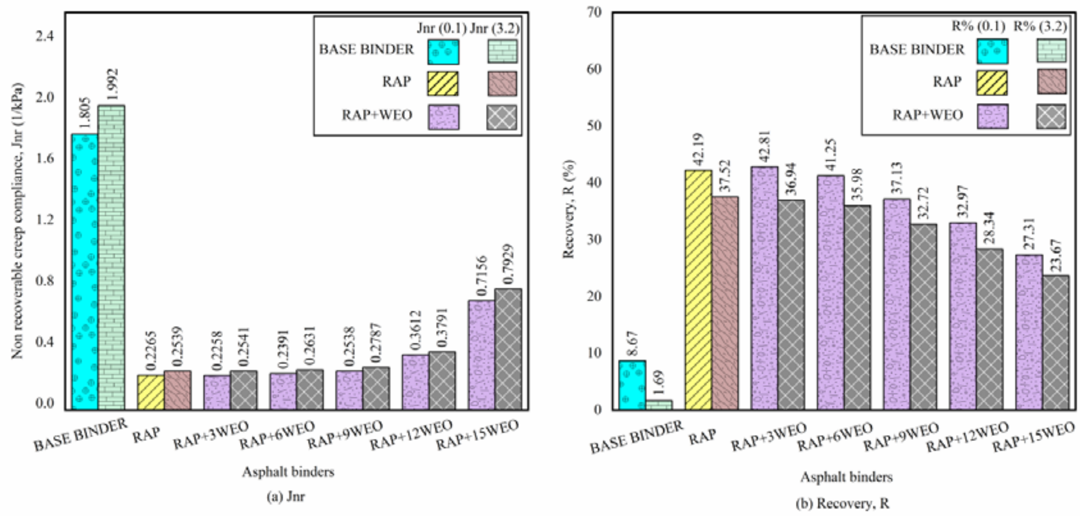

Figure (8): Jnr and recovery test results of WEO-rejuvenated binders; (a) Jnr and (b) recovery

Linear Amplitude Sweep (LAS) Test

In order to predict the life of bitumen samples in terms of fatigue, the numbers of failure cycles at two different strain levels, 2.5% and 5%, are shown in Figure 9. At a 2.5% strain rate, the aged bitumen needed a larger number of cycles for its failure, although when the load is increased to 5%, a drastic decrease is observed in the fatigue life of RAP bitumen. This may be attributed to its hardness property. The fatigue life at 2.5% strain level is less suitable for assessing the fatigue parameter of bituminous pavement (Elkashef and Williams, 2017). No appreciable effect of rejuvenator dose (for both rejuvenators) is observed at 2.5% strain. Fatigue life (N_f) first drastically reduces from 22647 (RAP) to 14177 (with 3% WCO) and then keeps on increasing slowly with higher doses up to 15948 (with 13.5% WCO). Similar trend is observed in case of WEO. However, at 5% strain, a continuous increase in (N_f) is observed from 2532 (RAP) to 4891 (with 13.5% WCO). In case of WEO-rejuvenated samples, the trend is not that pronounced. Hence, significant improvement is observed in fatigue life of RAP with WCO as compared to WEO. Moreover, the overall fatigue-life trends imply that the addition of waste oils improve the fatigue performance remarkably.

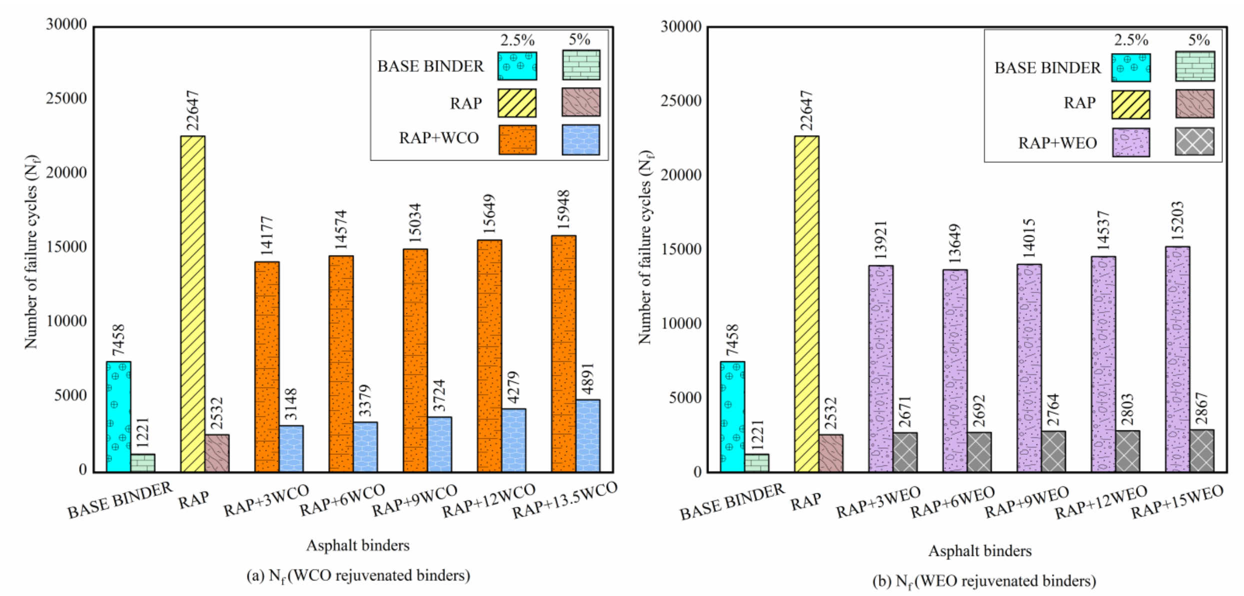

Figure (9): Number of failure cycles (N_f) for different binders; (a) N_f (WCO-rejuvenated binders) and (b) N_f (WEO-rejuvenated binders)

Superpave Fatigue Parameter Test

The fatigue parameter (G*sinδ) is used to characterize the cracking resistance of asphalt binder under continuous stress at intermediate temperatures. The results of G*sinδ for asphalt binder with different waste-oil contents are shown in Figure 10 at an intermediate temperature of 25°C. It may be observed from the figure that due to stiffer and brittle nature of RAP, it has the highest value of G*sinδ. However, with increased WEO and WCO percentages, the G*sinδ values decreased, indicating improvement in the fatigue resistance of the RAP binder, as WEO and WCO rejuvenators soften the aged RAP binder. Similar improvement in fatigue resistance was observed by Prashanth et al. (2019). It is noticeable that with the addition of 13.5% of WCO, there is a drastic decrease in G*sinδ of about 21.5%. This indicates the advantage of WCO over WEO for better fatigue resistance. Finally, the addition of waste oils with RAP brought drastic differences in fatigue and rutting behaviours. Therefore, an appropriate decision is to be made for the usage of waste oils as rejuvenators to improve the performance of RAP binders.

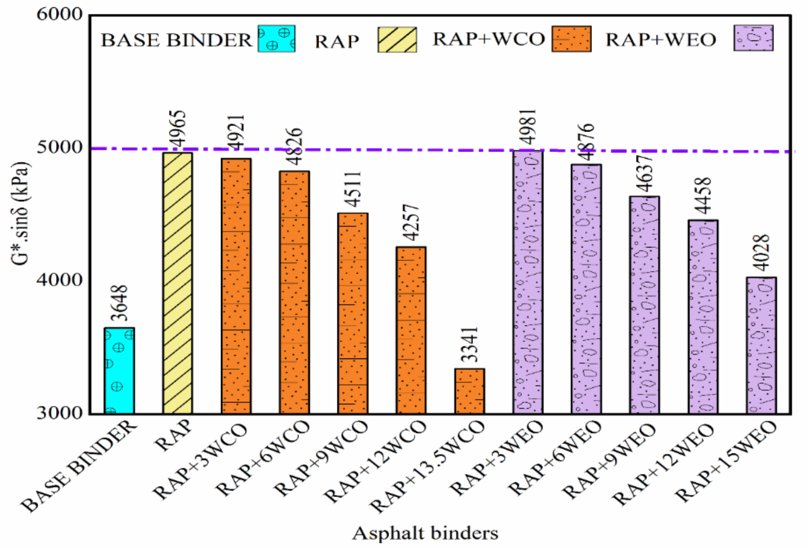

Figure (10): Superpave fatigue parameter of different WCO-and WEO-modified binders

CONCLUSIONS

This experimental study evaluates the potential of WCO and WEO as rejuvenators mixed with an aged binder and compares both rejuvenators' performance by evaluating their physical and rheological properties. The specific conclusions are discussed as follows:

1. The penetration and ductility of RAP bitumen increases by the increase of the proportions of WCO and WEO, while the softening point and viscosity decrease, which is a clear indication of the enhancement of workability of an aged binder. Furthermore, penetration value, softening temperature and kinematic viscosity follow a polynomial pattern, while ductility and dynamic viscosity follow an exponential behavior with the increase in doses of both rejuvenators within the test range.
2. Physical properties and viscosity test results reveal that at an optimal dose of 13.5% of WCO and 15% of WEO, RAP bitumen performs similar to virgin VG30-grade bitumen.
3. The substantial decline in complex-shear modulus (G*) and increase in phase angle (δ) with the addition of the rejuvenators demonstrate that both rejuvenators are capable of improving the stiffness of aged binder. Moreover, complex-shear modulus (G*) and phase angle (δ) of RAP bitumen modified with 13.5% of WCO and 15% of WEO resembles with that of virgin bitumen at all frequencies (in the range of 0.1 to 100 rad/s), which also validates that both WCO and WEO can be used as rejuvenators.
4. The rutting resistance of the aged-bitumen sample is maximum due to its oxidative nature. It decreases with increasing proportions of waste oils owing to the softening of rejuvenated binders. However, adding waste oils makes the RAP binder softer and more liable to rutting. Therefore, from the rutting viewpoint, the use of RAP along with waste oils may not be appropriate in regions where rutting is the prevailing distress type.
5. Superpave rutting parameter (G*/sinδ), MSCR test (non-recoverable creep compliance (Jnr) and % recovery (R) parameters are used to study the rut resistance of bitumen samples. Results revealed that at optimal doses of waste oils, rejuvenated RAP bitumen samples perform better than the base binder.
6. The results of superpave fatigue parameter (G*sinδ) and LAS test performed on rejuvenated RAP bitumen samples with optimal doses of waste oils clearly indicate improved fatigue behavior. As compared to WEO, WCO has a higher potential to enhance the fatigue resistance of RAP binder.

Thus, it can be deduced that rutting resistance was compromised by adding waste oils, but fatigue behavior of binders was improved considerably.

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