

Rheological Characterization of Asphalt Binders Containing Rejuvenated Reclaimed Asphalt Pavement

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Abstract

The use of reclaimed asphalt pavement (RAP) in freshly hot mixed asphalt (HMA) can save on material costs, preserve energy, and protect the environment. Employing limited amount of RAP in the production of asphalt mixes can result in similar performance as normal mixtures. However, adding more RAP can reduce the HMA's mixing efficiency and could make the asphalt mixture more susceptible to fatigue and low-temperature cracking. Vegetable oil can act as a rejuvenator and reduce the HMA deficiencies with a high RAP percentage. This study investigated the potential effect of two vegetable oils; namely soybean oil (SOY) and sunflower oil (SnF), as rejuvenators on the properties of asphalt binders that contain 40% of RAP binder. To determine the optimum dosage of the rejuvenators (SOY and SnF), the properties of the rejuvenated RAP binders were carried out by conducting the penetration, softening point, viscosity, dynamic shear rheometer (DSR), and bending beam rheometer (BBR) tests. The test results indicated that vegetable oils could provide better fatigue and low-temperature cracking resistance with acceptable rutting performance. Furthermore, it is observed that, for the abovementioned properties, the addition of the 6%SOY and 3%SnF were more feasible in restoring the 40RAP binder to its original properties.

Keywords: Reclaimed Asphalt Pavement, Asphalt binder rejuvenator, Vegetable-oils, Rheological tests.

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1. INTRODUCTION

In recent years, due to the rapid growth of road construction, a huge amount of old asphalt pavements are produced in the process of demolition of road structures, which may need to be properly disposed of (Ren *et al.*, 2020; Farooq and Mir, 2017; Hettiarachchi *et al.*, 2019). The use of reclaimed asphalt pavement (RAP) could result in economic and environmental benefits if a certain percentage of asphalt binder required in freshly hot mixed asphalt (HMA) is replaced with RAP aged asphalt binder (Zhang *et al.*, 2019a; Seidel and Haddock, 2014; Hill *et al.*, 2013).

Several countries, such as the USA, Japan, and Netherlands, have started employing a large amount of RAP, which has shown the likelihood of total recycling being implemented successfully in pavement engineering. Yet, the utilization of RAP pavement materials in the construction of roads is not very

popular in the Kingdom of Saudi Arabia, while it is a crucial need for the country. Kabir *et al.*, (2016) reported that the Gulf Cooperation Council (GCC) produces roughly 80-120 million tons of waste per year, 53% of which are construction and demolition waste. It has been stated by the authors that Saudi Arabia is the Gulf's biggest contributor to solid waste generated from construction sites in the Gulf. This massive amount of demolition waste is the result of the country's rapid modernization and infrastructure improvements, which have resulted not only in the need to dispose of old construction materials but also in an increase in demand for construction materials such as aggregate and sand collected from local sources. As a result of this circumstance, various studies have concluded that using recycled materials in newly constructed projects in Saudi Arabia is an essential demand (Husain and Assas, 2013). Therefore, attempts are made in this study to employ an efficient strategy by utilizing a certain

amount of RAP in freshly HMA that can minimize the construction debris placed into landfills, and reduce the pressure on natural resources.

Although there are many advantages to employing RAP materials in asphalt mixtures, some studies have revealed that using the RAP at a high proportion can impact the asphalt mixture's cracking resistance and low-temperature performance (Mirhosseini *et al.*, 2019; Al-Qadi *et al.*, 2007; Ding *et al.*, 2016; Zhao *et al.*, 2013; Ziari *et al.*, 2020; Rodrigues *et al.*, 2020). Thus, in several countries, the use of RAP in the production of new asphaltic mixtures has been limited to low amounts of 15-25% RAP (Majid *et al.*, 2012). Yousefi *et al.*, (2021) determined that employing RAP up to 20% in the production of asphalt mixes can result in similar performance as normal mixtures. Instead, it has been claimed that employing RAP up to 30% or higher can reduce the workability and low temperature cracking resistance of the mix. As the asphalt binder ages, it loses its strain-tolerant qualities; that is to say, asphaltenes in the binder flocculate, the ratio of maltenes/asphaltenes is decreased, and the binder becomes stiffer and brittle (Zhang *et al.*, 2019b). For this reason, rejuvenators are added to improve some of the properties of the asphalt mixtures containing high RAP materials (Yang, 2013).

In general, a rejuvenator is defined as an asphalt additive capable of restoring the aged asphalt binder's initial properties (i.e., chemical or physical) (Saha *et al.*, 2020). Petroleum compounds are very common rejuvenators that are used to recover the characteristics of the aged RAP binder. However, in elevated recycling temperatures, petroleum oils easily volatilize, resulting in only just a small amount of RAP materials (less than 30%) being used in recycled asphalt pavement (Williams and Raouf, 2010). Similarly, vegetable oils as a rejuvenator agents have gained popularity in recent years due to their environmental friendliness (Tarar *et al.*, 2020).

Vegetable oils, namely soybean oil (SOY) and sunflower oil (SnF), are potential sources that are abundant and is a viable method for adding to RAP binders. Their addition in the RAP binder increases the ratio of maltenes to asphaltenes of asphalt binders by increasing maltene content (Tarar *et al.*, 2019). In a study, Elkashef *et al.*, (2018) examined the influence of soybean oil (SOY) at a quantity of 0.75 percent (weight of neat binder) of the two virgin (PG58-28) and polymer-modified (PG64-28) binders to enhance the binder's resistance to low temperature. The authors reported that the efficiency of the rejuvenator was evident with improved fatigue and low-temperature resistance while not destroying the rutting resistance. Likewise, adding 1% -2% soybean oil (SOY) to asphalt binders increased the elastic characteristics of the asphalt binder (Portugal *et al.*, 2018). Sunflower oil is also appealing as a rejuvenator agent for the

modification of the RAP binder. In another study, Shirzad *et al.*, (2016) who used a 5% of sunflower oil for the rejuvenation of RAP aged binder reported that the viscosity value decreased with 49.2% as compared to the unmodified RAP aged binder. These can be explained by the fact that the modified binder's elasticity is increased by the addition of rejuvenator content, which means that rejuvenators are essential in increasing the percentage of maltenes to asphaltenes in the RAP aged binders.

The use of RAP binder could result in environmental and economic benefits if partial replacement of neat asphalt binder is used with the rejuvenated RAP (Hill *et al.*, 2013). Several studies in the exceeding review have explored that researchers investigated the rheological properties either neat binder or RAP binder alone with a vegetable-based rejuvenator. However, the importance of dispersion of a neat asphalt binder, RAP asphalt binder, and rejuvenating agent when vegetable oils are used is still limited. Meanwhile, most of the previous studies evaluated the effect of vegetable oils on the aged asphalt binder separately rather than comparatively. Therefore, the main objective of this study was to investigate and compare the effect of the two local available vegetable (soybean (SOY) and sunflower (SnF)) oils on the asphalt binder properties that contain a part of the aged RAP binder. To comparatively evaluate the effectiveness of rejuvenators, various rejuvenator doses of 0, 3, and 6% are added to the RAP aged asphalt binder with an intermediate value of 40% RAP. Based on the comparison, the rheological properties of binders are measured by several testing approaches such as the consistency, viscosity, DSR, and the BBR. The optimum dosage of rejuvenators (SOY and SnF) oils is defined to restored the rheological properties of the RAP-modified binders to their original state that could satisfy the Superpave binder requirements.

2. EXPERIMENTAL PROGRAM

2.1 Materials

The neat asphalt binder with a penetration grade of 60/70 was used as control binder because this grade binder is commonly used in the Kingdom of Saudi Arabia. The neat binder was sourced from Saudi-Aramco Ras-Tannurah refinery, a Saudi Arabian public petroleum company. The two rejuvenators (SOY and SnF) oils that are utilized in this study were locally accumulated. Some of the important characteristics of rejuvenators, neat asphalt binder, and RAP aged binder after the laboratory testing are shown in Table 1, 2 & 3. The RAP samples were collected from the King Abdullah Road located in the city of Jeddah, with a service life of 4-year. The RAP aged binders were extracted from the RAP materials following standard ASTM D2172 (ASTM 2011).

Table-1: Physical properties of SOY and SnF oils as rejuvenator agents

Properties	Rejuvenators	
	SOY oil	SnF oil
Dynamic viscosity @ 25°C (Pa.s), AASHTO T-316	0.063	0.0608
Specific gravity @ 25°C, ASTM D70	0.9798	0.9171
Flash point (°C) ASTM D93	255	275

Table-2: Physical properties of neat and RAP asphalt binders

Properties	Neat binder 60/70	RAP binder
Specific gravity @ 25°C, ASTM D70	1.030	1.054
Penetration value (0.1mm) @ 25°C	64	40.5
Softening point (°C)	45	58

Table-3: Rheological properties of neat and RAP asphalt binders

Properties	Specification	Temperature (°C)	Neat binder	RAP binder
Viscosity unaged binder (mPa.s)	AASHTO T316	135	494	1265
Viscosity unaged binder (mPa.s)	AASHTO T316	165	123	342
Rutting unaged binder (kPa)	AASHTO T315	64	1.62	6.42
Rutting RTFO binder (kPa)	AASHTO T315	64	2.74	9.58
Rutting PAV binder (kPa)	AASHTO T315	25	2683	9240

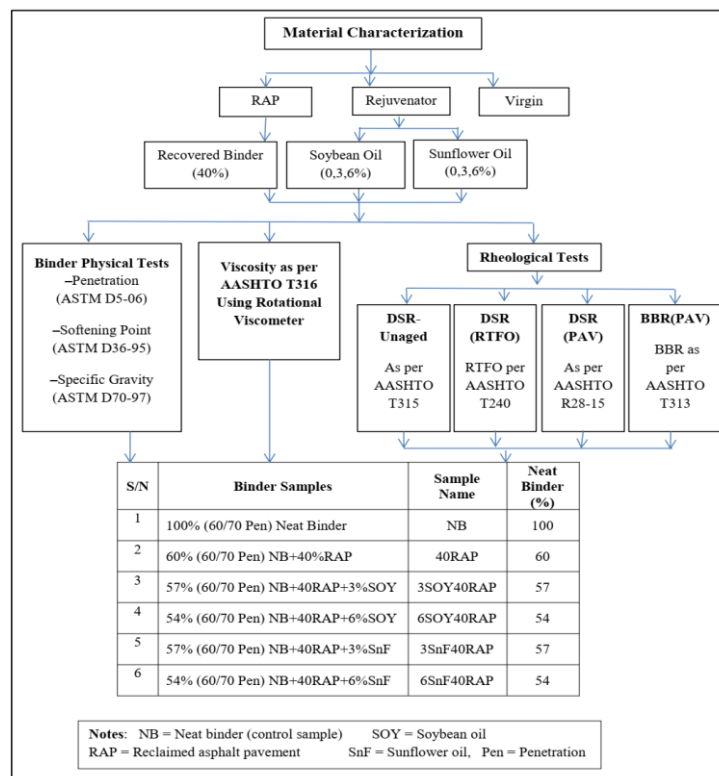
2.2 Experimental Plan

After the extraction of the aged asphalt binder from the RAP materials, the two commercial asphalt rejuvenators (SOY and SnF) oils were added to the 40% RAP extracted binders at different percentages of 0, 3, and 6% (by the total weight of neat asphalt binder). The detailed experimental plan of the study is shown in Figure 1.

2.3 Conventional Tests of Asphalt Binder

The fundamental physical tests of the neat asphalt binder, RAP extracted aged binder, and all other

rejuvenated RAP aged binders were examined using the following asphalt binder conventional tests. The effect of the rejuvenator on the binder penetration grade was utilized to identify the consistency of asphalt binders at a temperature of 25°C according to ASTM D5 (ASTM 2006). The softening point test of rejuvenated RAP binders was used to classify the impact of adding rejuvenators on the values of temperature resistance of asphalt binders as per ASTM D36 (ASTM 1995). And the specific gravity test was carried out according to the ASTM D70 standard (ASTM 1997).

**Fig-1: Study experimental program flow chart**

2.4 Viscosity Test

The viscosity test is used to define an asphalt binder's mixing and compaction temperatures. In this study, the viscosity test was carried out at temperatures of 135°C and 165°C using the rotational viscometer (RV) at a fixed rotation speed of 20rpm as per to AASHTO T316 (AASHTO 2013a).

2.5 Binder Rheology Tests

2.5.1 Dynamic Shear Rheometer (DSR) Test

The (DSR) test was used to examine the high-temperature performance of the neat asphalt binder, the aged asphalt binder that is extracted from the RAP materials, and the RAP aged asphalt binder that was rejuvenated using the SOY and SnF oils. The DSR test was performed at temperatures of 58, 64, and 70°C for unaged, and short term aging (RTFO-aged) binder samples in order to calculate the complex shear modulus (G^*) and the phase angle (δ). Following the AASHTO T315 method, the unaged and short-term age binder samples were tested using the 25 mm diameter plate with a 1mm gap (AASHTO 2012). The rolling thin film oven (RTFO) test that simulates the short-term ageing process was performed at 163°C for 85 min following AASHTO T240 standard (AASHTO 2013b). As per AASHTO T240, the loss of volatiles in rejuvenated RAP binders were measured by loss on heating using RTFO. The pressure age vessel (PAV) test that simulates the long-term ageing process was performed as per AASHTO R28-15 (AASHTO 2015). To determine asphalt binder's fatigue parameter

($G^* \cdot \sin \delta$), the DSR test was conducted on the PAV-aged binder samples at temperatures of 22 and 25°C using a diameter plate of 8 mm with a 2 mm gap.

2.5.2 Bending Beam Rheometer (BBR) Test

The asphalt binder flexural creep stiffness was measured using the Bending Beam Rheometer test equipment. In this study, the BBR test was conducted on the neat asphalt binder, RAP aged asphalt binder, and rejuvenated RAP asphalt binders. The PAV-aged asphalt binders that simulate the long-term aged were considered for this test. The creep stiffness (S_t) and m -value of the rejuvenated RAP binders were measured over a several testing temperature of (-6, -12 and -18°C) as per the AASHTO T313 standard (AASHTO 2006).

3. RESULTS AND DISCUSSION

3.1 Binder Physical Properties

The specific gravity test results of the SOY and SnF rejuvenators added to the 40% RAP aged asphalt binder are given in Figure 2. It is shown that the value of specific gravity of the binder with SOY oil is greater than that with the same amount of SnF oil, indicating that the SnF oil is less heavy than the SOY oil. This reduction in specific gravity value is the result of the lower specific gravity of SnF oil compared to that of the SOY oil (as shown in Table 1), which demonstrates that the SnF rejuvenator may further efficiently decreases the hardness of the RAP aged binder.

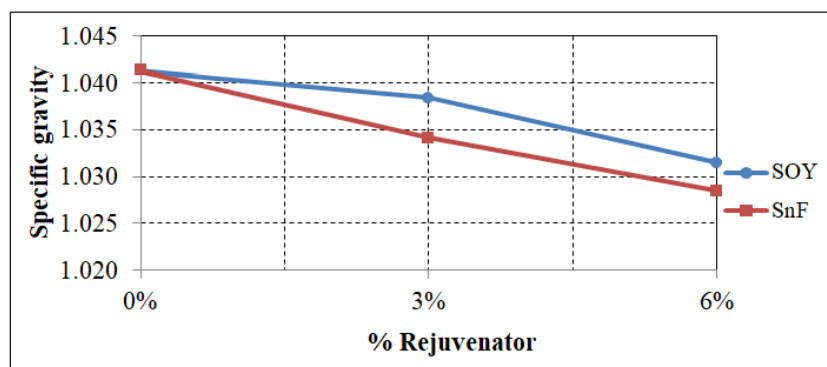


Fig-2: Specific gravity test results of 40RAP aged binder rejuvenated with SOY and SnF oils

The penetration test is used to assess the consistency of the binders. Figure 3 illustrates the results attained from the penetration test for the samples of neat binder, 40RAP aged binder, and 40RAP aged binders rejuvenated with SOY and SnF oils at different percentages of 0, 3, and 6% (by the weight of neat binder). Based on the penetration testing result, the penetration of the binder failed to reach the target penetration grade value of 60/70 when 40RAP aged binder was added. The penetration of the rejuvenated 40RAP aged binder increased as the rejuvenator amount in the RAP aged binder is increased. The rise in the penetration grade is because of the reduction in the ratio

of asphaltenes to maltenes (Tarar *et al.*, 2020). As shown in Table 4, the values of the penetration of rejuvenated 40RAP aged binder that contain 6%SOY and 3%SnF are nearly similar to the value of the neat binder. However, the rejuvenated 40RAP aged binder having 6%SnF had a higher penetration value as compared to the neat binder. This can be supported by Amira *et al.*, (2019) who investigated the effect of waste vegetable oil used into the aged asphalt binder at a percentage of 2, 3, 3.5 and 4% that found a similar reduction in the consistency of the aged asphalt binder. It could be also noted that the influence of SnF rejuvenator addition on the penetration values is greater

than that with the same content of SOY rejuvenator, this reduction is the result of the lower specific gravity of SnF oil, which demonstrates that the SnF rejuvenator

can decrease the stiffness of RAP aged binder more effectively.

Table-4: Penetration and softening point values of neat, 40RAP and rejuvenated 40RAP binders

Properties	Binders					
	NB	40RAP	3SOY40RAP	6SOY40RAP	3SnF40RAP	6SnF40RAP
Penetration (0.1 mm) @ 25°C as per ASTM D5	64	56.5	60.5	65	63.5	68
Softening Pointing as per ASTM D36	45	48.8	46.5	45	46	44

The softening point test for the neat binder, 40RAP aged binder, and rejuvenated 40RAP aged binders was conducted following the ASTM D36

standard (ASTM 1995). As illustrated in Figure 4, the softening point temperature of the neat binder was 45°C (as the minimum required temperature).

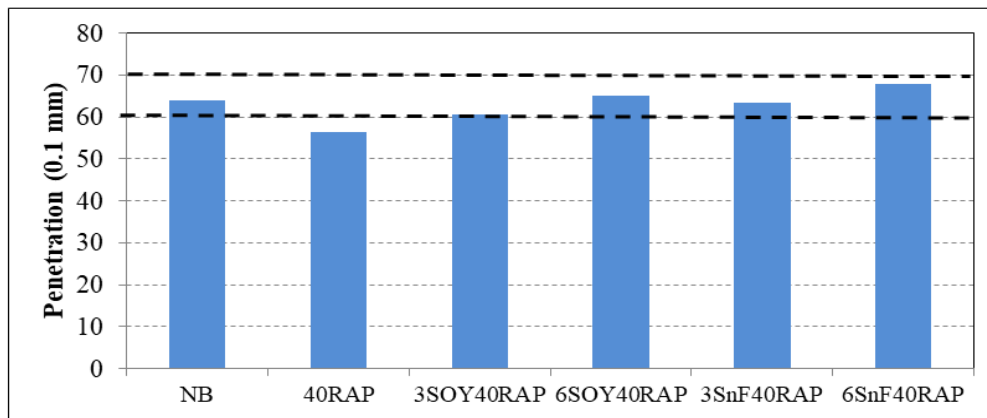


Fig-3: Penetration values of neat binder, 40RAP binder, and rejuvenated 40RAP modified asphalt binders

As expected, the binder sample with 40RAP aged binder showed the highest softening point temperature value (i.e., 48.8°C), while the values of rejuvenated 40RAP aged binder decreased the softening point temperature markedly with the addition of SOY and SnF rejuvenators. The softening point temperature of the rejuvenated 40RAP aged binder reduced to 46.5°C and 46°C when 3%SOY and 3%SnF were added, respectively. A reduction in the softening point temperature was also obtained by Amira *et al.*, (2019) who found the same trend of decrease in the softening point values when 3% rejuvenators was added, which means the lower temperature sensitivity. Likewise, the softening point temperature of 6%SOY into the rejuvenated 40RAP aged binder had a similar softening point temperature value to the neat binder. In addition, adding the 6%SnF into the 40RAP aged binder, the softening point temperature value of the binder was 44°C, which is lower as compared to the neat binder. Thus, the use of SnF oil decreased the hardness of the RAP aged binder more effectively than those with similar contents of SOY oil, suggesting that the SnF oil is lighter and may decrease more effectively the

stiffness of the RAP aged binder as compared to the SOY oil.

3.2 Loss on Heating (RTFO)

The loss on heating test is used for simulating the short-term aging of asphalt binder during mixing and placing. The mass loss by percentages of the neat binder, RAP aged binder, and all other rejuvenated RAP aged binders are given in Figure 5. It is demonstrated that the 40RAP aged binder substantially reduced more mass loss (0.71%) as compared to the neat binder that was only (0.53%). This may most likely be due to the incomplete distillation of solvent from the RAP aged binder during the extraction. On the other hand, the percentage of mass loss in the rejuvenated 40RAP aged binders has increased slightly with the addition of vegetable oils whereas 6SnF40RAP binder exceeded the permitted 1 percent mass loss, which can be due to the presence of additional volatiles in the vegetable oil (Shen *et al.*, 2007). Zaumanis *et al.*, (2014) and Hasan *et al.*, (2019) also observed a similar tendency in the reduction of mass loss when the RAP aged binders were rejuvenated with vegetable oils.

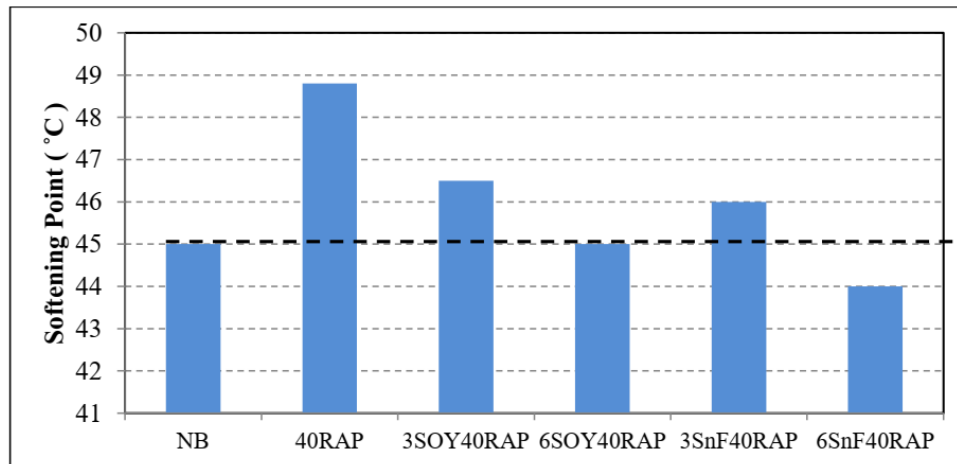


Fig-4: Softening point temperature values of neat binder, 40RAP binder, and rejuvenated 40RAP binders

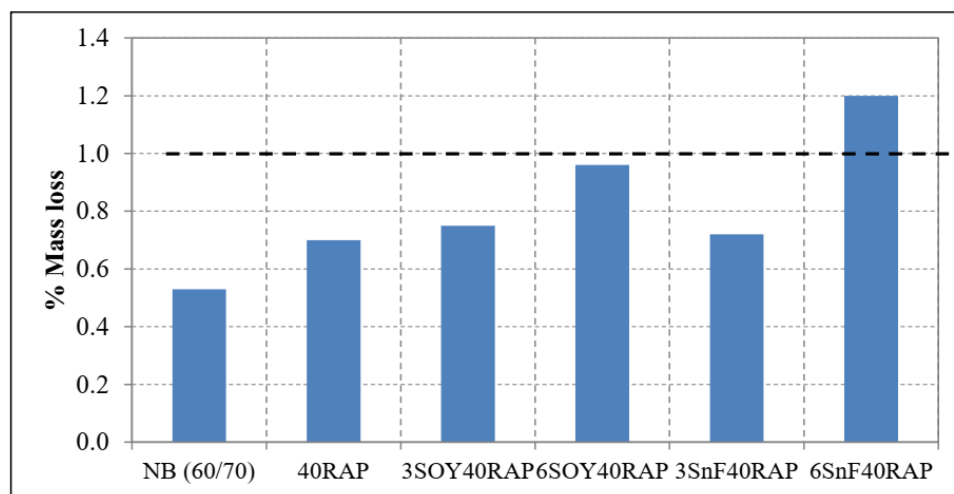


Fig-5: Mass loss after rolling thin film oven (RTFO)

3.3 High-Temperature Viscosity Test

As the asphalt binder's viscosity decreases, it allows for effective aggregate coating, improves the flow characteristics of the asphalt binder, and lowers the processing temperature that reduces energy needs and emission of volatile organics. In this study, the viscosity characteristics are carried out according to the AASHTO T316 standard with a cup and bob Brookfield rotational viscometer at temperatures of 135 and 165°C (AASHTO 2013a). Figure 6 shows the rotational viscosity results of asphalt binders. As it is expected, the unmodified 40RAP aged binder indicated the highest values of viscosity, while a significant decrease in the values occurred due to the addition of rejuvenators into the 40RAP aged binder, which is vital in decreasing the proportion of asphaltenes in the recovered asphalt binder (Tarar *et al.*, 2019). Adding 6% SOY to the 40RAP aged binder results in nearly

similar viscosity value to the neat binder. This result is consistent with the findings by Mirhosseini *et al.*, (2019) who utilized 10% date seed oil with 20RAP aged binder at a temperature of 110 and 135°C, and achieved a reduction in the viscosity values that were close to the neat binder. Similarly, the rejuvenated 40RAP aged binder blended with 6% SnF reduced the viscosity value below the neat binder. For instance, the addition of 6% SnF to the 40RAP aged binder at a temperature of 135°C reduced the viscosity value by 56% as compared to the unmodified 40RAP aged binder. Shirzad *et al.*, (2016) who used a 5% of sunflower oil for the rejuvenation of RAP aged binder reported that the viscosity value decreased with 49.2% as compared to the unmodified RAP aged binder, this can be explained by the fact that the modified binder's elasticity is increased by the addition of rejuvenator content (Tarar *et al.*, 2019).

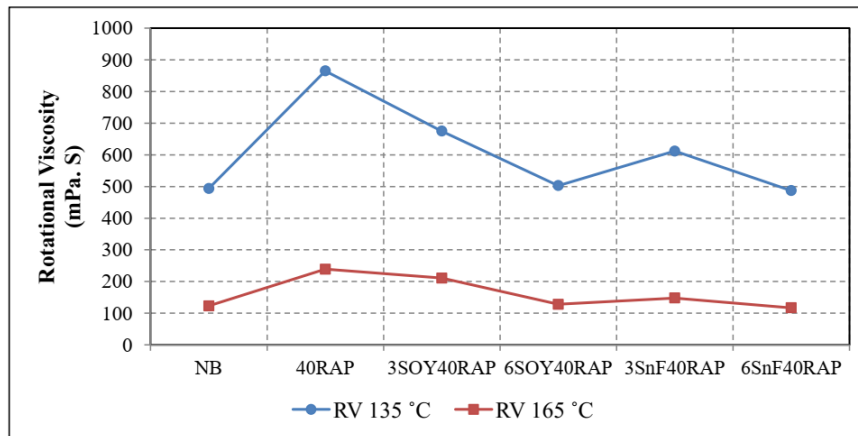


Fig-6: Rotational viscosity of neat binder, 40RAP binder, and rejuvenated 40RAP modified asphalt binders

3.4 Rutting Resistance

The findings of the rutting resistance factor ($G^*/\sin\delta$), from the DSR test, are presented in Figure 7. As expected, the neat binder satisfied Superpave's specified minimum requirement at 64°C, and the rutting

resistance value of the 40RAP aged binder at the tested temperatures is much higher as compared to the neat binder. Whereas, with the inclusion of the binder's rejuvenator agents, there is a downward tendency in the values of the rutting parameter of ($G^*/\sin\delta$).

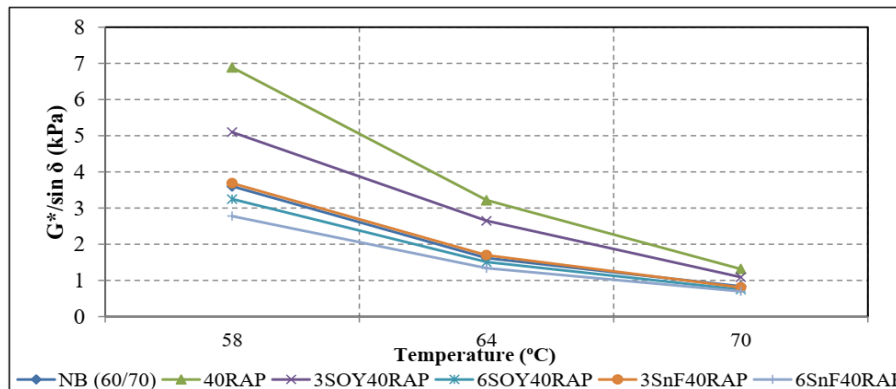


Fig-7: $G^*/\sin\delta$ values of neat binder, 40RAP binders, and rejuvenated 40RAP binder at un-aged

By adding 6%SOY and 3%SnF, the $G^*/\sin\delta$ values of the 40RAP aged binder are enhanced and come nearly identical to the rutting resistance values of the neat binder. Furthermore, with the addition of more SnF rejuvenators (i.e., 6%SnF), the $G^*/\sin\delta$ values are less than those obtained for the neat binder meaning further susceptibility to rutting resistance. This occurrence was also found in a study carried out by Mirhosseini et al. (2019) who found comparable trends for 30% RAP aged binder rejuvenated with vegetable oil.

After the short-term ageing (RTFO-aged), a similar tendency to unaged binder with a slight change is observed. The rutting resistance factors are higher for RTFO-aged binders than the unaged asphalt binders. The rutting resistance factor ($G^*/\sin\delta$) values of the 40RAP aged binder rejuvenated with 3%SOY are higher as compared to the neat binder. As shown in Figure 8, it is emphasized that the same trend with a slight increase for the binder with 3%SnF rejuvenation was observed as compared to the neat binder. In contrast, the ($G^*/\sin\delta$) value for the 40RAP aged

binder samples with higher rejuvenator contents (i.e., 6%SOY or 6%SnF) is lower than the neat binder at all testing temperatures. The values derived from the rutting parameter are found to be affected by the age. Conner et al. (2020) who examined the rejuvenated 40% aged asphalt binder with 10% waste vegetable oil found that after the short term aging (RTFO) the rutting parameters increased for all rejuvenated asphalt binder blends.

3.5 Intermediate Temperature Performance

The intermediate temperature performance on the long-term aged samples (PAV-aged) with different amount of SOY and SnF rejuvenators is studied to evaluate the binder samples fatigue parameter ($G^*\sin\delta$). Except the 40RAP aged binder, the stiffness values of all binders was lower as compared to the Superpave binder specified maximum value that is, ($G^*\sin\delta < 5000$ kPa). The effect of the rejuvenator on the fatigue parameter of the rejuvenated 40RAP aged binder at testing temperatures of 22 and 25°C is given in Figure 9.

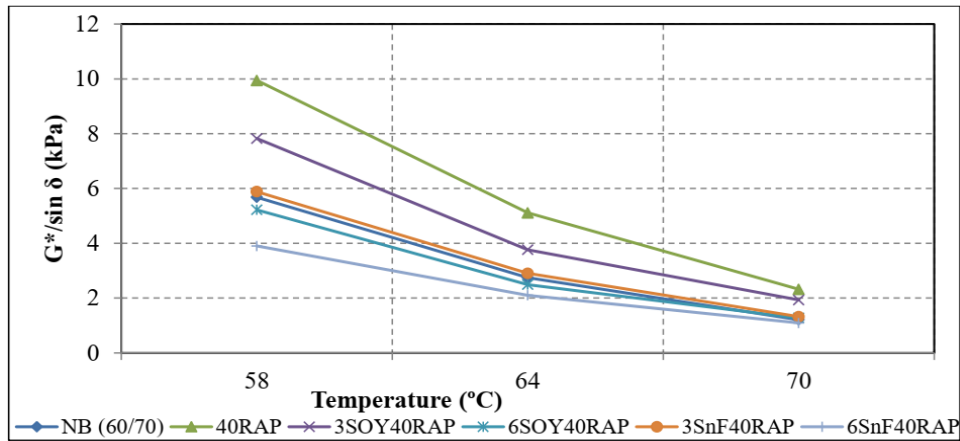


Fig-8: $G^*/\sin \delta$ values of neat binder, 40RAP binders, and rejuvenated 40RAP binder at RTFO-aged

It is shown that with the increase in the rejuvenator content, the fatigue parameter decreased, which means that there is an improvement in the fatigue resistance performance. The asphalt binder with 3% SnF has nearly similar stiffness value to that the neat binder whereas the rejuvenated 40RAP aged binders with 6% SOY and 6% SnF have lower stiffness to the neat binder. This is also supported by Jie *et al.*, (2017) who

reported that there is a reduction in the fatigue parameter for rejuvenated aged binder when the amount of rejuvenator was kept between 2 to 10%. Similarly Elkashef *et al.*, (2018) who added soybean derived oil in the aged asphalt binders, concluded that the 6% soybean oil shown a significant effect on the intermediate temperature characteristics.

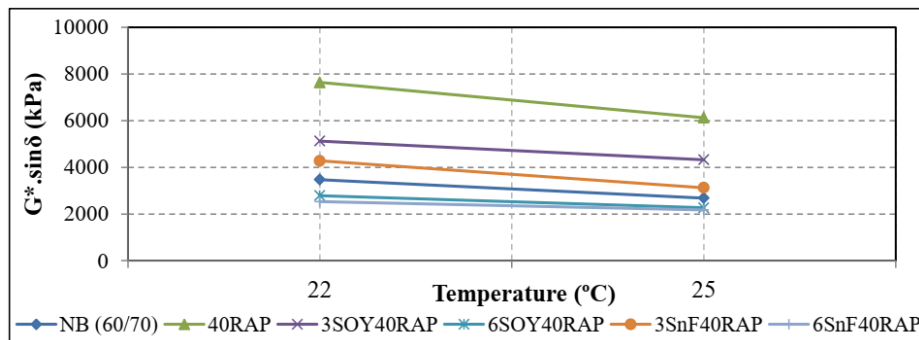


Fig-9: The $G^*. \sin \delta$ values of neat binder, 40RAP binders, and rejuvenated 40RAP binder at PAV-aged

3.6 Low-Temperature Resistance

To characterize the binder's susceptibility to low-temperature cracking, the PAV-aged asphalt binder samples are tested in the BBR testing machine. Figure 10 summarizes the creep stiffness and creep m-value for the neat binder, 40RAP aged binder, and rejuvenated 40RAP aged binder at testing temperatures of (-6, -12, and -18°C). As shown in Figure 10, it can be noticed that the rejuvenators have a significant influence on the reduced low-temperature stiffness of the rejuvenated RAP aged binders, implying that the toughness of the rejuvenated 40RAP blend has increased and the likelihood of the thermal cracking at low temperatures is decreased. As an instance, the addition of the 3%SnF and 6%SnF at -12°C temperature decreased the low-temperature stiffness by 35% and 49.22%, respectively, as compared to the 40RAP aged binder. This could be related to the lubricating properties of the vegetable oil, which has a low fluidity state at low temperatures (Mirhosseini *et al.*, 2018).

The m-value represents the binder's relaxation value over time. Greater m-value indicates that the asphalt binder is further resistant to low-temperature cracking (Saha *et al.*, 2020). The BBR test was used to assess the creep stiffness of the aged RAP asphalt binder with different rejuvenator types and contents at reference temperatures of -6, -12 and -18°C (Amira *et al.*, 2019). The resulted m-value for the neat binder, 40RAP aged, and rejuvenated RAP aged binders are given in Figure 11. It is illustrated that the RAP aged binders m-value has increased with the addition of rejuvenator agents. With reference to Figure 11, at a temperature of -12°C, the 40RAP aged sample has a creep rate of 0.243, which is much lesser than 0.3 (the Superpave binder specification criteria that is, m-value ≥ 0.30) while adding the 6%SOY and 3%SnF to the 40RAP aged binder has increased the m-value to greater than 0.30 (AASHTO T313-06). The findings is consistent with the results by Jie *et al.*, (2017) who found almost similar increase in the m-value for rejuvenated RAP binders. A comparable trend was also

found by Mirhosseini *et al.*, (2018) who used 5 and 6% vegetable oils for RAP aged binder modification at temperatures of -12 and -18°C, which has reported that the neat asphalt binder fulfills the standard specification requirements at -12°C but fails at -18°C, it was also

reported that the rejuvenated 40RAP aged binder met the specification requirement by adding a 6% rejuvenator, meaning that adding more oils can improve the asphalt binder's low temperature resistance.

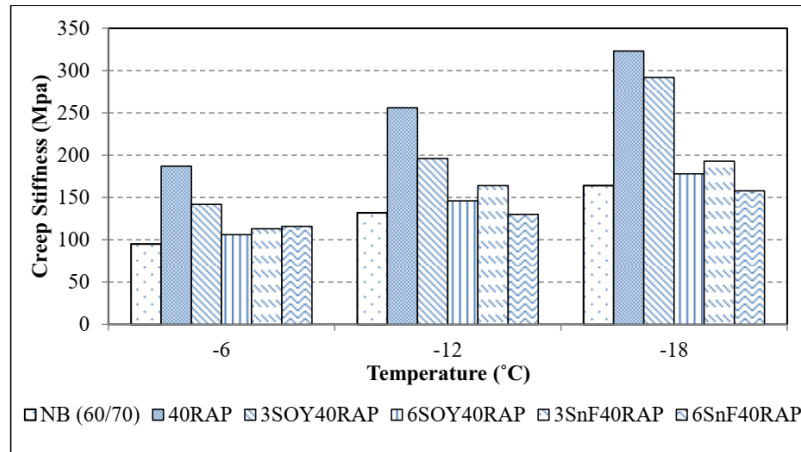


Fig-10: Creep stiffness of neat binder, 40RAP binders, and rejuvenated 40RAP binder at PAV-aged

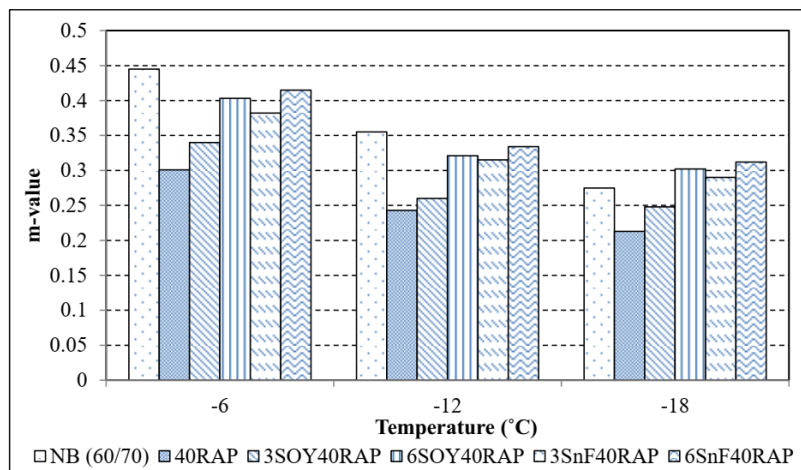


Fig-11: The m-values of neat binder, 40RAP binders, and rejuvenated 40RAP binder at PAV-aged

4. CONCLUSIONS

The effects of rejuvenators on the properties of 40RAP aged modified asphalt binders were investigated in this study. The SOY and SnF vegetable oils were used to rejuvenate 40RAP aged asphalt binders. The asphalt binders were subjected to property testing, viscosity, and rheological tests. As a result of the findings of this study, they reflected the following conclusions:

- The asphalt binder conventional tests have shown that the rejuvenators can effectively recover the RAP aged binder with a 3 to 6% content. When compared to SOY, the SnF rejuvenator more efficiently decreased the stiffness and increased the plasticity of the rejuvenated 40RAP aged binder. At selected contents, rejuvenated RAP aged binders increased the penetration values and reduced the softening points.

- The rejuvenator contents' effect on the viscosity of rejuvenated 40RAP aged binder has shown better performance. The viscosity values of the extracted 40RAP aged binder rejuvenated with 3% SnF and 6% SOY were nearly similar to the neat binder. In the same way, the viscosity values of the rejuvenated 40RAP aged binder were reduced efficiently as the percentage of the rejuvenator was increased. Therefore, a lower viscosity enables effective aggregate coating and allows for less mixing and compaction on the site, which can save fuel consumption and reduce volatile organics emissions.
- According to the DSR testing results, adding SOY and SnF as a rejuvenator agents to the 40% RAP asphalt binders has satisfactory performance against rutting. The rutting resistance factor ($G^*/\sin\delta$) of the 40RAP aged

binder was enhanced and became nearly similar to the rutting resistance factor of the neat asphalt binder when 3% SnF and 6% SOY rejuvenators were added. However, increasing the proportion of SnF in binders (>3%) makes them more susceptible to rutting resistance. Therefore, a large amount of RAP could be employed in the SnF modified binder blend that could help to retain the rutting resistance of the neat binder.

- Adding rejuvenators to extracted 40% RAP aged binder has also shown a better tendency to low-temperature cracking. The rejuvenated binder's creep stiffness was within the Superpave specification criteria, demonstrating that the SOY and SnF oils as a rejuvenator agents reduced the low-temperature resistance of the aged binder. The 40RAP aged binder at a temperature of -12 and -18°C has an m-value smaller than 0.30, while the 40RAP binders rejuvenated with SOY and SnF at the mentioned temperatures have a greater m-value (> 0.30), which can satisfy the Superpave requirements.

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