



Performance of Aged Asphalt Binder Treated with Various Types of Rejuvenators

Munder Bilema^{1, 2*}, Yusri Bin Aman², Norhidayah Abdul Hassan³, Zaid Al-Saffar⁴, Kabiru Ahmad⁵, Kabiru Rogo³

¹ Department of Civil Engineering, Faculty of Engineering, Benghazi University, Benghazi, Libya.

² Department of Highway and Traffic Engineering, Faculty of Civil Engineering and Environmental, University Tun Hussein Onn Malaysia, 86400 Parit Raja, Batu Pahat, Johor, Malaysia.

³ Department of Geotechnics & Transportation, School of Civil Engineering, Faculty of Engineering, Universiti Teknologi Malaysia, 81310 Johor Bahru, Johor, Malaysia.

⁴ Building and Construction Engineering, Technical College of Mosul, Northern Technical University, Mosul, Iraq.

⁵ Department of Civil Engineering, Faculty of Engineering, Bayero University Kano, 3011 Kano State, Nigeria.

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Abstract

High demand for asphalt binders in road construction verifies the need of finding alternative materials through asphalt pavement recycling. This paper investigated the impact of different rejuvenators on the performance of an aged asphalt binder. Virgin Olive oil, virgin cooking oil, waste cooking oil, virgin engine oil, and waste engine oil were added to a 30/40 penetration grade aged asphalt binder at a fixed oil content of 4% for all types. The wet method was used to blend the rejuvenators and aged asphalt binder. The physical, rheological, and chemical properties of the rejuvenated asphalt binder were evaluated using several laboratory tests which include penetration, softening point, bleeding, loss on heating, storage stability, penetration index, ductility, viscosity, dynamic shear rheometer, and Fourier transform infrared spectroscopy. The outcomes of the physical properties showed that the olive, waste, and virgin cooking rejuvenators can restore the aged asphalt binder to a penetration grade of 60/70. In contrast, the virgin and waste engine oil required a more quantity of oil to rejuvenate the aged asphalt binder. A sufficient amount of rejuvenator could regenerate the $(G^*/\sin \delta)$, (δ°) , and (G^*) for the aged asphalt binder. The addition of virgin olive and cooking oils in aged asphalt led to a rutting issue. No chemical reactions were observed with the addition of rejuvenators but they give an impact on reducing the oxidation level of the aged asphalt binder. As a result, further research should be performed on waste cooking oil given that it is inexpensive and provides excellent performance results.

Keywords: Rejuvenators; Aged Asphalt Binder; Physical; Chemical; Rheological Properties.

1. Introduction

Asphalt binder is a primary material used as a binder for the construction of road. The demand for asphalt binder is high due to the increase in the infrastructure development and construction work [1]. Reclaimed asphalt pavements (RAP) is a by-product of the milling process of pavement surface. RAP consists of the wearing course or binder

* Corresponding author: mondo199131@gmail.com

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course, or both layers. RAP can be recycled for the construction of dams, fills, [2, 3], or gravel roads. In most cases, RAP is recycled into the road pavement as a base or surface material given its cost-effectiveness, environmentally friendly attribute, and good performance [4]. The quality of RAP may not be the same as the quality of virgin materials, but adding RAP into fresh mixtures can minimise the material costs [5]. There are various factors that influence the performance of the recycled mixture, such as the amount of RAP, the type of binder, aging process [6, 7], and the addition of a rejuvenator [8]. The addendum of high amount of RAP causes in workability and cracking failures. By applying various types of waste oils in aged asphalt, it will provide a significant effect on the asphalt pavement properties [9]. Using waste cooking oil (WCO) is a smart solution to producing sustainable road asphalt pavement, and it can positively affect the safety, aging, and pavement characteristics of aged asphalt [10, 11].

In the last decade, many studies have been conducted to rejuvenate asphalt pavement by using recycled waste cooking oil [12-14]. Ahmad et al. [15] performed a study using oil extracted from discarded fruit on the aged asphalt. The outcomes present that it enhances the workability and coating of the asphalt mixture. In addition, Malaysian asphalt researcher has been exploring ways and means the discarded fruit oil can soften the asphalt and recover the characteristics of the aged asphalt by adding rejuvenator of 10% per total proportion of the asphalt [16]. Guarin et al. [17] used fish oil to restore the reclaimed asphalt pavement binder properties. Additionally, previous studies have concluded that WCO could enhance the physical characteristics of the aged asphalt, such as penetration and softening point. Also, the addition of WCO increased the penetration value and decreased the softening point value of the aged asphalt [11, 18]. Adding the WCO or waste vegetable oil can enhance the viscosity characteristics of asphalt by providing the optimal oil percentage. In asphalt binder properties, the ductility value correspondingly increased with an increasing oil percentage [19, 20] because the oil gives the asphalt binder lower viscosity and a higher flash point, which can sufficiently rejuvenate the aged asphalt binder. It is a great challenge to find an environmentally friendly alternative to maintaining aged asphalt binders. In terms of asphalt binder rheology, the isochronal curve can be defined as G^* and δ° in various temperatures using the DSR. The G^* measures the stiffness of the material, and the δ° measures the angle between the strain and stress (elasticity) [21]. The DSR experiment has become a helpful method for characterizing the asphalt rheology at high, medium, and low temperatures.

Furthermore, the use of Waste Cooking Oil (WCO) and Waste Engine Oil (WEO) enhances and restores the aged asphalt binder properties. Some previous studies have indicated that adding the appropriate amount of WCO or WEO could reduce the G^* and slightly raise the δ° [22, 23]. Moreover, the addition of WCO 5% per total weight of the asphalt could lower the failure temperature of an aged asphalt [24]. Yang et al. [25, 26] performed studies using oil from waste resources to rejuvenate an aged asphalt binder and summarized that increasing the amount of oil in the binder could increase the rutting parameter, G^*/\sin . However, the chemical functional groups of the aged asphalt were found to be identical to those of the virgin asphalt binder when the appropriate percentages of domestic waste bio-oil were added to the aged asphalt. In addition, the rejuvenator can decrease the presence of carbonyl and sulfoxide in the chemical groups, which softens the aged asphalt binder [27].

The increment in the RAP amount in asphalt pavements raises the possibility of cracking and workability issues, which is the main cause for construction companies to start using rejuvenators. By having the rejuvenators in the mix, the construction companies could increase the portion of RAP used in the asphalt pavement by 100%. On the other hand, some construction companies are unenthusiastic to use rejuvenators due to the possibility of rutting and bleeding issues [28]. Thus, an accurate selection of the rejuvenator is necessary to restore aged asphalt properties. Some criteria should be considered for the selection of rejuvenators, such as workability, fully coated asphalt mixture, less harmful emissions, and ability to restore the chemical and physical properties of asphalt. Therefore, it is indispensable to explore the utilization of new potential rejuvenators used with the aged asphalt as completed in this study.

1.1. Objectives

The aim of this study is to evaluate the effects of different types of oils on aged asphalt binders, which is essential in asphalt pavement recycling in order to find the best rejuvenator for energy saving and to reduce the environmental impact. Three critical properties were investigated namely the physical, rheological, and chemical properties of the rejuvenated asphalt binders. In order to achieve the objective, a detailed plan is shown in Figure 1.

2. Materials and Methods

2.1. Materials

The asphalt binder with 60/70 penetration grade was supplied by the Kemaman Bitumen Company located in Subang Jaya, Selangor, Malaysia. The oils used in this study were olive oil, waste cooking oil (palm oil), virgin cooking oil (palm oil), waste engine oil, and virgin engine oil. The waste cooking and engine oils were filtered using 150-mm diameter filter papers to remove the small particles that may affect the quality of the rejuvenators. Based on the previous study, the treated oil gives a noticeable enhancement on the physical and rheological characteristics of the aged asphalt in comparison with the untreated oil [29]. Additionally, the waste and virgin cooking oils were collected

from a local restaurant, and the waste and virgin engine oils were obtained from a local automotive repair shop in Batu Pahat, Johor, Malaysia. The waste cooking oil had been used for frying fresh fries three times before disposal, and the waste engine oil had been used for 5000km or more before disposal. The flashpoint, viscosity, and loss on heating were tested to confirm that the oils can be blended with the aged asphalt binder. All oils in this study chosen based on the availability. Table 1 presents the physical characteristics of the different types of oils.

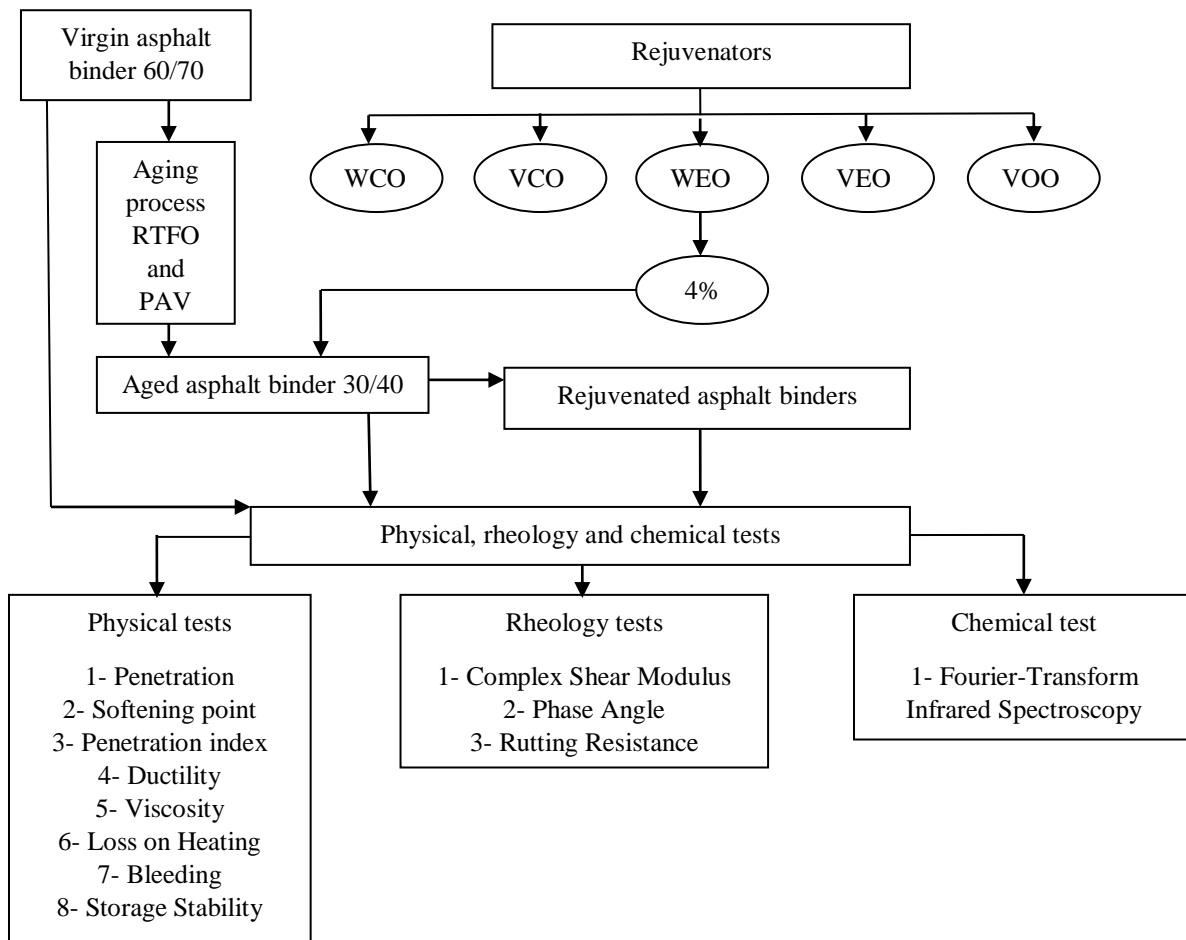


Figure 1. Research methodology of this study

Table 1. Physical characteristics for several types of oils

Physical properties	Result value				
	Virgin cooking oil	Waste cooking oil	Virgin engine oil	Waste engine oil	Virgin olive oil
Flash point (°C)	240	233	228	198	272
Viscosity at 30°C (cp)	42	46.2	54.9	64.2	29.8
Loss on heating (%)	0.14	0.74	0.69	4.5	0.07

2.2. Sample Preparation

The aging operation was done according to rolling thin film oven (RTFO) ASTM D2872 and pressure aging vessel (PAV) ASTM D6521. After the aging procedure was achieved, the aged asphalt binder was examined by a penetration test to measure the grade of the aged asphalt binder. The result of the penetration test was a 30/40 grade asphalt binder. Figure 2 shows the high shear mixer device and hot plate stirrer.

The same amount of the different types of oil, 4%, was added to all the aged binder samples, the same percentage of oil was added to show the quality of the oils. The asphalt binders were mixed using a high shear mixer. First, the aged asphalt was heated in the furnace for two hours at 150°C, which was the mixing temperature for each blend. Second, after two hours, the aluminum cup was transferred from the furnace and placed on the hot plate for 5min before mixing in order to adjust the mixing temperature. Last, the speed used to blend the rejuvenators with the aged asphalt binder was 1500rpm, and the mix was continuously stirred for 20min by the high shear mixer [13]. In addition, to avoid long-term storage, all physical, chemical, and rheological tests were conducted within one week after the mixing process.



Figure 2. High mixer shear device and hot plate stirrer

2.3. Experimental Tests

The penetration test was performed as stated by ASTM D5. [30]. The experiment employed a 1-mm diameter needle. The asphalt binder samples were 100g and performed at a temperature of 25°C while the needle was inserted for 5s into each asphalt sample. The softening point of each asphalt sample was determined based on ASTM D36. [31]. The penetrometer (Figure 3) contains a 100g needle and a device to release and lock at any position. The penetration index used to measure the temperature susceptibility and classify the asphalt binder type. The ductility test employed a ductilometer, and each asphalt specimen was elongated at a constant rate of 5 cm/ min, according to ASTM D113 [32] at 25°C. The extended distance was measured in centimeters. Figure 4 displays the ductility device. The viscosity experiment was used to determine the flow behavior of the asphalt binder. Viscosity was determined at two temperatures by using a rotational viscometer at 135°C for the compacting temperature and 165°C used for the mixing temperature. The test procedure is in accordance with ASTM D4402 [33]. Approximately 30g of asphalt was heated in an oven until it was conducive to pouring into the sample chamber, and with various types of asphalt binder chose the proper spindle. The sampling took place in the chamber of a thermos container. After the desired temperature was stable for approximately 20 to 30 minutes, the spindle was lowered into the chamber to measure the viscosity. Figure 5 shows the rotational viscometer device. The storage stability experiment was performed to explore the homogeneity of the aged asphalt incorporating the different type of oils.

This experiment was conducted accordance to ASTM D5892. [34]. In particular, the asphalt binder was poured into the aluminum tube (30cm height and 3cm diameter). The asphalt binder samples placed in an oven at $163\pm 5^{\circ}\text{C}$ for 48 hours. The asphalt binder samples were subsequently placed in a freezer at -10°C for 4 hours to solidify them. The Following that, the asphalt binder was cut into three equal sections after cooling. Finally, both ends (upper and lower sections) of the sample were subjected to the softening point test by testing the differences of temperature between both segments. The asphalt binder was deemed stable if the temperature between the top and bottom sections differed by no more than 2.2°C. The bleeding experiment steps was performed accordance to Zaumanis et al. [35]. The bleeding experiment used to explore the skid resistance in the asphalt. The bleeding test in this study involved several steps. Firstly, 35g of asphalt binder was poured into the short term aged container before the sample covered with a filter paper was placed under the pressure of 0.6 g/cm² for 5 minutes in every hour for a total of 7 hours. Following that, it was placed in an oven at 46°C for 7 hours. The wetness of the filter paper was evaluated every hour according to the scale of 0 to 3, where 0 denotes not wet and 3 means fully wet. Therefore, the total calculated score in this study ranged from 0 to 21, and the value of the bleeding result has no unit. The dynamic shear rheometer device used to determine the stiffness and elastic behavior of the asphalt binders at various temperature according to AASHTO T-315 [36]. The Fourier-transform infrared spectroscopy device utilized to explore the chemical structure of the asphalt binder for unaged and short-term aged asphalt. Table 2 shows the physical, rheological, and chemical properties tests for the asphalt binder and the requirement for the 60/70 grade virgin asphalt binder. Figure 6 shows the FTIR spectroscopy device.



Figure 3. Penetration test device



Figure 4. Ductility device



Figure 5. Rotational viscometers

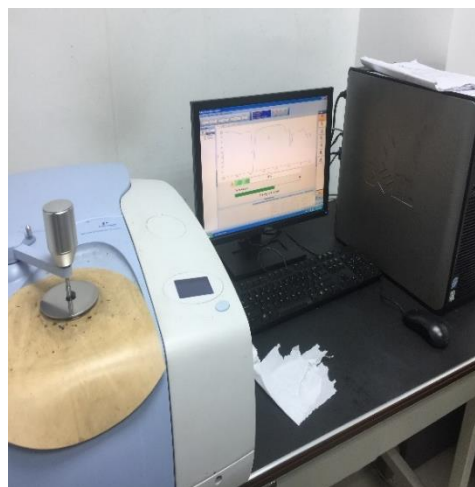


Figure 6. FTIR spectroscopy device

Table 2. Physical, Rheology and Chemical properties tests for asphalt binder

Asphalt binder tests	Tests Method	The requirement of the virgin binder 60/70
Penetration at 25°C (mm)	ASTM D5	60 – 70
Softening Point (°C)	ASTM D36	48 – 52
Ductility at 25°C (cm)	ASTM D113	Min. 100
Viscosity at 135°C, 165°C	ASTM D4402	-
Storage stability (°C)	ASTM D5892	Different Less than 2.2 °C
Bleeding	-	0-21
Penetration index	-	-2 to 2
Loss on heating (%)	AASHTO T240	0.05-0.5, Max. 1.00
Dynamic Shear Rheometer	AASHTO T315	-
Fourier-transform infrared spectroscopy	-	600-4000

3. Results and Discussion

3.1. Physical Properties

3.1.1. Penetration and Softening Point

Figure 7 shows the penetration values of asphalt binder modified with different oil types. Based on the figure, samples contain the waste, and virgin engine oils have the lowest penetration values among the rejuvenators. Furthermore, the aged asphalt binder has the lowest penetration values among all asphalt binders due to the oxidation, which drove to an increment in the hardness level of the asphalt binder. However, olive oil has the highest penetration values than other oils related to excellent physical properties, such as its low viscosity and loss on heating. In addition, the waste and virgin cooking oils show reasonable results similar to the virgin asphalt binder 60/70. Therefore, the

result of the penetration indicates that all types of oils in this research could recover the aged asphalt with respect to the optimal oil percentage. The WCO and VCO asphalt binders had similar penetration values due to the excellent WCO physical properties, such as proper viscosity and lower weight loss. Zhang et al. [37] reported that the quality of oil strongly affects the penetration values, which agreed in this study. The increment in the penetration value is related to the enormous proportion of oleic acid in vegetable oils which has a considerable impact on the behavior of the age asphalt [38].

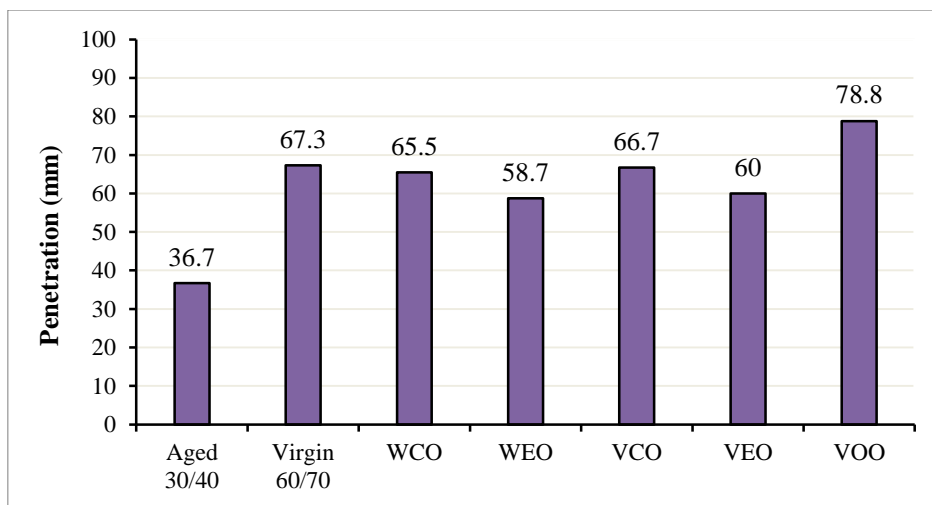


Figure 7. Results of the penetration for several sorts of rejuvenators

The softening point experiment shows the asphalt binder transformation from a highly viscous state to a low viscous state. Figure 8 shows the result of the softening point for the aged asphalt and rejuvenated asphalt. It can indicate that the aged asphalt has the greatest softening point value because the aged asphalt binder requires a higher temperature to melt. The increase of the period of aging drove to an increment in the softening point of the asphalt [39]. As expected, olive oil has a significant effect on the aged asphalt, as seen in the reduction of the softening point values. Moreover, the result shows that the waste and virgin engine oils have a slight impact on the aged asphalt binder. Consequently, the amount of waste and virgin engine oils needs to be increased to obtain a similar result to the virgin asphalt. Also, the virgin and waste cooking oils modified asphalt achieve an acceptable result that was closer to the virgin asphalt. The outcome concluded that investigation of the physical properties for the oils is substantial before used as a rejuvenator to restore the aged asphalt binder. Previous study has reported that using petroleum rejuvenators such as WEO and VEO has a slight impact on the behavior of the aged asphalt. The existence of a high asphaltene ratio leads to an increase in the proportion of oil needed to restore the aged asphalt [40].

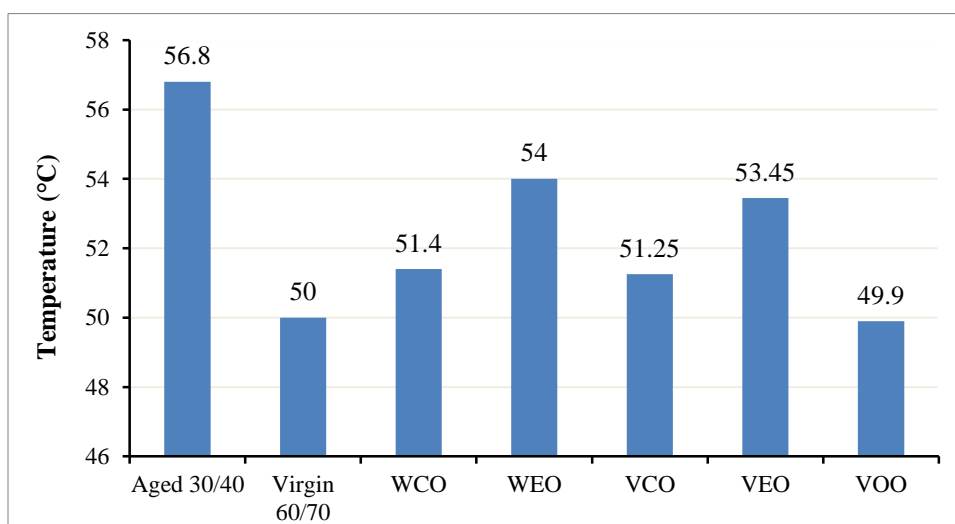


Figure 8. Results of softening point for asphalt binders

3.1.2. Penetration Index

The penetration index was utilized to categorize the type of asphalt binder. Additionally, the penetration index was used to classify each asphalt binder into one of three groups: conventional paving asphalt binder, blown asphalt binder, and temperature-susceptible asphalt binder. Table 3 shows the effects of each type of oil on the penetration

index values. The conventional paving asphalt binder has a range between -2 and 2 [16]. The result indicates that all the PI values of the asphalt binders were within the range of the conventional paving asphalt binder. For asphalt containing virgin and waste cooking oil, the PI values were the closest to the virgin binder value. A similar trend was concluded by Zargar et al. [41] while investigating the impact of the WCO on the behavior of the aged asphalt. They found that WCO can adjust the temperature susceptibility of aged asphalt but it does not similar the virgin asphalt binder value. The increment in the PI values indicates lower temperature susceptibility and higher elastic demeanor [42]. The waste and virgin engine oil has the lowest impact on the aged asphalt binder among all rejuvenators. According to Burke and Hesp [43], waste engine oil has a slight effect on the penetration index.

Table 3. Penetration index results for different asphalt binders

Binder ID	Penetration index
VOO	-0.05
VCO	-0.17
VEO	0.072
WCO	-0.19
WEO	0.14
Virgin 60/70	-0.4
Aged 30/40	-0.34

3.1.3. Ductility

The ductility describes the deformation and flexibility of the asphalt binder [44]. Figure 9 shows the impacts of the various types of oils on the ductility of aged bitumen. The result shows that the aged asphalt binder has the lowest ductility values due to the oxidation of the asphalt binder. Moreover, the sample rejuvenated with waste engine oil does not pass the requirement of the ductility, as it requires an increment in the amount of the engine oil necessary to recover the aged asphalt binder properties. In contrast, all the other asphalt binders passed the ductility requirement of being more than 100 cm at 25°C. Olive oil had a considerable impact on the ductility result, and the result was higher than that of the virgin asphalt binder with only 4% of oil. Furthermore, the waste and virgin cooking oils had values of 114 cm and 124 cm, respectively, comparable to virgin asphalt binder. The same outcomes were gained by Xinxin et al. [45], who found that the waste vegetables oil has a significant impact on the ductility result with respect the optimal oil content. Previous study concluded that the addendum of the WCO increase the ductility value and enhance the cracking resistance of the asphalt [19].

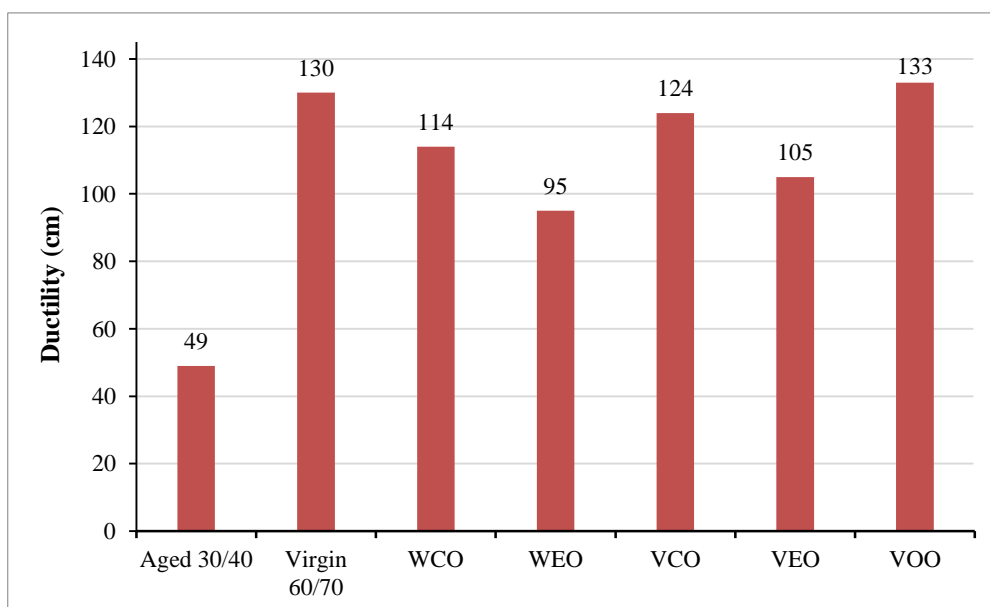


Figure 9. Ductility of asphalt binders containing several sorts of rejuvenators

3.1.4. Viscosity

The viscosity was characterized by evaluating the flow of asphalt binder under the mixing and compaction temperatures. Figure 10 illustrates the effect of the oils on the viscosity of the aged asphalt for the mixing and compaction temperatures. There is decrement in the viscosity values when the temperature was increased from 135°C to 165°C. The result shows that the viscosity of the asphalt decreases when the oil was added to the mix, which means

that the oil content can lower the compaction and mixing temperatures of the asphalt mixture. Sample with olive oil has the most significant effect on the viscosity compared to the other oils and the virgin asphalt binder. In addition, the virgin cooking oil achieved almost the same viscosity as the virgin asphalt binder. Su et al. [46] concluded that the optimal proportion of WCO can enhance the workability of the aged asphalt binder. In addition, the samples require an increasing amount of waste and virgin engine oils in order to recover the aged asphalt binder and comparable to the virgin asphalt 60/70. The higher viscosity resulted from asphalt content WEO may be related to the high value in the loss on heating experiment. The particles' existence in the WEO can impede the workability of the asphalt and drove to increase the viscosity. The 30/40 aged asphalt has the highest viscosity values in both temperatures among all the other asphalt binders. The same outcomes were gained by Guarin et al. [17]. They had detected that the high asphaltene to maltene ratio in the aged asphalt drove to an increment in the viscosity value. The aged asphalt incorporating VCO, VEO, and VOO has a higher impact on the viscosity at 135°C, in comparison with the other oils.

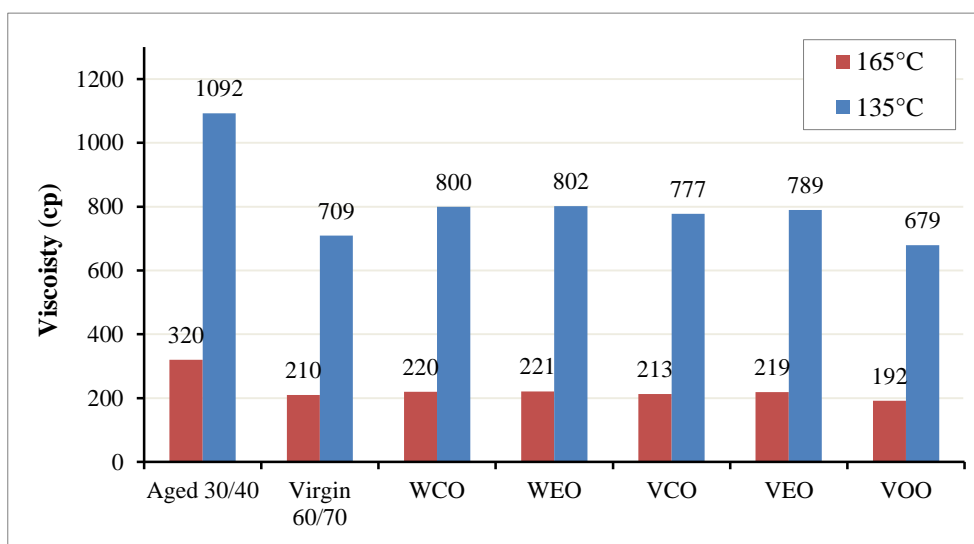


Figure 10. Viscosity result of asphalt binders

3.1.5. Loss on Heating

The specifications range of weight loss due to heating is between 0.05 and 0.5% [47] or less than 1% for the SuperPave specifications. The loss on heating is a fundamental parameter, a high percentage of loss on heating result may cause in workability issue of the asphalt. Figure 11 shows the weight loss of asphalt binder due to heating. It was observed that the waste engine oil has the highest amount of weight loss compared with other oil types due to a high amount of the small metal particles in the waste engine oil. A resemble trend was mentioned by Zaumanis et al. [34] while investigating the impact of different rejuvenators on the behavior of the aged asphalt. They had detected that the aged asphalt incorporating waste engine oil has the highest loss on weight value among the other rejuvenators. Furthermore, the waste and virgin cooking oils have a result comparable to that of the virgin asphalt binder, with a weight loss of 0.28 and 0.27%, respectively. Overall, all the samples tested are within the specification.

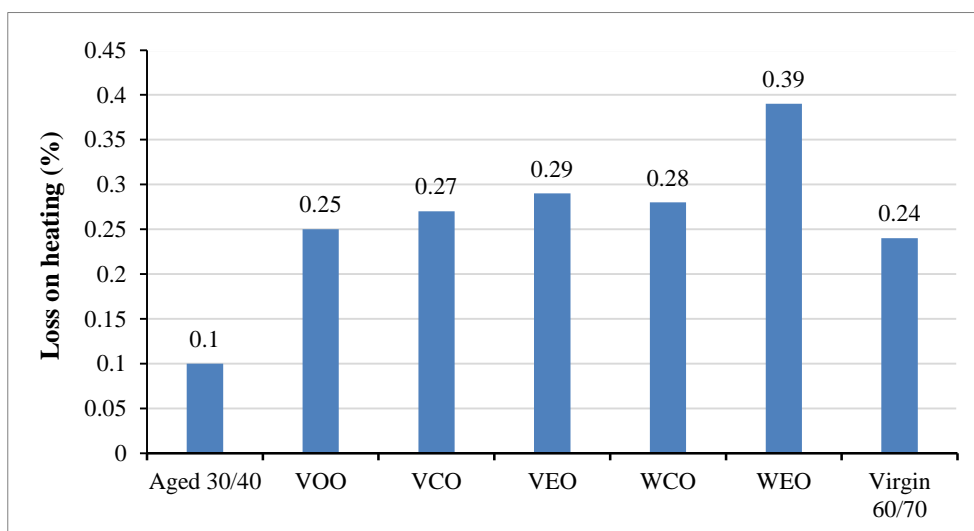


Figure 11. Loss on the heating result of asphalt binders

3.1.6. Bleeding

Bleeding is one of the most common issues when adding a high amount of rejuvenator to an aged asphalt binder which can lead to low skid resistance [34]. The bleeding values have no unit. Figure 12 shows the bleeding values for all the asphalt binder samples. The result demonstrates that there was a significant increase in the bleeding value when a rejuvenator with 4% olive oil was added. In contrast, waste engine oil has the lowest bleeding values among the types of oil used. However, the waste cooking oil, virgin cooking oil, and virgin engine oil have reasonable values compared with that of the virgin asphalt binder. This supports the finding of Zaumanis et al. [34], where a high percentage of oil added could lead to bleeding issues. On the other hand, the loss on the oily components in the aged asphalt drove to low bleeding value. Among the other rejuvenators, olive oil with low viscosity gives the highest bleeding value while the waste engine oil with high viscosity gives the lowest bleeding value. It can be concluded that the superior physical characteristic of the oil leads to enhance in the characteristic of the aged asphalt.

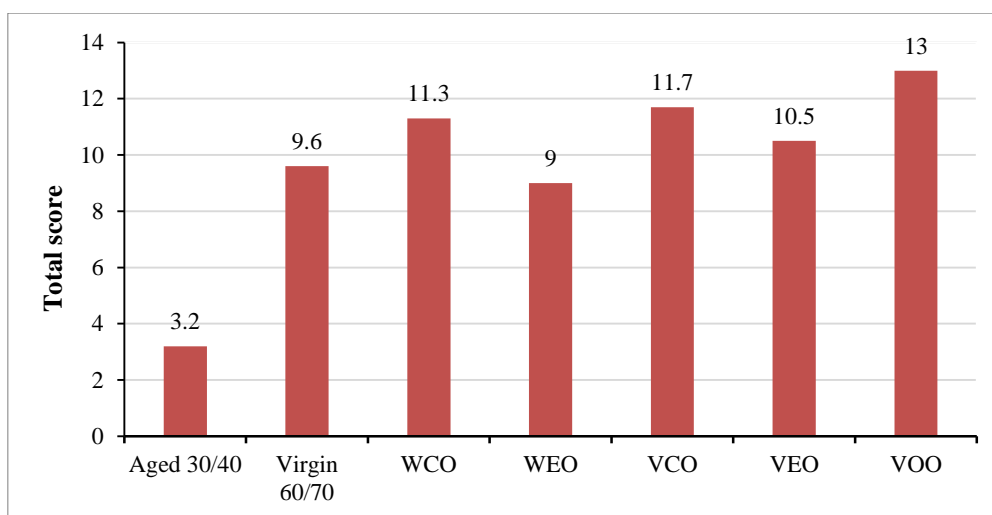


Figure 12. Bleeding result of asphalt binders

3.1.7. Storage Stability

Figure 13 illustrates the storage stability values of all the asphalt binders tested. The result shows that the least difference in temperatures was found for the aged asphalt binder and the one added with the waste engine oil as a rejuvenator particularly at 0.5°C. In contrast, the waste cooking oil and olive oil rejuvenators have the highest difference in temperature at 2°C but still within the acceptable range of less than 2.2°C. This high penetration index results related to the low viscosity of the olive oil and waste cooking oil. In addition, the virgin cooking oil and virgin engine oil have comparable results to the virgin asphalt binder with a difference of 1.5°C and 1°C, respectively. Consequently, all the samples tested are within the specification. Excessive addition of the oil will negatively affect the storage stability of the asphalt binder. This is agreed with the study done by Abdullahi et al. [44], who concluded that there was no storage issue found when up to 5% of the oil was added to an aged asphalt binder. According to Al-Saffar et al. [48], the waste engine oil has low storage stability value due to a similar chemical structure and molecularly as the asphalt binder.

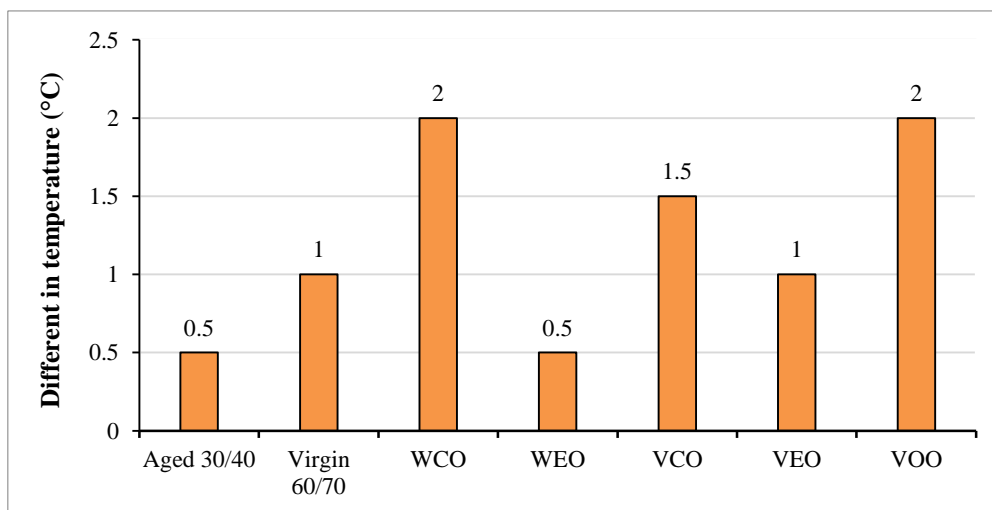


Figure 13. Storage stability result of asphalt binders

3.2. Rheological Properties

3.2.1. Complex Shear Modulus

The G^* is known as the stiffness of the asphalt binder at various temperatures and loading rates. Additionally, it is known as the ratio of the maximum stress to the maximum strain [10, 21]. The HAKE software was used to perform the dynamic shear rheometer test. The 60/70 penetration grade virgin asphalt binder was used for comparison with the aged asphalt treated with different rejuvenators. Figure 14 shows the change in behavior of the asphalt binder due to the addition of rejuvenators at various temperatures. The complex shear modulus for the virgin cooking oil and olive oil have the lowest G^* values resemble to the virgin asphalt binder, which means that both oils have the ability to restore the aged asphalt properties with less amount of oil than the other rejuvenators: 25 and 29 kPa at 46°C, respectively. In contrast, WCO, WEO, and VEO were slightly less effective, with higher values than the virgin asphalt binder: 39, 38, and 40 kPa at 46°C, respectively. In addition, the failure temperature was obtained at 76°C for both modified and the virgin asphalt binder samples. The complex shear modulus values show significant differences between the different types of oils on the aged asphalt. Therefore, the considerable decrease in the complex shear modulus was related to the addition of the rejuvenators, which demonstrates that these rejuvenators are excellent candidates to decrease the hardness of the aged asphalt binder. According to previous studies, the addition of oil decreased the complex shear modulus, which supports the results obtained from this study [15, 49].

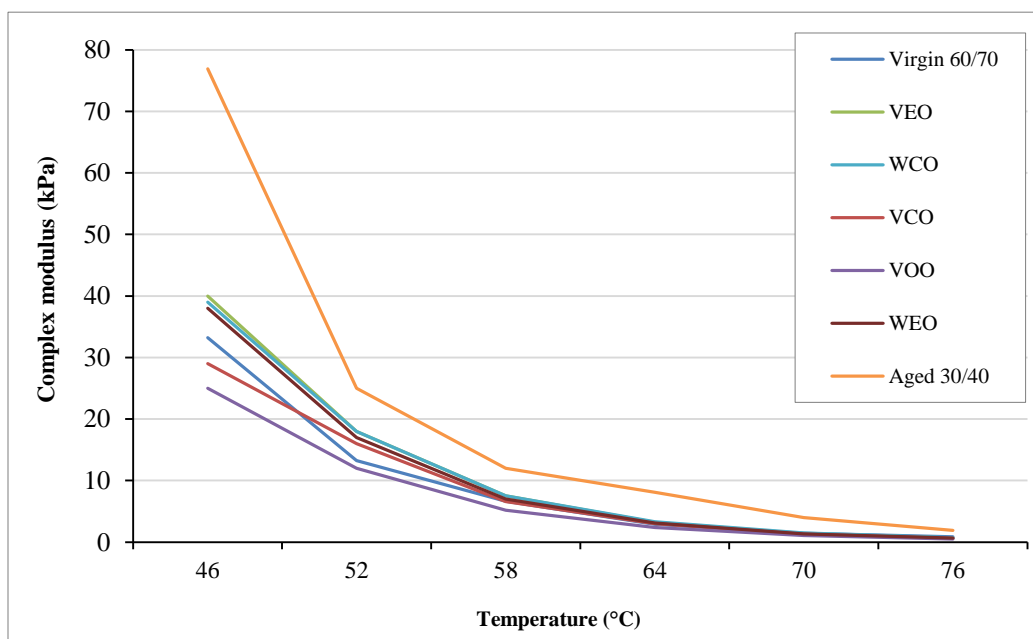


Figure 14. Effect of different rejuvenators on the complex modulus

3.2.2. Phase Angle

The δ° is the angle between the shear stress and the shear strain. Additionally, the δ° range values range from 0° to 90° [50, 51]. The dynamic shear reading was taken at a control frequency of 1.63 Hz, which represents a vehicle speed of 100 km/h. The effects of the different rejuvenators on the phase angle are shown in Figure 15. The findings indicate that the addition of oil leads to an increment in the δ° values. The figure shows that the increase in the phase angle corresponds to a rise in the temperature. Furthermore, the olive oil and virgin cooking oil have similar phase angles compared to that of the virgin asphalt binder at 79° and 77° , respectively. However, the addition of the other types of oils should be increased in order to obtain a similar result to the virgin asphalt binder. Furthermore, the virgin and waste engine oils have the lowest phase angle, particularly 71° and 72° at 46°C , respectively. The phase angle and complex shear modulus values clearly demonstrate that the aged asphalt binder needs different percentages of oil content, and that depends on the physical properties of the oils. The rheology criteria give an accurate understanding when investigating the impact of the different rejuvenators on the behavior of the aged asphalt binder, in comparison with physical properties experiments.

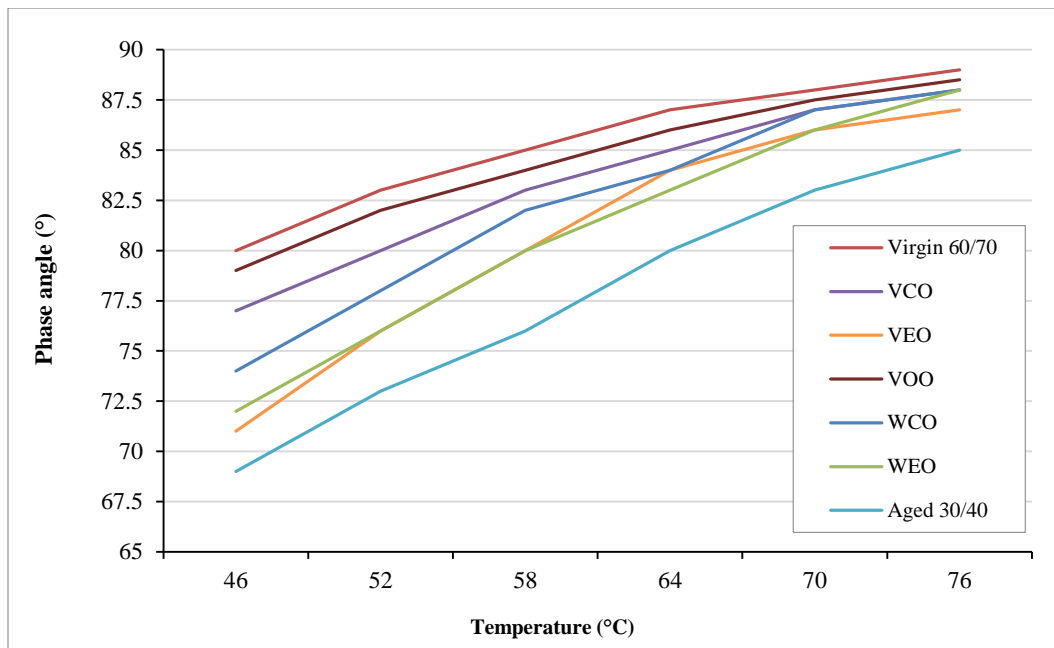


Figure 15. Effect of different rejuvenators on the phase angle

3.2.3. Rutting Resistance

The rutting resistance parameter, $G^*/\sin \delta$, describes the unrecoverable deformation of an asphalt binder under a consistent load at different temperatures [21, 36]. Figure 16 shows a significant decrease in the rutting parameter with an increase in temperature. Moreover, the quality and type of oil can strongly affect the rutting resistance parameter. The findings show that the rutting parameter for the virgin engine oil and the olive oil, is observed at 42.3 kPa and 25.5 kPa, respectively. Additionally, the olive oil and virgin cooking oil have the lowest rutting resistance of the oils due to their low viscosity. On the other hand, the WCO, VCO, and WEO need a higher amount of oil, more than 4%, to restore the aged asphalt binders. This outcome is an agreement with the previous research done by Maharaj et al. [52], where the utilized of the WCO could lower the rutting resistance parameter of the aged asphalt binder. In addition, there is a massive reduction of 24.6% in the rutting parameter of the aged asphalt resemble to the virgin asphalt when a 4% olive oil rejuvenator is added to the 30/40 penetration grade aged asphalt binder. Others, there is a 25.1% increase in the rutting parameter when 4% of virgin engine oil was added to the aged binder, in comparison with virgin asphalt binder. As outlined in previous research by Rasman et al. [47], it was concluded that the rutting resistance decreases with the addendum of oil, as well as the increase in heat.

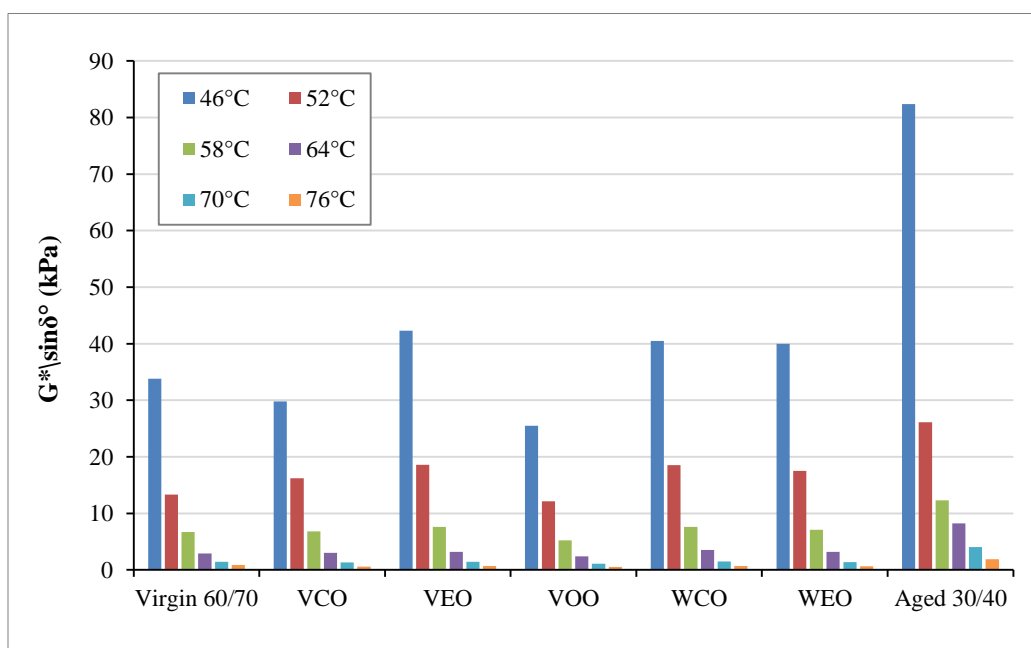


Figure 16. Rutting resistance parameter result for different rejuvenators

3.3. Chemical Composition

3.3.1. Fourier-Transform Infrared Spectroscopy, FTIR

FTIR was utilized to determine the changes in the chemical group in the asphalt. In this study, the chemical groups of the asphalts were characterized using the PerkinElmer instrument analysis. Additionally, the test was conducted within a spectrum ranging from 600cm^{-1} to 4000cm^{-1} at a temperature of 22°C . In the case of the aging asphalt binder, changes in the peaks corresponding to sulfoxide and carbonyl functional groups were found, as mentioned in previous studies [53, 54]. The spectrum range for carbonyl functional groups is between 1670cm^{-1} and 1820cm^{-1} , and the spectrum peak for sulfoxide functional groups is 1030cm^{-1} . Figure 17 illustrates the chemical functional groups of the various types of oils added to the aged asphalt binder.

From the figure, the differences in peaks for the asphalt binders in this study can be found in four primary bonds: the polymeric bond found between 3200cm^{-1} and 3500cm^{-1} O-H stretching, the carbonyl bond found between 1670cm^{-1} and 1820cm^{-1} C=O stretching, the sulfoxide bond found at 1030cm^{-1} S=O, and the aromatic bond located between 769cm^{-1} and 839cm^{-1} C-H plane bending. Furthermore, $1670\text{-}1820\text{cm}^{-1}$ C=O stretching bond was utilized as an index to find and determine the relative oxidation of virgin, aged, and bio-asphalt binders. According to previous research, the bonds at $1670\text{-}1820\text{cm}^{-1}$ represents carbonyl bonds C=O, and the values of the bonds at $1670\text{-}1820\text{cm}^{-1}$ increased with an increased amount of oil. The olive oil and virgin cooking oil had results that were reasonably similar to those of the virgin asphalt binder, which means that the type of oil added can reduce the values of the carbonyl bond. However, the WCO, WEO, and VEO require higher amounts of oil to afford similar results to those of the virgin asphalt binder. The band at 1030cm^{-1} represents the sulfoxide bond S=O, and the sulfoxide bond had an inverse relation with the addition of the oil. In other words, a higher amount of oil decreased sulfoxide bond values. According to Tayh et al. [55], adding oil to aged asphalt binder leads to reduced sulfoxide bond values. No new chemical group was found with the addendum of the different oils in the aged asphalt. On the other hand, it was found that a reduction in the sulfoxide and carbonyl bonds is related to an increased ratio of the maltenes to the asphaltenes. As a result, the bio-binders and virgin binder have similar chemical groups, and it was found that there is no chemical reaction found between the different types of oils and aged asphalt binder, which agreed with previous research done by Poulikakos et al. [56].

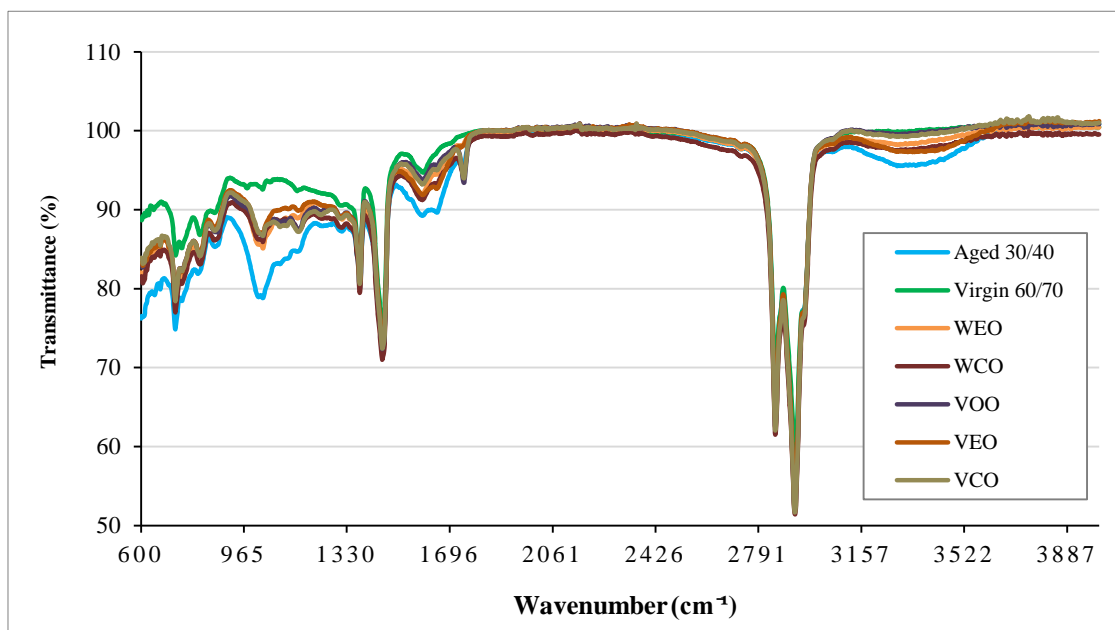


Figure 17. Chemical functional groups of different rejuvenators

4. Conclusions

The main conclusions are as follows:

- The penetration and softening point values are increase and decrease with an increase in the amount of oils respectively. The waste and virgin engine oils require a higher amount of oil, greater than 4%, to restore the properties of the 30/40 aged asphalt. For loss on heating, all the aged, virgin and rejuvenated asphalt binders are within the acceptable range.
- The physical characteristics of the aged asphalt were enhanced by adding 4% of any type of oils, and the viscosity values were slightly different due to the quality of the oil. In addition, all the rejuvenators except the

waste engine oil met the requirement of the ductility result, which is greater than or equal to 100 cm. Most of the asphalt binders have comparable results to the virgin asphalt binder, although the olive oil has a higher bleeding value, which may lead to low skid resistance. Additionally, all the tested samples are storage stable.

- Adding rejuvenators to a partially aged asphalt binder reduces the hardness of the asphalt binder (G^*), and slightly increased the δ° . The virgin olive oil had the most significant effect on the asphalt rheology which could lead to rutting issue. Meanwhile the addition of waste cooking oil in the aged asphalt enhanced the rutting resistance.
- The FTIR result for all the rejuvenators was found to be identical, with slight differences related to the quality of the oil. Consequently, similar functional groups were revealed for all the asphalt binders, with no new chemical reactions.
- Overall, there is no doubt that all rejuvenators in this study could restore the aged asphalt, but the addition of rejuvenators should be at optimum dosage. The high rejuvenator dosage could lead to a rutting issue as the low rutting result for the virgin olive oil. Meanwhile, the low rejuvenator dosage could fail to restore the physical properties as the ductility result for waste engine oil.

5. Declarations

5.1. Author Contributions

M.B.; Conceptualization, Writing-original draft, Methodology, Investigation, Formal analysis. Y.B.A.; Supervision, Resources. N.A.H.; Supervision, Funding acquisition. Z.A.; Writing - review & editing. K.A.; Writing - review & editing. K.R.; Data curation, Software. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

The data presented in this study are available in article.

5.3. Funding and Acknowledgements

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5.4. Conflicts of Interest

The authors declare no conflict of interest.

6. References

- [1] Foroutan Mirhosseini, Ali, Seyed Amid Tahami, Inge Hoff, Samer Dessouky, and Chun-Hsing Ho. "Performance Evaluation of Asphalt Mixtures Containing High-RAP Binder Content and Bio-Oil Rejuvenator." *Construction and Building Materials* 227 (December 2019): 116465. doi:10.1016/j.conbuildmat.2019.07.191.
- [2] Dinis-Almeida, Marisa, João Castro-Gomes, Cesare Sangiorgi, Salah E. Zoorob, and Márcia Lopes Afonso. "Performance of Warm Mix Recycled Asphalt Containing up to 100% RAP." *Construction and Building Materials* 112 (June 2016): 1–6. doi:10.1016/j.conbuildmat.2016.02.108.
- [3] Hussain, Arshad, and Qiu Yanjun. "Effect of Reclaimed Asphalt Pavement on the Properties of Asphalt Binders." *Procedia Engineering* 54 (2013): 840–850. doi:10.1016/j.proeng.2013.03.077.
- [4] Saride, Sireesh, Deepti Avirneni, and Sarath Chandra Prasad Javvadi. "Utilization of Reclaimed Asphalt Pavements in Indian Low-Volume Roads." *Journal of Materials in Civil Engineering* 28, no. 2 (February 2016): 04015107. doi:10.1061/(asce)mt.1943-5533.0001374.
- [5] Al-Saffar, Zaid Hazim, Haryati Yaacob, Mohd Khairul Idham Mohd Satar, and Ramadhansyah Putra Jaya. "The Tailored Traits of Reclaimed Asphalt Pavement Incorporating Maltene: Performance Analyses." *International Journal of Pavement Engineering* (September 23, 2020): 1–14. doi:10.1080/10298436.2020.1824294.
- [6] Li, Xinjun, Mihai O. Marasteanu, R. Christopher Williams, and Timothy R. Clyne. "Effect of Reclaimed Asphalt Pavement (Proportion and Type) and Binder Grade on Asphalt Mixtures." *Transportation Research Record: Journal of the Transportation Research Board* 2051, no. 1 (January 2008): 90–97. doi:10.3141/2051-11.
- [7] Huang, Baoshan, Guoqiang Li, Dragan Vukosavljevic, Xiang Shu, and Brian K. Egan. "Laboratory Investigation of Mixing Hot-Mix Asphalt with Reclaimed Asphalt Pavement." *Transportation Research Record: Journal of the Transportation Research Board* 1929, no. 1 (January 2005): 37–45. doi:10.1177/0361198105192900105.

- [8] Xie, Zhaoxing, Hashim Rizvi, Caitlin Purdy, Ayman Ali, and Yusuf Mehta. "Effect of Rejuvenator Types and Mixing Procedures on Volumetric Properties of Asphalt Mixtures with 50% RAP." *Construction and Building Materials* 218 (September 2019): 457–464. doi:10.1016/j.conbuildmat.2019.05.093.
- [9] Milad, Abdalrhman, Aizat Mohd Taib, Abobaker G. F Ahmeda, Mohmed Solla, and Nur Izzi Md Yusoff. "A Review of the Use of Reclaimed Asphalt Pavement for Road Paving Applications." *Jurnal Teknologi* 82, no. 3 (April 6, 2020). doi:10.11113/jt.v82.14320.
- [10] Cao, Xinxin, Hao Wang, Xuejuan Cao, Wei Sun, Hongzhou Zhu, and Boming Tang. "Investigation of Rheological and Chemical Properties Asphalt Binder Rejuvenated with Waste Vegetable Oil." *Construction and Building Materials* 180 (August 2018): 455–463. doi:10.1016/j.conbuildmat.2018.06.001.
- [11] Eriskin, Ekinhan, Sebnem Karahancer, Serdal Terzi, and Mehmet Saltan. "Waste Frying Oil Modified Bitumen Usage for Sustainable Hot Mix Asphalt Pavement." *Archives of Civil and Mechanical Engineering* 17, no. 4 (September 2017): 863–870. doi:10.1016/j.acme.2017.03.006.
- [12] Asli, Hallizza, Esmail Ahmadinia, Majid Zargar, and Mohamed Rehan Karim. "Investigation on Physical Properties of Waste Cooking Oil – Rejuvenated Bitumen Binder." *Construction and Building Materials* 37 (December 2012): 398–405. doi:10.1016/j.conbuildmat.2012.07.042.
- [13] Bilema, M A, M Y Aman, N A Hassan, and N F A Abdullah. "Investigation on Rheology and Physical Properties of Asphalt Binder Blended with Waste Cooking Oil." *IOP Conference Series: Materials Science and Engineering* 527 (May 29, 2019): 012045. doi:10.1088/1757-899x/527/1/012045.
- [14] Cavalli, M.C., M. Zaumanis, E. Mazza, M.N. Partl, and L.D. Poulikakos. "Effect of Ageing on the Mechanical and Chemical Properties of Binder from RAP Treated with Bio-Based Rejuvenators." *Composites Part B: Engineering* 141 (May 2018): 174–181. doi:10.1016/j.compositesb.2017.12.060.
- [15] Ahmad, Kabiru Abdullahi, Mohd Ezree Abdullah, Norhidayah Abdul Hassan, Nura Usman, Mohd Rosli Mohd Hassan, Munder A. M. Bilema, Saeed Modibbo Saeed, and Ahmad Batari. "Effect of Bio Based Rejuvenator on Mix Design, Energy Consumption and GHG Emission of High RAP Mixture." *IOP Conference Series: Earth and Environmental Science* 140, no. 1 (April 2018): 012086. doi:10.1088/1755-1315/140/1/012086.
- [16] Abdul Raman, Noor Azah, Mohd Rosli Hainin, Norhidayah Abdul Hassan, Farid Nasir Ani, M.Naqiuddin M.Warid, Mohd Khairul Idham, and Rosmawati Mamat. "Effect of Bio-Oil from Empty Fruit Bunch on Penetration Index of Asphalt Binder." *Jurnal Teknologi* 77, no. 23 (December 13, 2015). doi:10.11113/jt.v77.6680.
- [17] Guarin, Alvaro, Abdullah Khan, Ali Azhar Butt, Björn Birgisson, and Nicole Kringos. "An Extensive Laboratory Investigation of the Use of Bio-Oil Modified Bitumen in Road Construction." *Construction and Building Materials* 106 (March 2016): 133–139. doi:10.1016/j.conbuildmat.2015.12.009.
- [18] Al-Omari, Aslam A., Taisir S. Khedaywi, and Mohammad A. Khasawneh. "Laboratory Characterization of Asphalt Binders Modified with Waste Vegetable Oil Using SuperPave Specifications." *International Journal of Pavement Research and Technology* 11, no. 1 (January 2018): 68–76. doi:10.1016/j.ijprt.2017.09.004.
- [19] Chen, Meizhu, Binbin Leng, Shaopeng Wu, and Yang Sang. "Physical, Chemical and Rheological Properties of Waste Edible Vegetable Oil Rejuvenated Asphalt Binders." *Construction and Building Materials* 66 (September 2014): 286–298. doi:10.1016/j.conbuildmat.2014.05.033.
- [20] Dony, A., J. Colin, D. Bruneau, I. Drouadaine, and J. Navaro. "Reclaimed Asphalt Concretes with High Recycling Rates: Changes in Reclaimed Binder Properties According to Rejuvenating Agent." *Construction and Building Materials* 41 (April 2013): 175–181. doi:10.1016/j.conbuildmat.2012.11.031.
- [21] Bilema, Munder Abdullah Mohamed, Mohamad Yusri Aman, and Kabiru Abdullahi Ahmad. "Investigating the Rheological and Physical Properties for Unaged of Crumb Rubber-Modified Binders Containing Warm Mix Asphalt Additive." *Lecture Notes in Civil Engineering* (May 13, 2018): 1389–1400. doi:10.1007/978-981-10-8016-6_100.
- [22] Orešković, M., S. Bressi, G. Di Mino, and D. Lo Presti. "Influence of Bio-Based Additives on RAP Clustering and Asphalt Binder Rheology." *Bearing Capacity of Roads, Railways and Airfields* (July 20, 2017): 1301-1306. doi:10.1201/9781315100333-173.
- [23] Zaman, Shah, Jawad Hussain, Syed Bilal Ahmad Zaidi, Naeem Ejaz, and Hammad Hussain Awan. "Field Assessment of Non-Nuclear Methods Used for Hot Mix Asphalt Density Measurement." *Civil Engineering Journal* 5, no. 8 (August 25, 2019): 1820–1831. doi:10.28991/cej-2019-03091374.
- [24] Chen, Meizhu, Feipeng Xiao, Bradley Putman, Bingbing Leng, and Shaopeng Wu. "High Temperature Properties of Rejuvenating Recovered Binder with Rejuvenator, Waste Cooking and Cotton Seed Oils." *Construction and Building Materials* 59 (May 2014): 10–16. doi:10.1016/j.conbuildmat.2014.02.032.

- [25] Yang, Xu, Zhanping You, Qingli Dai, and Julian Mills-Beale. "Mechanical Performance of Asphalt Mixtures Modified by Bio-Oils Derived from Waste Wood Resources." *Construction and Building Materials* 51 (January 2014): 424–431. doi:10.1016/j.conbuildmat.2013.11.017.
- [26] Yang, Xu, Zhanping You, and Qingli Dai. "Performance Evaluation of Asphalt Binder Modified by Bio-oil Generated from Waste Wood Resources." *International Journal of Pavement Research & Technology* 6, no. 4 (2013): 431–439. doi:10.6135/ijprt.org.tw/2013.6(4).431.
- [27] Sun, Zhaojie, Junyan Yi, Yudong Huang, Decheng Feng, and Chaoyang Guo. "Properties of Asphalt Binder Modified by Bio-Oil Derived from Waste Cooking Oil." *Construction and Building Materials* 102 (January 2016): 496–504. doi:10.1016/j.conbuildmat.2015.10.173.
- [28] Zaumanis, Martins, Rajib B. Mallick, Lily Poulidakos, and Robert Frank. "Influence of Six Rejuvenators on the Performance Properties of Reclaimed Asphalt Pavement (RAP) Binder and 100% Recycled Asphalt Mixtures." *Construction and Building Materials* 71 (November 2014): 538–550. doi:10.1016/j.conbuildmat.2014.08.073.
- [29] Nordiana, M, W A Wan Nur Aifa, M R Hainin, M W Muhammad Naquiddin, A H Norhidayah, Y Haryati, A Juraidah, and P J Ramadhansyah. "Rutting Resistance of Untreated and Treated Waste Cooking Oil in Bitumen after Aging Condition." *IOP Conference Series: Earth and Environmental Science* 244 (March 7, 2019): 012041. doi:10.1088/1755-1315/244/1/012041.
- [30] ASTM Standard, 'ASTM D5. Standard Test Method for Penetration of Bituminous Materials', The American Society of the International Association for Testing and Materials, (2006).
- [31] ASTM Standard, ASTM D36. Standard Test Method for Softening Point of Bitumen (Ring-and-Ball Apparatus) ring and ball apparatus bitumen. The American Society of the International Association for Testing and Materials, (2016).
- [32] ASTM Standard, ASTM D113. Standard Test Method for Ductility of Bituminous Materials. The American Society of the International Association for Testing and Materials, (2012).
- [33] ASTM Standard, ASTM D4402. Standard Test Method for Viscosity Determination of Asphalt at Elevated Temperatures Using a Rotational Viscometer. The American Society of the International Association for Testing and Materials, (2012).
- [34] ASTM Standard, ASTM D5892. Standard Specification for Type IV Polymer-Modified Asphalt Cement for Use in Pavement Construction. The American Society of the International Association for Testing and Materials, (2012).
- [35] M. Zaumanis, R. B. Mallick, and R. Frank, 'Use of Rejuvenators for Production of Sustainable High Content Rap Hot Mix Asphalt', XXVIII International Baltic Road Conference, (2013).
- [36] AASHTO, AASHTO T-315. Standard Method of Test for Determining the Rheological Properties of Asphalt Binder Using a Dynamic Shear Rheometer (DSR). The American Association of State Highway and Transportation Officials, (2016).
- [37] Zhang, Dong, Meizhu Chen, Shaopeng Wu, Jingxiang Liu, and Serji Amirhanian. "Analysis of the Relationships between Waste Cooking Oil Qualities and Rejuvenated Asphalt Properties." *Materials* 10, no. 5 (May 6, 2017): 508. doi:10.3390/ma10050508.
- [38] Baghaee Moghaddam, Taher, and Hassan Baaj. "The Use of Rejuvenating Agents in Production of Recycled Hot Mix Asphalt: A Systematic Review." *Construction and Building Materials* 114 (July 2016): 805–816. doi:10.1016/j.conbuildmat.2016.04.015.
- [39] Hamzah, Meor Othman, and Zulkurnain Shahadan. "Effects of aging on the physical, rheological and chemical properties of virgin bitumen incorporating recovered reclaimed asphalt pavement binder." *Australian Journal of Basic and Applied Sciences* 5, no. 5 (2011): 1323–1331.
- [40] DeDene, Christopher D., and Zhanping You. "The Performance of Aged Asphalt Materials Rejuvenated with Waste Engine Oil." *International Journal of Pavement Research & Technology* 7, no. 2 (2014): 145–152. doi:10.6135/ijprt.org.tw/2014.7(2).145.
- [41] Zargar, Majid, Esmail Ahmadinia, Hallizza Asli, and Mohamed Rehan Karim. "Investigation of the Possibility of Using Waste Cooking Oil as a Rejuvenating Agent for Aged Bitumen." *Journal of Hazardous Materials* 233–234 (September 2012): 254–258. doi:10.1016/j.jhazmat.2012.06.021.
- [42] Dehouche, Nadjet, Mustapha Kaci, and Khadija Ait Mokhtar. "Influence of Thermo-Oxidative Aging on Chemical Composition and Physical Properties of Polymer Modified Bitumens." *Construction and Building Materials* 26, no. 1 (January 2012): 350–356. doi:10.1016/j.conbuildmat.2011.06.033.
- [43] Burke, Kezia, and S. A. Hesp. "Penetration testing of waste engine oil residue modified asphalt cements." In *Proceedings of the first conference of transportation research group of India (CTRG)*, (2011): 7–10.
- [44] Abdullahi Ahmad, Kabiru, Mohd Ezree Abdullah, Norhidayah Abdul Hassan, Nura Usman, and Kamarudin Ambak. "Investigating the Feasibility of Using *Jatropha Curcas* Oil (JCO) as Bio Based Rejuvenator in Reclaimed Asphalt Pavement (RAP)." Edited by M.J. Zainorizuan, L. Yee Yong, L. Alvin John Meng Siang, O. Mohamad Hanifi, R. Siti Nazahiyah, and A. Mohd Shalahuddin. *MATEC Web of Conferences* 103 (2017): 09013. doi:10.1051/mateconf/201710309013.

- [45] Xinxin, Cao, Cao Xuejuan, Tang Boming, Wang Yuanyuan, and Li Xiaolong. "Investigation on Possibility of Waste Vegetable Oil Rejuvenating Aged Asphalt." *Applied Sciences* 8, no. 5 (May 11, 2018): 765. doi:10.3390/app8050765.
- [46] Su, Jun-Feng, Jian Qiu, Erik Schlangen, and Ying-Yuan Wang. "Investigation the Possibility of a New Approach of Using Microcapsules Containing Waste Cooking Oil: In Situ Rejuvenation for Aged Bitumen." *Construction and Building Materials* 74 (January 2015): 83–92. doi:10.1016/j.conbuildmat.2014.10.018.
- [47] Rasman, Maisarah, Norhidayah Abdul Hassan, Mohd Rosli Hainin, Ramadhansyah Putra Jaya, Yaacob Haryati, Nurul Athma Mohd Shukry, Mohd Ezree Abdullah, and Nurul Hidayah Mohd Kamaruddin. "Engineering Properties of Bitumen Modified with Bio-Oil." Edited by Yaacob Haryati, Mohd Yunus Nor Zurairahetty, and Ibrahim Izni Syahrizal. *MATEC Web of Conferences* 250 (2018): 02003. doi:10.1051/mateconf/201825002003.
- [48] Al-Saffar, Zaid Hazim, Haryati Yaacob, Mohd Khairul Idham Mohd Satar, Mhmood Khleel Saleem, Ramadhansyah Putra Jaya, Choy Jau Lai, and Ekarizan Shaffie. "Evaluating the Chemical and Rheological Attributes of Aged Asphalt: Synergistic Effects of Maltene and Waste Engine Oil Rejuvenators." *Arabian Journal for Science and Engineering* 45, no. 10 (August 9, 2020): 8685–8697. doi:10.1007/s13369-020-04842-7.
- [49] Singh-Ackbarali, Dimple, Rean Maharaj, Nazim Mohamed, and Vitra Ramjattan-Harry. "Potential of Used Frying Oil in Paving Material: Solution to Environmental Pollution Problem." *Environmental Science and Pollution Research* 24, no. 13 (March 28, 2017): 12220–12226. doi:10.1007/s11356-017-8793-z.
- [50] Mills-Beale, Julian, Zhanping You, Elham Fini, Boubacar Zada, Chee Huei Lee, and Yoke Khin Yap. "Aging Influence on Rheology Properties of Petroleum-Based Asphalt Modified with Biobinder." *Journal of Materials in Civil Engineering* 26, no. 2 (February 2014): 358–366. doi:10.1061/(asce)mt.1943-5533.0000712.
- [51] Zhang, Ran, Hainian Wang, Zhanping You, Xin Jiang, and Xu Yang. "Optimization of Bio-Asphalt Using Bio-Oil and Distilled Water." *Journal of Cleaner Production* 165 (November 2017): 281–289. doi:10.1016/j.jclepro.2017.07.154.
- [52] Maharaj, Rean, Vitra Ramjattan-Harry, and Nazim Mohamed. "Rutting and Fatigue Cracking Resistance of Waste Cooking Oil Modified Trinidad Asphaltic Materials." *The Scientific World Journal* 2015 (2015): 1–7. doi:10.1155/2015/385013.
- [53] Cavalli, M.C., M. Zaumanis, E. Mazza, M.N. Partl, and L.D. Poulidakos. "Aging Effect on Rheology and Cracking Behaviour of Reclaimed Binder with Bio-Based Rejuvenators." *Journal of Cleaner Production* 189 (July 2018): 88–97. doi:10.1016/j.jclepro.2018.03.305.
- [54] Foroutan Mirhosseini, Ali, Amir Kavussi, Seyed Amid Tahami, and Samer Dessouky. "Characterizing Temperature Performance of Bio-Modified Binders Containing RAP Binder." *Journal of Materials in Civil Engineering* 30, no. 8 (August 2018): 04018176. doi:10.1061/(asce)mt.1943-5533.0002373.
- [55] Tayh, Sady Abd, R. Muniandy, S. Hassim, and F. M. Jakarni. "Chemical Analysis and Consistency Characterization of Domestic Waste Bio-Asphalts." *Lecture Notes in Civil Engineering* (May 13, 2018): 1441–1451. doi:10.1007/978-981-10-8016-6_104.
- [56] Poulidakos, Lily D., Salomé dos Santos, Moises Bueno, Simon Kuentzel, Martin Hugener, and Manfred N. Partl. "Influence of Short and Long Term Aging on Chemical, Microstructural and Macro-Mechanical Properties of Recycled Asphalt Mixtures." *Construction and Building Materials* 51 (January 2014): 414–423. doi:10.1016/j.conbuildmat.2013.11.004.