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Performance Evaluation of Asphalt Binder Modified by Bio-oil Generated from Waste Wood Resources

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Abstract: Bio-oils are thought to be potentials for petroleum asphalt binders used in asphalt pavement because of the renewability and environmental friendliness. The aim of this study is to investigate the performances of asphalt binders modified by bio-oils generated from waste wood resources. Three types of bio-oils generated from wood waste resources are used in this study: the original bio-oil (OB), de-watered bio-oil (DWB) and polymer modified bio-oil (PMB). OB, DWB and PMB were added into the base asphalt PG 58-28 at 5% and 10% by weight. The rotational viscometer (RV), dynamic shear rheometer (DSR), rolling thin film oven (RTFO), pressure aging vessel (PAV) and bending beam rheometer (BBR) were conducted to evaluate the rheological properties of bio-oil modified asphalt binders. The Superpave™ binder specification was used to evaluate the performances of bio-oil modified asphalt binders. The test results show that the addition of bio-oil can lower the mixing temperature of asphalt mixtures while improve the high temperature performance of asphalt binders. However, the medium and low temperature performances were sacrificed. Comparison among the three types of bio-oil modified asphalt binders showed that PMB modified asphalt binders had the highest stiffness, followed by the DWB and OB modified binders. The OB had the lowest effect on the base asphalt binder compared to other two types of bio-oils.

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Key words: *Asphalt performance; Bio-oil; High temperature performance; Mixing Temperature; Polymer modified.*

Introduction

With the limited inventory and more advanced refining technology of crude oil, asphalt industry is facing the short supply for long term running. Researchers have been making effort to reduce petroleum asphalt usage in an environmentally friendly manner. Recycling asphalt pavement (RAP) material is an effective way to reduce the usage of fresh asphalt. Some other approaches that can reduce the asphalt consumptions include using crumb rubber modified (CRM) asphalt [1], E-waste modified asphalt [2], waste engine oil (WEO) modified asphalt [3]. Using these materials can improve the asphalt binder properties while reduce the consumption of fresh asphalt. Another approach to reduce the use of petroleum asphalt is to find alternative materials that can partially or fully replace the petroleum asphalt. Similar as the bio-fuel in the energy area, bio-oil generated from biomass materials is a potential option. In fact, some researchers have been focusing on the generation and property characterization of bio-oils. It is found that a wide range of biomass materials can be the resources of bio-oil, such as yard waste [4], microalgae [5], leather waste [6], wood waste [7], animal waste [8, 9] and cornstover [10].

The generation of bio-oil is through a fast pyrolysis, in which biomass materials are fast heated to a high temperature (450-600℃) in the absence of air. During this process, three main components are generated, the organic vapor, pyrolysis gases and biochar. After the cooling and condense of the organic vapor, bio-oil is produced. The typical properties of bio-oils generated from wood resources [13] are shown in Table 1. Previous studies showed that bio-oils generated from this process have similar rheological properties as the petroleum asphalt binder [9, 11, 12].

Bio-oils used in this study were generated from waste wood resources through pyrolysis at about 500℃. Before the pyrolysis, the waste wood resources were processed with sizes of several millimeters. The schematic of the generation process for bio-oil from waste wood resources is illustrated in Fig. 1. Because of the water content in the waste wood resources, the original bio-oil contains about 20% water content by weight. Williams et al [14] has conducted research on the physicochemical behaviors during the preliminary pyrolysis and the chemical and physical properties of this type of bio-oils. In addition, Raouf and Williams [7] developed an approach to reduce the water content of the original bio-oils..

Many previous studies focused on the generation method and the basic chemical and physical properties of bio-oil modified asphalt binders. Fini et al [8] used pyrolysis approach to generate bio-oils from swine waste and found it can improve the low temperature performance of asphalt binders. Zofka and Yut [15] generated bio-oils from waste coffee grounds and found them can serve as a good solvent for the petroleum asphalt binders. Raouf and Williams

Table 1. Typical Properties of Bio-oils Generated from Wood Resources.

Physical Property	Value
Moisture Content (wt%)	15-30
Specific Gravity	1.2
Elemental Composition (C, H, O, N) (wt%)	(54-58, 5.5-7.0, 35-40, 0-0.2)
pH	2.5
Viscosity at 500℃ (cP)	40-100
Distillation residue (wt%)	Up to 50

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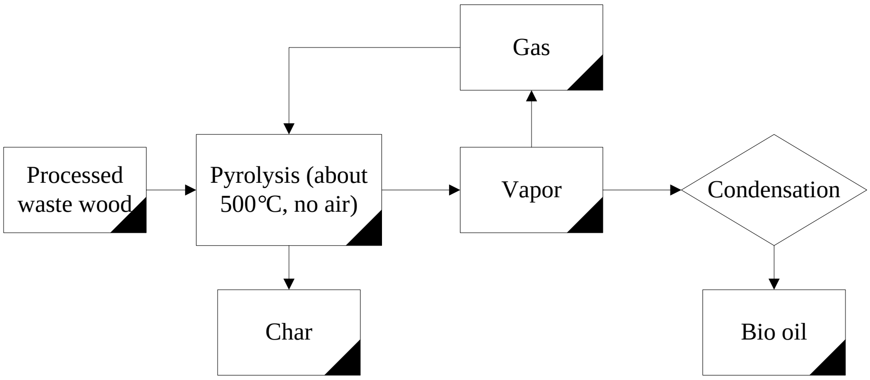


Fig. 1. The Schematic of the Pyrolysis Process for Waste Wood.

Table 2. Materials Used in this Study.

Binder Types	Descriptions
Control Binder	PG 58-28
5% OB	Binder Containing 5% Original Bio-oil and 95% PG 58-28 by Weight
10% OB	Binder Containing 10% Original Bio-oil and 90% PG 58-28 by Weight
5% DWB	Binder Containing 5% Dewatered Bio-oil and 95% PG 58-28 by Weight
10% DWB	Binder Containing 10% Dewatered Bio-oil and 90% PG 58-28 by Weight
5% PMB	Binder Containing 5% Polymer Modified Bio-oil and 95% PG 58-28 by Weight
10% PMB	Binder Containing 10% Polymer Modified Bio-oil and 90% PG 58-28 by Weight

[11] used bio-oils derived from cornstover to modify petroleum asphalt binders and found the theological properties of this types of bio-oil are similar and comparable as the petroleum asphalt binders.

In this research, three types of bio-oils were added into the traditional asphalt binder as extenders. These three types of bio-oil are: the original bio-oil (OB) from the pyrolysis process, which has about 20% of moisture content; the dewatered bio-oil (DWB) whose water content has been reduced to 5%-8% at the temperature 110℃ [14]; and the polymer modified bio-oil (PMB) in which 4% of polyethylene is added.

The objective of this study is to evaluate if bio-oil is a good extender for the petroleum asphalt binders. To achieve this goal, the effect of bio-oil on the rheological properties of asphalt binders is investigated because the theological properties of asphalt binders have great influence on the asphalt performance. A comprehensive property characterization is conducted through the laboratory test, including rotational viscometer (RV), dynamic shear rheometer (DSR), bending beam rheometer (BBR). The short- and long- term aging of asphalt binders are simulated by the rolling thin film oven (RTFO) and pressure aging vessel (PAV) test, respectively.

Material Preparation and Experimental Plan

Material Preparation

The materials used in this study include three types of bio-oils as the modifiers and the control asphalt binder PG 58-28. The three types of bio-oils are original bio-oil (OB), de-watered bio-oil (DWB) and polymer modified bio-oil (PMB). The bio-oils were added into the base asphalt PG-58 at 5% and 10% by weight. Thus, totally seven asphalt binders were investigated in this study, which are the control asphalt binder and the binders containing 5% and 10% OB, 5% and 105 DWB, and 5% and 10% PMB. The information of the materials used in this study is shown in Table 2. To prepare the bio-oil modified asphalt binders, the bio-oil and control asphalt binder were heated to 110 and 130℃, respectively. Then, the bio-oil and control asphalt binder were blended using a high shear mixer at 120℃ for 20 minutes with a speed of 5000 revolutions per minute.

Experimental Plan

The comprehensive rheological properties are investigated through Superpave™ asphalt binder test, including rotational viscometer (RV), dynamic shear rheometer (DSR), bending beam rheometer (BBR). The rolling thin film oven (RTFO) and pressure aging vessel (PAV) test are conducted to simulate the short- and long-term aging of asphalt binders during the construction and the service life, respectively. The RV test can determine the mixing and compaction temperatures of asphalt mixtures. The DSR test can obtain the dynamic shear modulus and the phase angle of asphalt binders. The DSR test for virgin and RTFO aged asphalt binders can characterize the high temperature performance of asphalt binders while the DSR test for PAV aged asphalt binders can indicate the fatigue performance. The BBR test for PAV aged asphalt binders is conducted for the low temperature performance of asphalt binder.

Rotational Viscometer (RV) Test

The RV test is to determine the viscosity at high temperatures and furthermore the workability of asphalt binders. The RV test for virgin asphalt binder can determine the mixing and compaction temperatures of asphalt mixtures during the construction. The RV test in this study follows the standard AASHTO T 316 [16]. The test temperatures were 90, 110, 130, 150 and 165℃.

Dynamic Shear Rheometer (DSR) Test

DSR test is to determine the visco-elastic property of asphalt binders in a broad range of temperatures and frequencies. The standard procedure of DSR test follows AASHTO T 315 [17]. In this study, the DSR test was conducted for virgin, RTFO- and PAV-aged asphalt binders. For virgin and RTFO aged asphalt binders, the test temperatures were 40, 46, 52, 58, 64 and 70℃ for the rutting performance characterization, and the frequencies were 0.1, 0.5, 1, 5, 10 and 25 Hz. For the PAV aged asphalt binders, the test temperatures were 13, 19, 25, 31 and 37℃ for the fatigue performance characterization, and the frequencies were 0.1, 0.5, 1, 5 and 10 Hz.

Rolling Thin Film Oven (RTFO) Test

The RTFO test is to simulate the short term aging of asphalt binders during the construction. The RTFO test in this study followed the standard test specified in AASHTO T 240 [18]. The asphalt binders are conditioned in the oven at 163℃ for 85 minutes.

Pressure Aging Vessel (PAV) test

The PAV test is to simulate the long term aging of asphalt binders during the service life. The PAV test in this study followed the standard test specified in AASHTO R 28 [19]. In the test, the RTFO aged asphalt binders are exposed in the aging condition of 2.1 MPa air pressure and 100℃ for 24 hours.

Bending Beam Rheometer (BBR) Test

The BBR test is to investigate the low temperature performance (thermal cracking) of asphalt binders. The test procedure follows AASHTO T 313 [20]. The materials used in the BBR test are the PAV aged asphalt binders. The Superpave^{TM} binder test recommends -18℃ as the test temperature for PG 58-28. To better understand the low temperature performance of asphalt binders, -12℃ was added as a second test temperature.

High and Low Critical Temperatures

The high and low critical temperatures are the highest and lowest temperatures the asphalt binder can work at. They are determined by the DSR and BBR test, respectively. According to the Superpave^{TM} specification, the $|G^*|/\sin\delta$ at 1.59 Hz (10rad/s) should be higher than 2.2 kPa after RTFO aging, while the creep stiffness and m-value should be lower than 300 MPa and higher than 0.3, respectively. Thus, the high critical temperature is determined when the $|G^*|/\sin\delta$ at 1.59 Hz is equal to 2.2 kPa. The low critical temperature is determined when the creep stiffness (S) is and m-value just pass the requirement.

Results and Discussions

Rotational Viscometer (RV) Tests

Fig. 2 illustrates the rotational viscosities of control asphalt binder and bio-oil modified asphalt binders before and after the standard RTFO aging. Before the RTFO aging, the rotational viscosities of 5% and 10% OB modified asphalt binders were 13.3% and 7.7% lower than the control asphalt binder in average, respectively; the rotational viscosities of 5% and 10% DWB modified asphalt binders were 12.1% and 7.6% lower than the control asphalt binder in average, respectively; the rotational viscosities of 5% and 10% PMB modified asphalt binders were 8.4% and 12.4% lower than the control asphalt binder in average, respectively. After the RTFO aging, the rotational viscosities of 5% and 10% OB modified asphalt binders were averagely 1.2% and 8.5% higher than that of the control binder, respectively; the rotational viscosities of 5% and 10% DWB modified asphalt binders were averagely 2.9% and 14.9% higher than that of the control binder, respectively; the rotational viscosities of 5% and 10% PMB modified asphalt binders were averagely 3.6% and 4.7% lower than that of the control binder, respectively.

The test results for virgin asphalt binders indicate that the bio-oils are overall softer than the control asphalt binder before RTFO aging. As a result, when the bio-oils were blended into the control asphalt binder, the viscosities decreased. The OB, DWB and PMB modified asphalt binders had rotational viscosities 10.5%, 9.8% and 10.3% lower than the control asphalt binder, respectively. This means that the three types of bio-oils had close effect on the rotational viscosity. Since the rotational viscosity of the asphalt binders can determine the mixing and compaction temperatures of asphalt mixture, the addition of bio-oil is likely to reduce the mixing and compaction temperatures of asphalt binders.

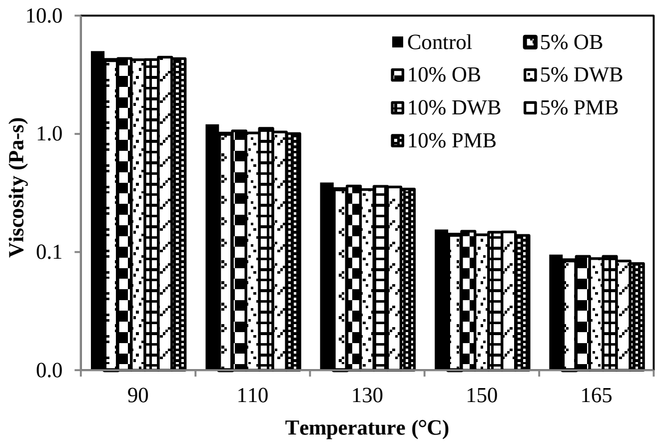
However, after the RTFO aging, both the OB and DWB modified asphalt binders showed higher viscosities than the control asphalt binder. Although the viscosities of PMB modified asphalt binders were still lower than that of the control asphalt binder, but the differences were much lower than those before the RTFO aging. Because the increase of the viscosity was resulted from the aging of asphalt binder, this means that the bio-oil modified asphalt binder aged faster than the control asphalt binder. To detailedly analyze the aging property of bio-oil modified asphalt binders, aging index is introduced. The aging index is determined as the ratio of the viscosities after and before the RTFO aging, as shown below [21]:

$$Aging\ index = \frac{viscosity\ of\ aged\ binders}{viscosity\ of\ vergin\ binders}$$

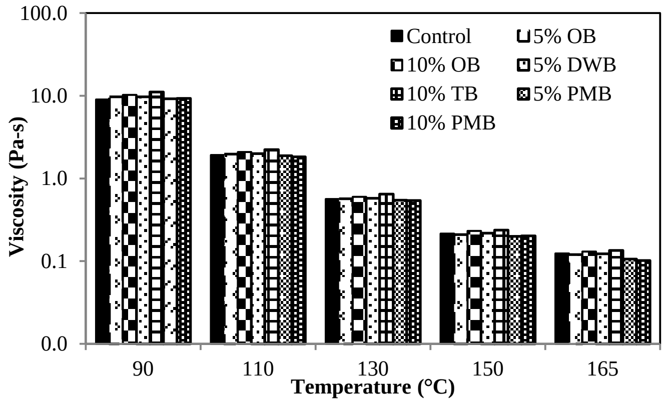
Based on the equation above, the aging indexes of the control and bio-oil modified asphalt binders were obtained and displayed in Fig. 3. The aging indexes of 5% and 10% OB, 5% and 10% DWB, and 5% and 10% PMB modified asphalt binders were 17.64%, 18.82%, 18.15%, 26.13%, 6.62% and 9.97% higher than the control asphalt binder, respectively. This shows that with the increase of bio-oil content, the aging index also increased. Comparison among the three types of bio-oils showed that the DWB modified asphalt binder had the highest aging index, followed by the OB and PMB modified asphalt binders. It is noticed that the PMB modified asphalt binders showed significantly lower aging index than the other two binders.

Dynamic Shear Rheometer (DSR) Test

$|G^*|/\sin\delta$ at high temperature (40-70℃) is an index for the rutting



(a) The rotational viscosities of bio-oil modified asphalt binders before RTFO aging



(b) The rotational viscosities of bio-oil modified asphalt binders before RTFO aging

Fig. 2. The Rotational Viscosities of Asphalt Binders Before and After RTFO Aging.

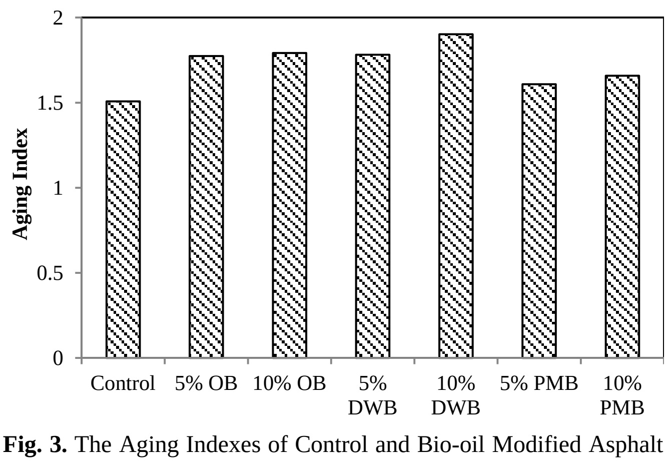


Fig. 3. The Aging Indexes of Control and Bio-oil Modified Asphalt Binders During RTFO Aging.

performance of asphalt binders [21]. Superpave^{TM} binder specification recommends minimum values of |G*|/sinδ for virgin and RTFO aged asphalt binders. In this study, the master curve for |G*|/sinδ at different temperatures and frequencies were generated using the principle of time-temperature superposition. The data at different temperatures were shifted with respect to time to plot a single curve. The |G*|/sinδ master curve is modeled using a sigmoidal function as below [22]:

$$\log\left(\frac{|G^*|}{sin\delta}\right) = \delta' + \frac{\alpha}{1 + \frac{1}{\exp^{\beta+\gamma(\log f_R)}}}$$

where: |G*|/sinδ is the dynamic shear modulus; δ is the phase angle of the asphalt binder; δ' and α are the fitting parameters for the data set; β and γ are parameters describing the shape of the sigmoidal function; f_R is the reduced frequency at reference temperature.

The shift factors for different temperatures are described as below:

$$\log a(T_i) = a(T_i)^2 + b\,T_i + c$$

where: $a(T_i)$ is the shift factor for temperatureT_i; a, b and c are coefficients of the function.

A typical master curve for |G*|/sinδ in this study is shown as Fig. 4, in which |G*|/sinδ at six temperatures and seven frequencies were plot in a single curve. The reference temperature was 58℃. The shift factors for each temperature were also shown.

DSR for Virgin and RTFO Aged Binders

Figs. 5 to 7 display the |G*|/sinδ master curves for control and bio-oil modified asphalt binders before and after RTFO aging. The |G*|/sinδ of OB, DWB and PMB modified asphalt binders were 6.3%, 0.4% and 16.8% higher than that of the control asphalt binder in average, respectively. The higher |G*|/sinδ of the PMB modified asphalt binder is possibly resulted from the polymers added in the bio-oil, which makes the bio-oil slightly stiffer. It is also observed from the master curve that the bio-oil modified asphalt binders had obviously higher |G*|/sinδ than the control asphalt binder in low reduced frequency area (high temperature and low frequency). Since it is thought that the |G*|/sinδ has a correlation with the rutting performance of asphalt binders, and rutting more easily to occur at high temperature and low frequency condition, the higher |G*|/sinδ of bio-oil modified asphalt binders in the low reduced frequency area is beneficial to the rutting performance.

After the RTFO aging, it is found that the bio-oil modified asphalt binders had |G*|/sinδ significantly higher than the control asphalt binder. Moreover, with the increase of bio-oil content in the asphalt binder, the |G*|/sinδ after RTFO aging also increased. The average |G*|/sinδ of 5% and 10% OB modified asphalt binders were 41.7% and 49.5% higher than that of the control binder, respectively; the average |G*|/sinδ of 5% and 10% TB modified asphalt binders were 41.2% and 71.3% higher than that of the control binder, respectively; the |G*|/sinδ of 5% and 10% TB modified asphalt binders were 59.7% and 65.6% higher than that of the control binder in average, respectively. The higher |G*|/sinδ of bio-oil modified asphalt binders is mainly from the fast aging of bio-oil and the enhancement of polymer.

It is also observed that the slope of the master curves of bio-oil modified asphalt binders were slightly lower than that of the control asphalt binder. Since a higher slope indicates higher temperature sensitivity, the test results indicate that bio-oil modified binders are less temperature sensitive than the control asphalt binder.

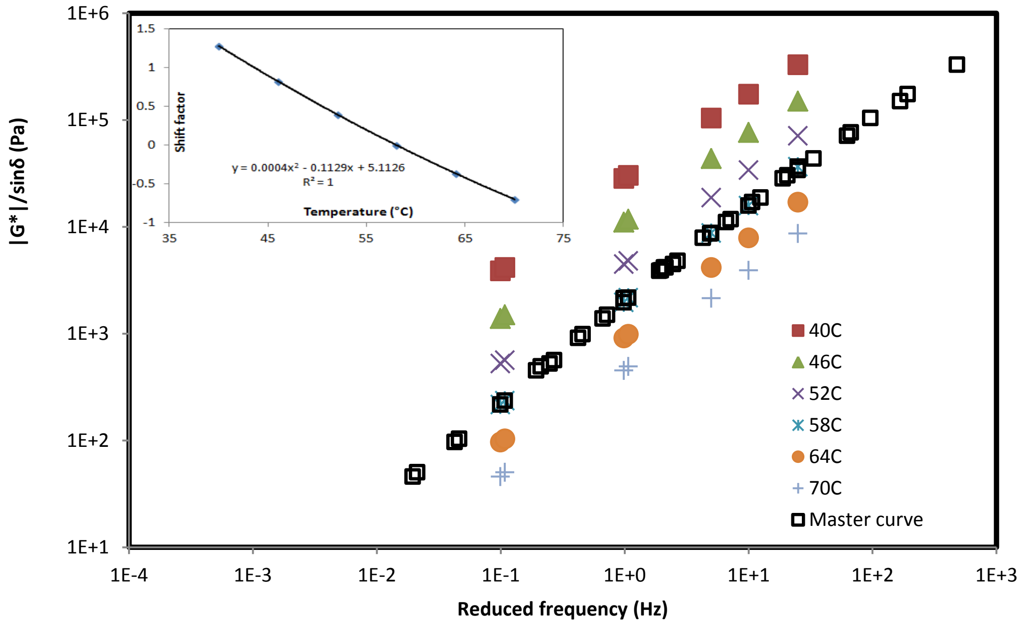


Fig. 4. Typical Master Curve and the Shift Factors for |G*|/sinδ.

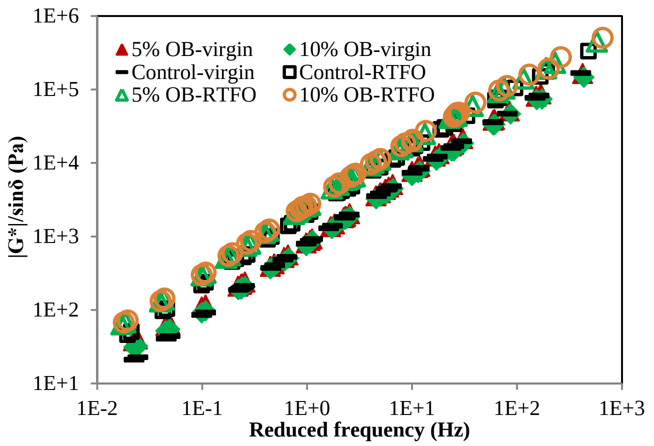


Fig. 5. |G*|/sinδ Master Curve Plot for Control Asphalt Binder, 5% and 10% OB Modified Asphalt Binders Before and After RTFO Aging.

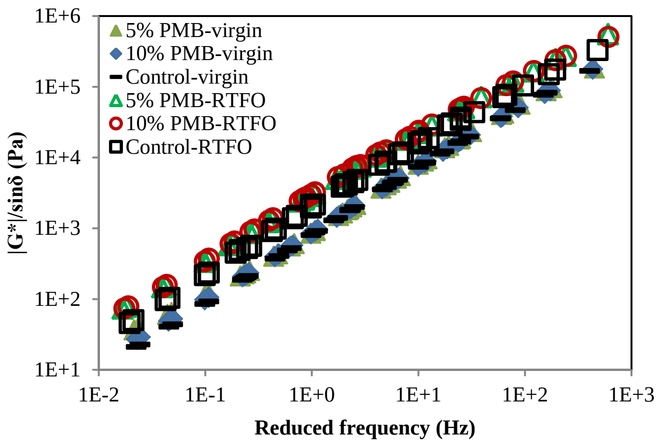


Fig. 7. | G*| Master Curve Plot for Control Asphalt Binder, 5% and 10% PMB Modified Asphalt Binders Before and After RTFO Aging.

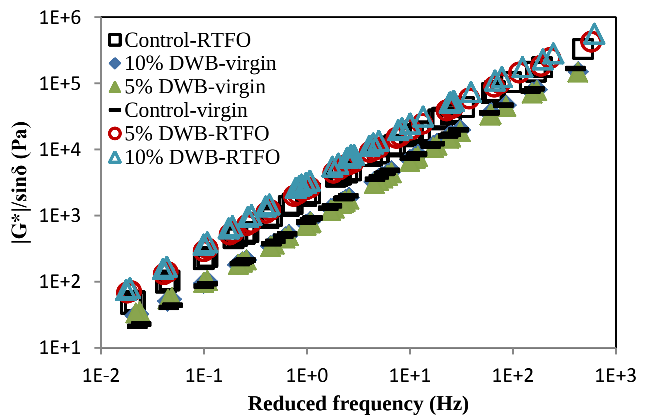


Fig. 6. | G*| Master Curve Plot for Control Asphalt Binder, 5% and 10% DWB Modified Asphalt Binders Before and After RTFO Aging.

When an asphalt pavement is open to traffic, the asphalt mixture has experienced short term aging. This means that it is more reasonable to evaluate the high temperature performance of asphalt binder based on the properties after short term (RTFO) aging. Superpave^{TM} specification recommends that a higher |G*|/sinδ at high temperature is desirable for the rutting resistance. Fig. 8 and Fig. 9 illustrate the G*/sinδ values of the RTFO aged asphalt binders at the three highest test temperatures. The frequencies were 0.1 and 10Hz, respectively. It is found that with the increase of bio-oil content, the G*/sinδ increased. This means that with the increase of bio-oil content, the high temperature performance of asphalt binders are improved. Comparison among the three types of bio-oils showed that the PMB modified asphalt binders had the highest G*/sinδ, followed by DWB and OB modified asphalt binders. The reason for the high G*/sinδ of PMB modified binders is that the polymer inside the bio-oil increased the asphalt stiffness. But this high

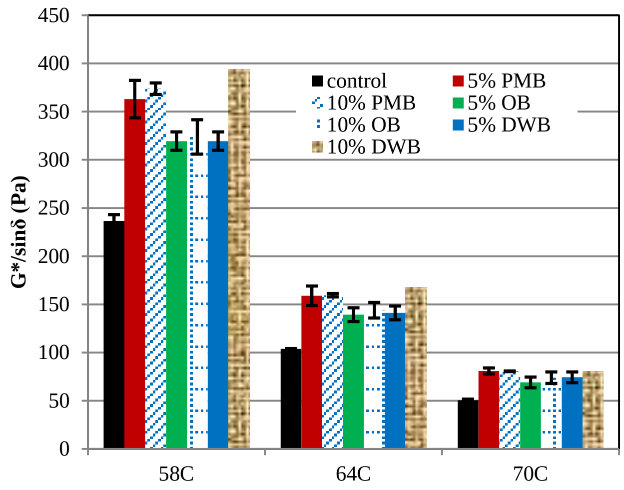


Fig. 8. G*/sinδ of RTFO Aged Binders at 0.1 Hz.

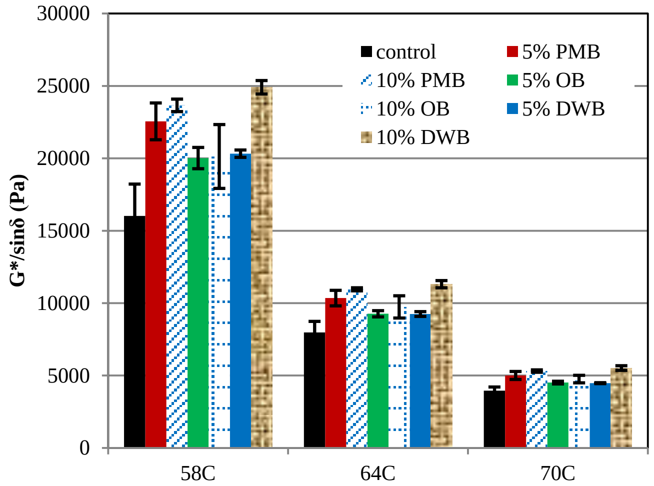


Fig. 9. G*/sinδ of RTFO Aged Binders at 10 Hz.

temperature performance improvement was limited due to the low content of the polymer in the asphalt blending. The reason for the lower G*/sinδ of OB modified asphalt binders compared to DWB modified binders is possibly that the moisture in the bio-oil prevented the fast aging of bio-oil during RTFO test.

Superpave^{TM} specification recommends minimum G*/sinδ value as 2.2 kPa for RTFO aged binders at the high critical temperature. Based on this, the high critical temperatures of the control asphalt binder and bio-oil modified asphalt binders were obtained based on the DSR test results, as shown in Fig. 10. It is observed that the high critical temperatures of all of the asphalt binders were higher than 58℃, which is the minimum high critical temperature according to Superpave^{TM} specification. In addition, with the increase of the bio-oil content, the high critical temperature also increased. The critical temperature of 5% and 10% OB, 5% and 10% DWB, and 5% and 10% PMB modified asphalt binders were 1.32, 1.48, 1.21, 2.69, 1.95 and 2.32℃ higher than that of the control asphalt binder, respectively. Comparison among the three types of bio-oils showed that the PMB modified asphalt binders had the highest critical temperature in average, followed by the DWB and OB modified asphalt binders. This is consistent with above results in the DSR test.

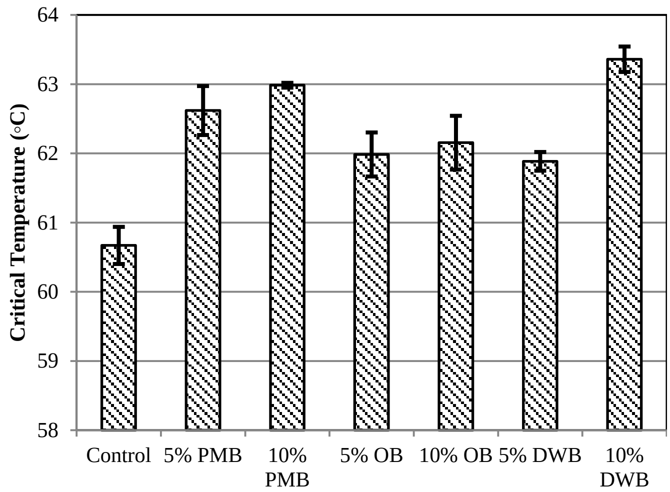


Fig. 10. High Critical Temperatures for RTFO Aged Asphalt Binders.

DSR for PAV Aged Binders

The DSR test for PAV aged asphalt binders was conducted to characterize the visco-elastic property and the fatigue resistance of asphalt binders at medium temperatures (13-37˚C**)**. It is thought that the fatigue performance of asphalt binders is related with the |G*|sinδ [22], so the master curve were constructed for the |G*|sinδ of asphalt binders in this study. Figs. 11 to 13 display the |G*|sinδ master curves control asphalt binder and three types of bio-oil modified asphalt binders after PAV aging. The reference temperature was 25˚C. It is observed that with the increase of bio-oil percent in the asphalt binders, the |G*|sinδ showed a significant increase. The |G*|sinδ of 5% and 10% OB modified asphalt binders were 164.2% and 253.3% higher than that of the control binder, respectively; The |G*|sinδ of 5% and 10% DWB modified asphalt binders were 140.6% and 195.8% higher than that of the control binder, respectively; The |G*|sinδ of 5% and 10% PMB modified asphalt binders were 164.1% and 240.7% higher than that of the control binder, respectively. Compared with the |G*|sinδ increase after the RTFO aging, it is found that the bio-oil modified asphalt binders ages also faster than the control asphalt binder during the standard PAV aging. Nevertheless, according to the Superpave^{TM} specification that |G*|sinδ <5000 kPa at 19˚C and 10 rad/s, all of the bio-oil modified asphalt binders can meet this requirement.

Bending Beam Rheometer (BBR) Test

The low temperature performances of asphalt binders are evaluated through the bending beam rheometer (BBR) test. Superpave^{TM} specification recommends a test temperature of -18℃ for PG 58-28. In this study, -12℃ was also selected for the test to obtain more information of asphalt binder properties at low temperatures. Table 3 and Table 4 show the creep stiffness and m-value at 60s for control asphalt binder and the three types of bio-oil modified asphalt binders at -12℃ and -18℃. Based on the test result, it is found that all of the bio-oil modified asphalt binders can meet the requirement for the creep stiffness, but most of the bio-oil modified asphalt

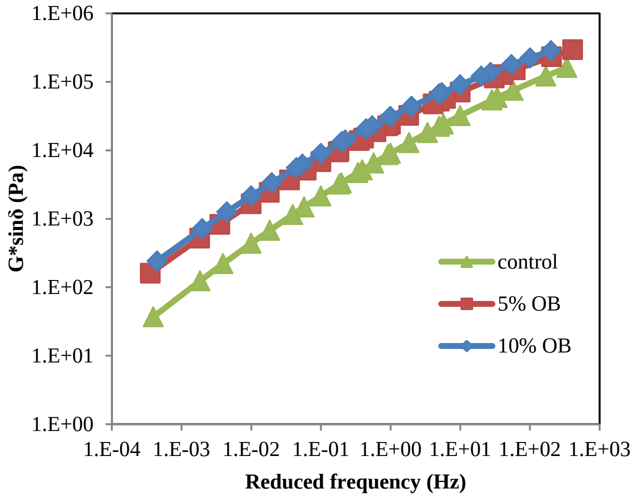


Fig. 11. |G*|/sinδ Master Curve Plot for Control Asphalt Binder and OB Modified Asphalt Binders.

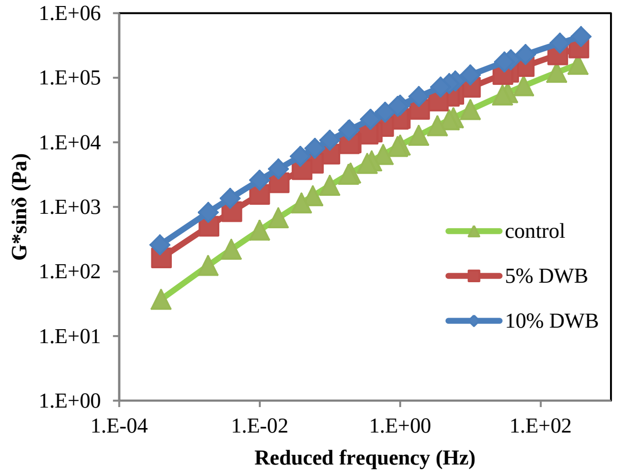


Fig. 12. |G*| Master Curve Plot for Control Asphalt Binder and DWB Modified Asphalt Binders.

binders failed the m-value results. The creep stiffness of 5% and 10% UTB modified binders were 32.3% and 47.7% higher than that of the control binder at -18℃. The m-values of 5% and 10% UTB modified asphalt binders were 0.19 and 0.60 at -18℃. The creep stiffness of 5% and 10% UTB modified binders were 36.6% and 42.0% higher than that of the control binder at -18℃. The m-values of 5% and 10% UTB modified asphalt binders were 0.56 and 0.66 lower than that of the control binder at -18℃. The creep stiffness of 5% and 10% PMB modified binders were 45.5% and 56.3% higher

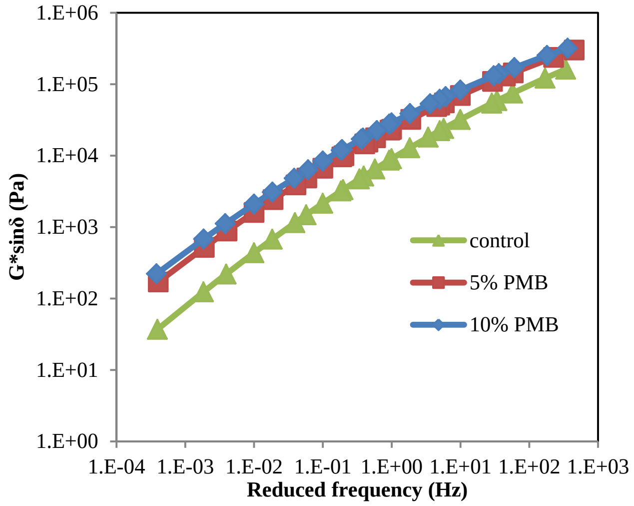


Fig. 13. |G*| Master Curve Plot for Control Asphalt Binder and PMB Modified Asphalt Binders.

than that of the control binder at -18℃. The m-value of 5% and 10% PMB modified asphalt binders were 0.53 and 0.72 lower than that of the control binder at -18℃. It is thought that lower creep stiffness and higher m-value are desirable for the low temperature performance. Thus, the addition of bio-oil would have negative effect on the low temperature performance of asphalt binders. Comparison among the three types of bio-oils showed that the OB modified asphalt binders had the lowest stiffness and highest m-value compared to the DWB and PMB modified asphalt binders. This indicates that the OB can perform better than the DWB and PMB at low temperature conditions.

To directly evaluate the effect of bio-oils on the asphalt low temperature performance, the critical low temperatures for each asphalt binder were obtained based on the BBR test results. The critical temperature was determined as the temperature where the creep stiffness and the m-value just pass the specification value. For most of the bio-oil modified asphalt binders, because the stiffness can meet the requirement, the critical low temperatures were determined by the m-values.

Fig. 14 shows the critical low temperatures of control and the bio-oil modified asphalt binders. Among all of the asphalt binders, only the control binder and 5% OB had the critical temperature lower than -18℃, which indicates a sacrifice of low temperature performance. Compared to the control binder, the 5% and 10% UTB modification increased the critical temperature by 0.63 and 3.33℃ respectively; 5% and 10% TB modification increased the critical temperature 3.58 and 4.73℃ respectively; The 5% and 10% PMB

Table 3. Creep stiffness and m-value from BBR test at -18℃.

Asphalt Binder	Creep Stiffness at 60s (MPa)			M-value at 60s		
	Testing Value	Specification	Pass or Fail	Testing Value	Specification	Pass or Dail
Control	176	<300	Pass	0.347	>0.3	Pass
5% OB	233.0	<300	Pass	0.328	>0.3	Pass
10% OB	260	<300	Pass	0.287	>0.3	Fail
5% DWB	240.5	<300	Pass	0.291	>0.3	Fail
10% DWB	250	<300	Pass	0.281	>0.3	Fail
5% PMB	256	<300	Pass	0.294	>0.3	Fail
10% PMB	275	<300	Pass	0.275	>0.3	Fail

Table 4. Creep Stiffness and M-value from BBR Test at -12°C.

Asphalt Binder	Creep Stiffness at 60s (MPa)	M-value at 60s	Pass or Fail
Control	46.4	0.414	Pass
5% OB	97	0.332	Pass
10% OB	121	0.369	Pass
5% DWB	92.8	0.337	Pass
10% DWB	103	0.330	Pass
5% PMB	108.9	0.375	Pass
10% PMB	122	0.348	Pass

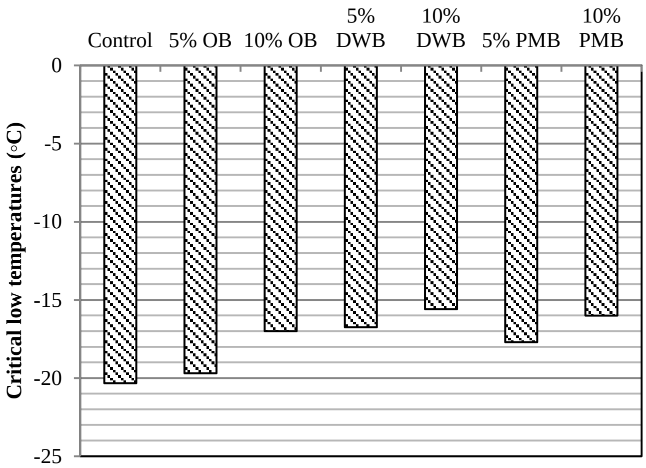


Fig. 14. |G*|/sinδ Master Curve Plot for Control Asphalt Binder and PMB Modified Asphalt.

modification increased the critical temperature by 2.62 and 4.32°C respectively. Comparison among the three types of bio-oils showed that the OB modified asphalt binders had the lowest critical temperature. This indicates that the OB as a modifier is better than DWB and PMB for the low temperature performance consideration.

Conclusions

In this study, the performance evaluation of asphalt binders modified by bio-oils derived from waste wood resources is conducted through laboratory binder tests. Based on the test result, some conclusions are made:

1) The addition of bio-oil can reduce the rotational viscosity of virgin asphalt binders, and hence can reduce the mixing temperature;
2) The addition of bio-oil can increase the |G*|/sinδ and improve the high temperature performance of asphalt binders;
3) Bio-oil has negative effect on the low temperature performance because of the higher stiffness and lower m-value.
4) Comparison among the three types of bio-oil modified asphalt binders showed that PMB modified asphalt binders had the highest stiffness, followed by the DWB and OB modified binders. The OB had the lowest effect on the base asphalt binder compared to other two types of bio-oils.

One of the main concerns of the application of bio-oil is the fast aging. To reduce the aging effect of bio-oil on the asphalt binder performance, one potential way is to reduce the short-term aging time, which will also require less construction time in the practice.

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