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100% RAP MIXES USING A SOYBEAN-DERIVED REJUVENATOR

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Abstract: Within the asphalt industry, interest in rejuvenators has grown more pronounced over the past several years. Rejuvenators are mainly used to restore aged asphalt to its original state. Thus, rejuvenators have made it possible to increase the amount of recycled asphalt pavement (RAP) in new flexible pavements. In this work, a proprietary soybean-derived rejuvenator is blended with a polymer modified PG 64-28 at a dosage of 0.75%. Complex shear modulus master curves were developed for the unaged, RTFO and PAV-aged control and modified binders, using frequency sweep DSR measurements. The results revealed that the soybean-derived rejuvenator improved low-temperature fatigue performance and lowered the complex shear modulus values at all test temperatures. The drop in the complex shear modulus was more prominent at high temperatures, accompanied by an increase in phase angles, which resulted in a decrease in rutting potential of the modified binder. The DSR results of the aging binders provided evidence of the continued performance of the soybean-derived rejuvenator even with long-term aging. The control and soybean-modified PG64-28 binders were then used to prepare dynamic modulus samples containing 100% RAP mixtures. The resulting rejuvenator dosage in the overall mixture was 0.12% of the total binder content. Dynamic modulus master curves were constructed for both the control and soybean-modified mixtures. The modified 100% RAP mixtures showed a slight reduction in dynamic modulus at high temperatures with no appreciable effect on the low temperature side, compared to the control 100% RAP mixtures.

1 Introduction

Recently there has been a rising interest in incorporating recycled asphalt pavement (RAP) into new mixtures. Increasing binder costs, declining supply of good virgin aggregates, and the desire to preserve the environment are among the main reasons behind this growing interest in RAP. The rich binder content in RAP can provide an economically feasible alternative to the more expensive virgin binder. Despite the compelling desire to use high RAP percentages, a recent survey revealed that the percentage of RAP usage has merely increased from 15% to 20% between the years 2009 to 2014 (Hansen and Copeland 2015). Transportation agencies and industry professionals are wary about using higher proportions of RAP in asphalt mixtures largely due to the effect the deteriorated aged binder might have on the overall mix performance. Aged RAP binder often exhibits excessively high stiffness and low creep values, making it prone to low temperature thermal cracking(Yu et al. 2014). Asphalt mixtures with high RAP percentages tend to be very difficult to field compact leading to their unexpected premature failure (Copeland 2011).

Asphalt mixtures with RAP usually make use of a variety of techniques, to mitigate the effect of the aged RAP binder. These techniques include adding a softer virgin binder, increasing the asphalt content, and utilizing warm-mix technology to minimize the short-term aging effect and lower asphalt absorption(Im, Karki, and Zhou 2016). None of these techniques however is sufficient to accommodate higher RAP content. The effect of adding a softer virgin binder on high RAP content mixtures was found insignificant (West et al. 2013). The introduction of rejuvenators have provided the impetus for researchers to further investigate mixtures with increasing RAP contents. Rejuvenators are additives to the RAP binder which partially or fully restore its aged properties to its original state, thereby paving the way to accommodating more RAP into asphalt mixtures. Pavement construction processes such as hot-in-place pavement recycling (HIR) are already using rejuvenators to mix heated and milled old pavements with virgin aggregates and virgin binder.

As a result of aging, asphalt loses a portion of its maltenes fraction at the expense of an increase in the more viscous asphaltenes fraction. Asphaltenes tend to have higher molecular weight and form a colloidal suspension in the lower molecular weight maltenes. An increase in the asphaltenes fraction have been shown to cause a noticeable increase in the penetration index (Firoozifar, Foroutan, and Foroutan 2011). Rejuvenators contain a high proportion of maltenes which rebalance the asphalt chemical composition. Various studies have investigated the change in stiffness and low temperature properties of the aged binder upon rejuvenation (Elseifi, Mohammad, and Cooper III 2011, Zaumanis, Mallick, and Frank 2015). It was found that rejuvenators reduce the aged binder stiffness as well as improving the low temperature cracking resistance. Blending charts are typically used to select an optimum dosage of the rejuvenator (Shen, Amirkhanian, and Aune-Miller 2007). Aged RAP binders tend to have higher viscosity which acts as a barrier to proper mixing and compaction. Using rejuvenators, the viscosity of the RAP binder can be reduced thus allowing for better mixing and blending with the virgin binder. Rejuvenators can be made of different materials including distilled tall oil, petroleum based aromatic extract, and organic oil (Zaumanis et al. 2014).

Durability of rejuvenators is an important criteria in assessing their performance. The long-term aging performance of five different rejuvenators showed great variability between them in terms of durability (Ali and Mohammadafzali 2015). Rejuvenators involving a petroleum neutral distillate, an oil-based bio-rejuvenator and a polyol ester pine showed accelerated aging. The effectiveness of a rejuvenator is also binder dependent. An aromatic extract rejuvenator worked effectively with an ABD type of binder from the Material Reference Library, PG58-10, but not as effectively with an AAD binder, PG58-28 (Yu et al. 2014).

This work comprises part of an ongoing project at Iowa State University to investigate the use of soybean oil and its derivatives as potential binder rejuvenators.

2 Materials and Methods

A polymer-modified binder PG64-28 was used in this study as the control binder. The rejuvenator used is a soybean-derived additive, which was added to the control binder at 0.75% by weight to produce a rejuvenated binder. Blending was done using a Silverson shear mill at 140^{o}C ±2^{o}C and 3000 rpm for one hour. Both the rejuvenated and control binders were aged using a Rolling Thin Film Oven (RTFO), and Pressure Aging Vessel (PAV) in preparation for further testing. RTFO aging was conducted according to ASTM D2872 at 163^{o}C for 85 minutes. Following RTFO aging, the binders were PAV aged as per ASTM D6521 for 20 hours at a temperature of 100^{o}C and a 2.1 MPa pressure.

The performance grading (PG) of the rejuvenated binder, as well as the control binder, was determined using Dynamic Shear Rheometer (DSR) and Bending Beam Rheometer (BBR) testing. To further assess the rheological properties of the binders, a frequency sweep test was run on the RTFO and PAV aged samples. A 25-mm diameter and 1-mm gap geometry was used for the RTFO samples while an 8-mm diameter and 2-mm gap geometry was used for the PAV aged samples. The frequency sweep extended over a range of frequencies from 0.6 to 100 rad/s. The frequency sweep was done at different temperatures starting from 34 ^{o}C to 70 ^{o}C with 6 ^{o}C increments, for RTFO aged samples, and from 4 ^{o}C to 34 ^{o}C with 6 ^{o}C increments, for PAV aged samples. The frequency sweep results were used to generate master curves at a reference temperature of 22 ^{o}C in case of PAV aged samples, and 58 ^{o}C for RTFO aged samples.

The viscosity of the control and rejuvenated binders was determined at different temperatures using a rotational viscometer according to ASTM D4402.

The recycled asphalt pavement (RAP) was milled from pavements in the State of Iowa, USA. The RAP was processed by crushing it to a nominal maximum aggregate size of 12.5 mm, and drying it in an oven at

110°C overnight. The binder content of the RAP was determined, using an ignition oven, to be 5.1%. The PG of the RAP binder was determined following extraction and recovery from RAP. Extraction was done using toluene as per ASTM D2172, Method A. Recovery of the extracted RAP binder was then performed using a rotary evaporator according to ASTM D5404. Nitrogen was continuously blown through the system to prevent further oxidation of the RAP binder during the recovery process. The RAP binder was considered RTFO aged such that the high temperature grading was determined directly from the extracted binder. Low temperature grading was determined using the PAV aged extracted binder.

Dynamic modulus specimens, using both the control and rejuvenated binders, were made from 100% recycled asphalt pavements (RAP). The control or rejuvenated binder was added to the RAP mix to bring the total binder content to 6%. Mixing was done at 160°C and compaction at 140°C. Specimens were compacted using a Superpave gyratory compactor (SCG) with a target air void of 7% ±0.5%. Three specimens were made using each of the control and rejuvenated binder, making a total of six specimens. Dynamic modulus testing was conducted according to AASHTO T342, at 4°C, 21°C and 37°C. The results of the dynamic modulus testing were used to construct master curves using the sigmoidal function.

3 Results and Discussion

3.1 Binder testing

The continuous critical high temperatures of all binders, as defined by AASHTO T315, were determined as shown in Table 1. The critical high temperatures criteria for the unaged and RTFO-aged binders correspond to $G^*/\sin\delta > 1.0$ kPa and $G^*/\sin\delta > 2.2$ kPa respectively. Additionally, the critical low temperatures using PAV aged binder were determined, for all binders, according to AASHTO T313. The continuous critical low temperature is determined, from the BBR test, using the flexural creep stiffness value (S) and the relaxation constant (m) at 60s of loading. The critical low temperature, listed in Table 1, is defined by $S < 300$ MPa and $m > 0.300$.

Table 1: Binder Properties

Binder	PG 64-28 Control	PG 64-28 Modified	RAP Binder
Unaged (High Temp.)	66.9	59.8	NA
RTFO (High Temp.)	66.7	60.5	108.6
PAV (Low Temp.)	-29.0	-30.2	-10.8
Performed Grade (PG)	64-28	58-28	106-10
Viscosity (Pa*s) at 135°C	0.7175	0.2975	1.885
Viscosity (Pa*s) at 150°C	0.385	0.1775	1.0775
Viscosity (Pa*s) at 165°C	0.2292	0.1275	0.38
Mass loss (%)	0.3	0.35	NA

The properties of the RAP determined were also determined, as shown in Table 1. The deteriorating effect of aging on the RAP binder is very obvious as evidenced by its PG and viscosity.

From the results in Table 1, it is evident that the modified binder showed a significant drop in the critical high temperature, compared to the control binder. This drop resulted in lowering the high temperature PG from 64 for the control binder to 58 for the modified binder. There was no significant change in the mass loss upon modification, which attests to the durability of the additive. With the addition of the soybean additive, there was a slight improvement in the continuous critical low temperature, from -29°C to -30.2°C, however with no effect on the low temperature PG.

There was a notable reduction in the viscosity of the modified binder at high temperatures. This high viscosity promotes better mixing with the RAP binder, even at low mixing temperatures. However, noting the low viscosity of the RAP binder, it is necessary to heat up the RAP binder to high mixing temperatures to get proper mixing with the virgin binder.

The rutting and fatigue resistance of a given binder is measured by the parameters G*/sinδ and G*sinδ respectively. The rutting parameter is determined, for the RTFO-aged samples, using DSR testing at a frequency of 10 rad/s and a shear strain of 1%, as shown in Figure 1. Similarly, the fatigue parameter, for the PAV-aged samples, was determined at a frequency of 10 rad/s and a shear strain of 1%, as shown in Figure 2. The soybean modified binder showed more rutting susceptibility compared to the control binder. This is in line with the drop in the critical high temperature of the binder and the increasing viscosity at high temperatures. The soybean modified binder, however, showed an increase in the fatigue resistance. The critical intermediate temperature defined as G*sinδ < 5000 KPa was shown to decrease upon modification denoting more resistance to fatigue. The continuous intermediate temperature dropped from 18.5ºC for the control binder to 15ºC for the soybean modified binder.

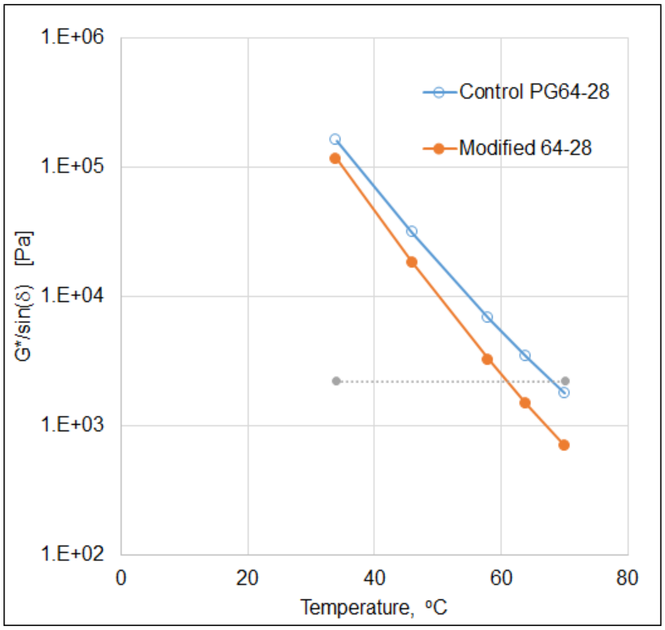

Figure 1: Variation of G*/sinδ parameter with temperature

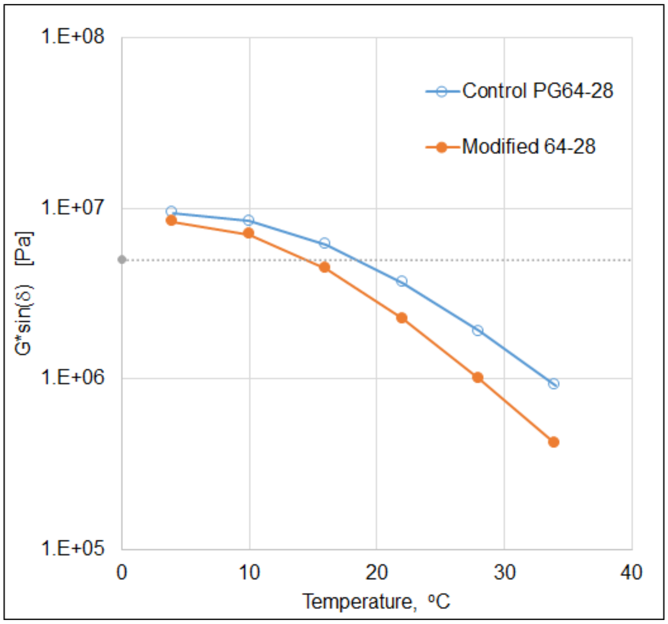

Figure 2: Variation of G*sinδ parameter with temperature

3.2 Binder master curves

The performance of binders can only be fully described using complex shear modulus master curves. Master curves provide an overall picture of the rheological performance of the binders at various temperatures and frequencies. The concept of time-temperature superposition is utilized to develop the master curves using the DSR frequency-temperature sweeps. The time-temperature superposition uses shift factors, to transform the modulus values at a given temperature to that of a reference temperature. The constructed master curve, at the specific reference temperature, plots the modulus values vs a reduced frequency or reduced time.

The master curves for the RTFO-aged and unaged binders were developed using a high temperature range from 34ºC to 70ºC. This range was selected to cover temperatures up to 6 ºC above the high temperature PG. The master curves for the PAV-aged binder were developed using a low temperature range from 4ºC to 34ºC. This temperature range was selected to cover intermediate and low temperatures. Testing at lower temperatures in the DSR was not possible as the accuracy of measurements decrease significantly which is inherent to DSR testing.

The master curves for the unaged and RTFO-aged binder, shown in Figures 3 and 4, were plotted at a reference temperature of 58ºC. The modified binder showed a consistent drop in the complex shear modulus at all frequencies. The drop in the complex shear modulus was more significant at lower frequencies, i.e. high temperatures.

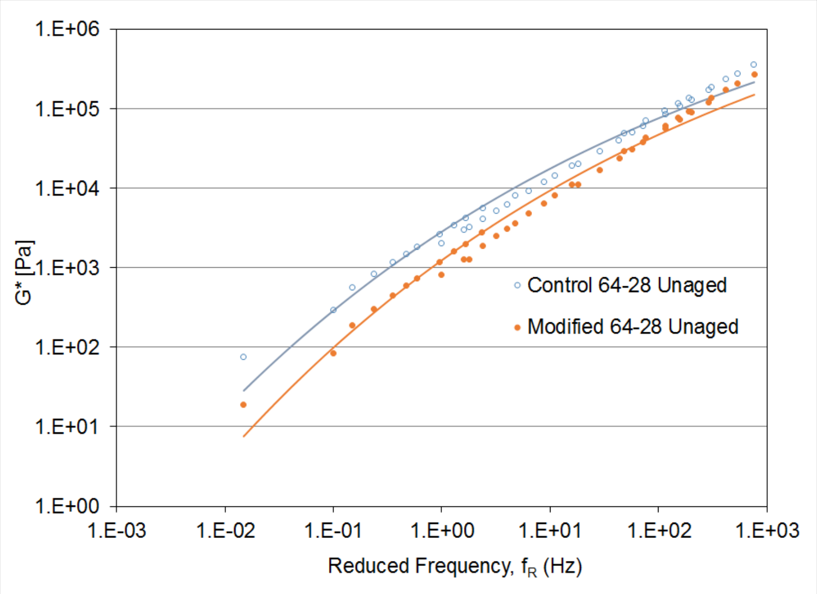

Figure 3: Master curves for Unaged binders

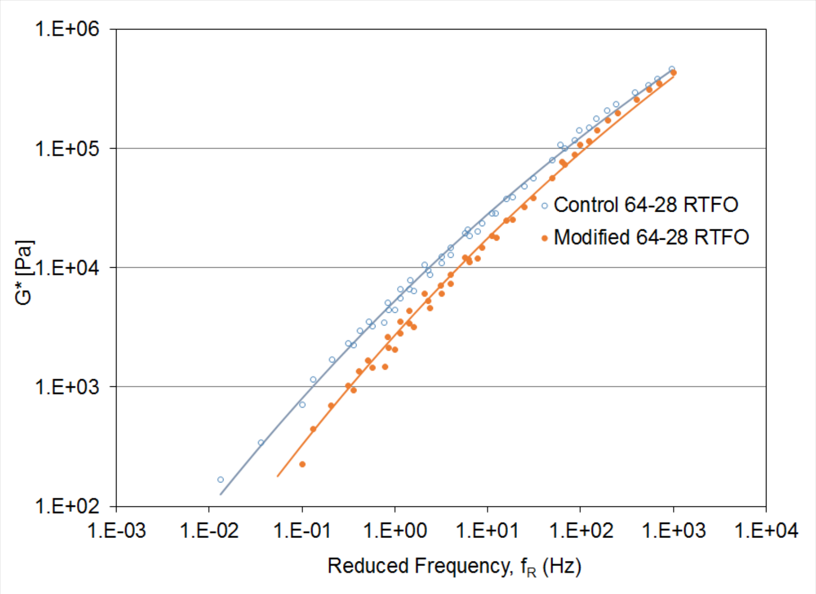

Figure 4: Master curves for RTFO-aged binders

This trend was also observed for the PAV-aged binder, plotted at a reference temperature of 22 ^{o}C, as shown in Figure 5. The extent of the drop in the complex shear modulus was comparable for the unaged, RTFO-aged and PAV-aged binder. These results indicate that the soybean-derived additive continued to impart the same effect on the control binder with aging. The sustained effect of the soybean-derived additive provides evidence to its durability. Hence, it can be concluded that the effect of the soybean-additive is not merely to induce temporary softening of the binder but rather a prolonged effect that continues under different aging conditions.

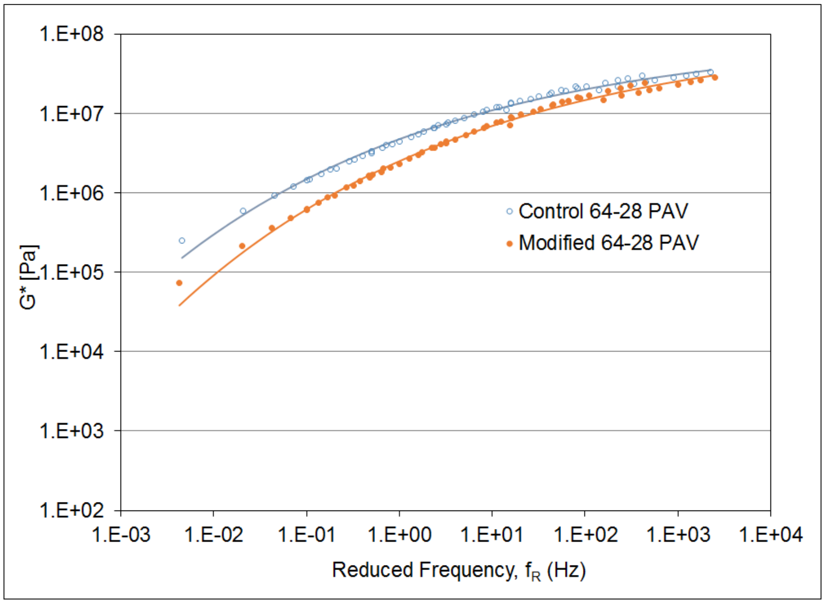

Figure 5: Master curves for PAV-aged binders

To study the impact of the soybean modification on the binder phase angles, master curves were plotted involving the variation of phase angle with reduced frequency. The same reference temperatures as above were used to construct the phase angle master curves, namely 58ºC for unaged and RTFO-aged binder and 22ºC for the PAV-aged binder. Figures 6-8 gives the master curves for the unaged, RTFO-aged and PAV-aged binders respectively. It is clear that there is a notable increase in the phase angle due to modification. This increase in phase angle denotes a more viscous behavior for the modified binder at all test temperatures and frequencies. Such increase in the phase angle was more pronounced at lower frequencies, i.e. higher temperatures as shown in Figures 6 and 7. The increase in the phase angles with modification, accompanied by the drop in shear modulus values, contributes to the lower rutting resistance exhibited by the modified binder.

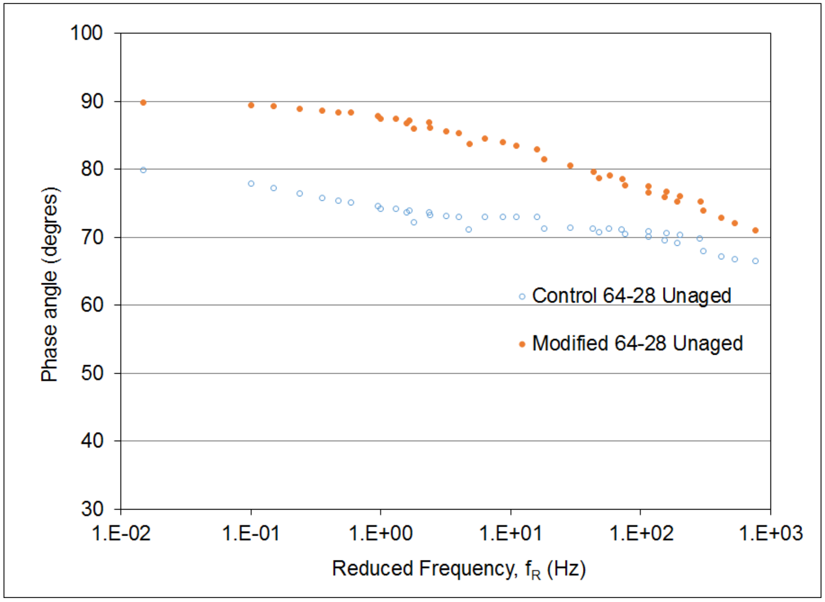

Figure 6: Phase angle master curves for Unaged binders

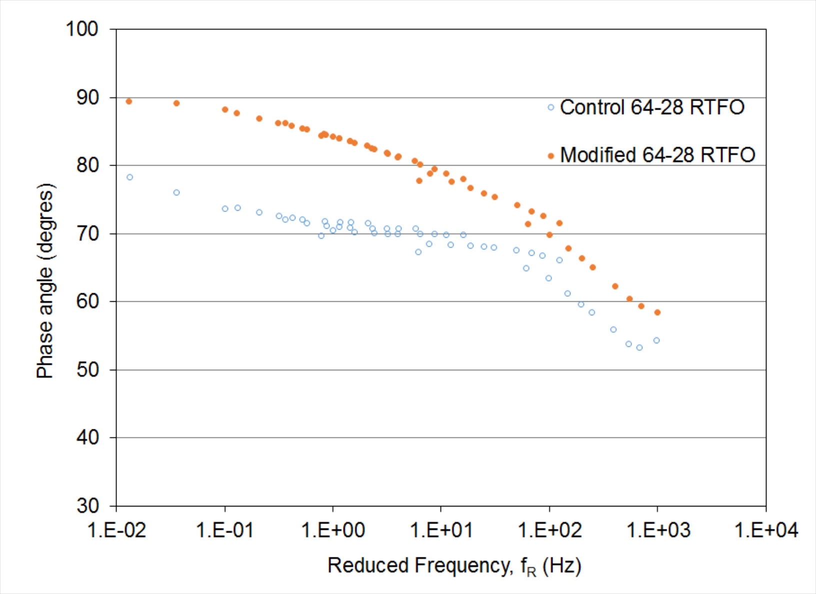

Figure 7: Phase angle master curves for RTFO-aged binders

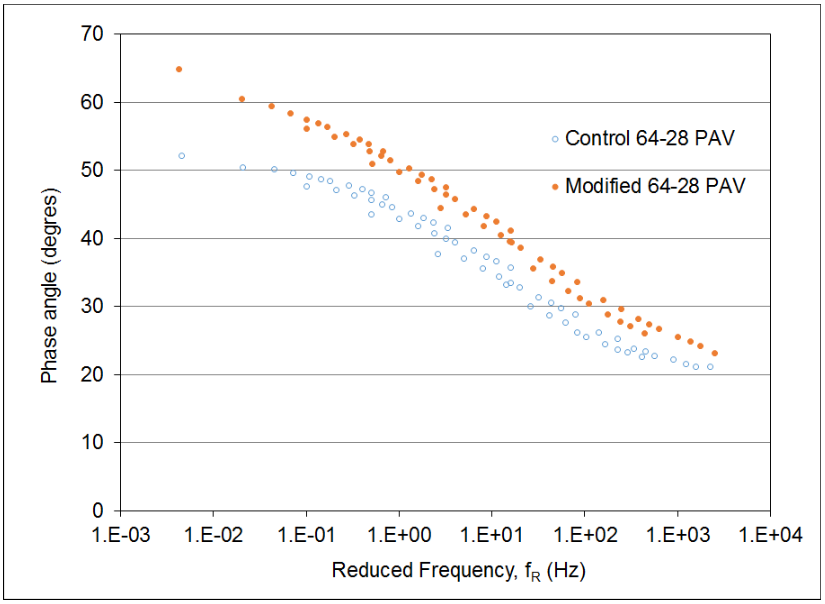

Figure 8: Phase angle master curves for PAV-aged binders

3.3 Dynamic modulus

Dynamic modulus testing provides a way to assess the stiffness of asphalt concrete mixtures under a wide range of temperatures and frequencies. The dynamic modulus test was introduced as a result of the work under NCHRP Project 9-19 (Witczak et al. 2002). Testing is done according to AASHTO T342. It is also a key parameter in AASHTOWare Pavement ME Design (AASHTO 2016).

A compressive haversine load is applied inducing axial deformation which was measured using three LVDTs placed at equal spacing around the specimen's circumference. The LVDTs were held in place using mounted brackets that were positioned on the specimens using glued buttons. The axial deformation was kept within the linear viscoelastic range of the material by controlling the micro-strain to be between 50-150 microstrain. The sigmoidal model, given by Equation 1, was used to develop the master curves.

$$[1]\ \log|E^*| = \delta + \frac{\alpha}{(1+e^{\beta+\gamma(\log(t_r))})}$$

where t_r is the reduced time of loading at the selected reference temperature, δ is the minimum value of E*, $\delta + \alpha$ is the maximum value of E*, and the parameters β and γ define the shape of the sigmoidal function.

The constructed master curves, for both the control and modified mixes, are shown in Figure 9. A reference temperature of 21ºC was used to present the master curves. It was noted that that the soybean-modified binder reduced the dynamic modulus of the mix at higher temperatures, however not significantly. The effect at low temperatures was hard to discern from the dynamic modulus results.

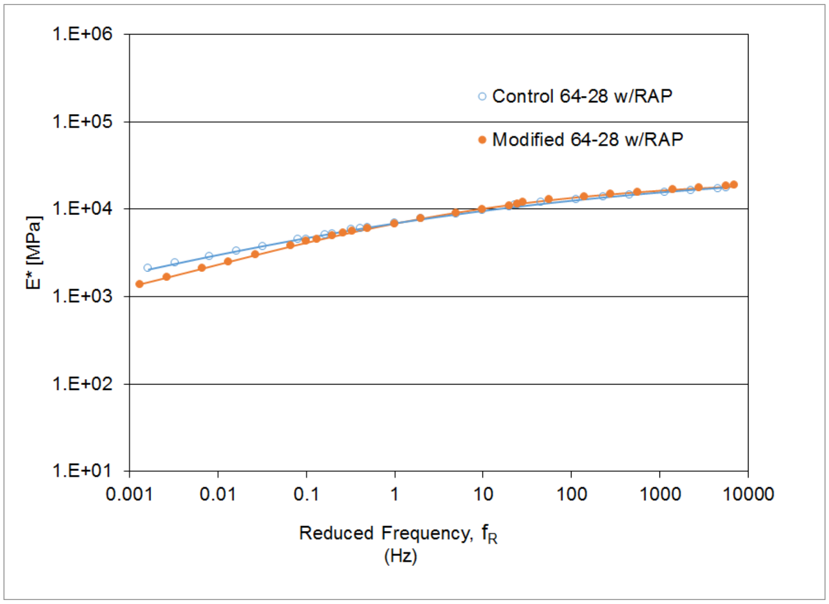

Figure 9: Dynamic modulus master curve for the control and modified mixtures

4 Summary and conclusion

This study explored the use of a soybean-derived additive on a polymer modified PG64-28 binder. A low dosage amounting to 0.75% by weight of binder was used. Dynamic Shear Rheometer (DSR) frequency sweep results indicated that the modified binder showed improved fatigue performance however at the expense of rutting resistance. Master curves for the modified binder, showed a consistent decrease in the complex shear modulus and consistent increase in the phase angle, at all test temperatures and frequencies, compared to the control binder. The effect was more pronounced at high temperatures. This finding was also verified by the continuous performance grading of the control and modified binders. The modified binder resulted in about 6ºC drop in the continuous high temperature PG and a slight drop of about 1.2ºC in the low temperature PG. The viscosity of the modified binder showed a significant reduction compared to the control binder at high temperatures, which should promote better mixing with RAP binder.

The study also attested to the durability of the soybean-derived rejuvenator, as revealed by the results of the PAV-aged and RTFO-aged binders. The performance of the soybean-derived rejuvenator was consistent for the unaged, RTFO-aged and PAV-aged binder, which indicates that the effect of the rejuvenator did not deteriorate with aging. The RTFO mass loss for both the control and modified binders was comparable. Hence, it can be concluded that the effect of the soybean modifier was sustained even after long-term aging.

Attempts to add the modified binder to a 100% RAP mix provided a slight reduction in the dynamic modulus at high temperatures, compared to mixes prepared with the control binder and 100% RAP. The effect at low temperatures was not significant. This is attributed to the low dosage of the soybean-derived modifier; 0.75% of the PG64-28, which amounts to approximately 0.12% of the total binder content including RAP binder. Another factor which might have contributed to the inappreciable difference between the control and modified mixtures is the extremely high stiffness of the aged RAP binder which would require higher dosages of the rejuvenator.

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