World Journal of Advanced Research and Reviews
eISSN: 2581-9615 CODEN (USA): WJARAI
Cross Ref DOI: 10.30574/wjarr
Journal homepage: https://wjarr.com/

(Research Article)

Characterization of asphalt binders extracted from field mixtures containing RAP and/or RAS

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World Journal of Advanced Research and Reviews, 2022, 13(01), 140–152

Publication history: Received on 21 November 2021; revised on 04 January 2022; accepted on 06 January 2022

Article DOI: https://doi.org/10.30574/wjarr.2022.13.1.0729

Abstract

The use of reclaimed asphalt pavement (RAP) and/or recycled asphalt shingles (RAS) in the asphalt mixtures is a common practice in the U.S.A. However, there is a controversy to date on how RAP/RAS interact with virgin asphalt binders (VABs) in asphalt mixtures. For mixtures containing RAP/RAS, the aged asphalt binders in RAP and air-blown asphalt binders in RAS alter the performances of the extracted asphalt binders (EABs). Thus, the rheological properties of EABs from these mixtures require more investigation. The focus of this paper was relating the high-temperature properties of EABs from field cores to the corresponding rolling thin film oven aged virgin asphalt binders (RTFO AVABs). Furthermore, a comparison of the effect of RAP and RAS on the high-temperature rheological properties of EABs was another objective. Different asphalt cores were collected from the field within two weeks after the pavement construction process in 2016. These cores represented eight asphalt mixtures with different asphalt binder replacement percentages by RAP, RAS, or both. The asphalt binders were extracted from these mixtures and considered as RTFO AVABs. The high-temperature rheological properties included the temperature sweep and frequency sweep testing and the multiple stress creep recovery testing. The EABs had higher stiffnesses and elasticates than the corresponding RTFO AVABs because of the aged binders in RAP/RAS. The binders in RAP interacted more readily with VABs than RAS binders.

Keywords: RAP; RAS; Extraction; Recovery; MSCR; Field Mixtures

1. Introduction

Recycling of asphalt pavements began with the 1973 oil embargo and the associated dramatic rise in crude oil prices, which reduced asphalt supply levels. During that time, agencies and contractors screened asphalt mixtures containing 80% reclaimed asphalt pavement (RAP). When the oil prices dropped, the proportion of RAP in asphalt mixtures decreased to 20%. This trend continued throughout the development of Superpave [1–3]. Between the 1980s and 1990s, recycled asphalt shingles (RAS) were used in asphaltic mixtures. In the mid to late 2000s, oil prices rose again, increasing demand for the use of RAP and RAS to reduce the overall cost [1, 2].

In 2002, the Missouri department of transportation (MoDOT) received its first request regarding using the post-consumer RAS in the asphaltic mixture in Saint Louis [2]. MoDOT implemented a demonstration project in December 2004 to assess the use of RAS in the pavement; this project was constructed in 2005 on Route 61/67 in St. Louis County, Missouri. MoDOT allowed using of RAS in asphalt mixtures through a provisional specification in 2006 followed by an official specification in 2008 [2]. The addition of RAS to asphalt mixtures as an alternative source of asphalt increased 80% from 2009 to 2012 [4].

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The use of RAP or RAS in asphalt mixtures reduces the demand for natural resources, reduces emissions during the production process, and decreases the quantities of materials dumped in landfills [5, 6]. Reclaimed asphalt pavement consists of aged asphalt binders and aggregates [7–9]. RAS contains oxidized air-blown asphalt binder percentage ranging from 19 to 36% by weight, granules (ceramic-coated or sand-sized natural aggregate) from 20 to 38% by weight, mineral filler/stabilizer (limestone, dolomite, or silica) from 8 to 40%, and fibers (fiberglass or cellulose backing) 2 to 20% by weight [4, 10]. Shingles shall be used in mixtures containing asphalt binder with a performance grade (PG) of 64–22. However, when the ratio of virgin effective binder to total binder is between 60 and 70% in the mixture, the grade of the virgin binder may be PG 58–28 or PG 52–28 instead of PG 64–22 [11]. Manufactured waste and tear-off are two types of shingles used in asphalt mixtures [12, 13].

The asphalt binder content in RAS was five times more than what was obtained from RAP [14]; however, the properties of both binders were different [15, 16]. The asphalt binder in RAS is oxidized by air blowing to reduce shingles in-service high-temperature deformations [4]. The asphalt in tear-off shingles is stiffer than the asphalt in manufactured waste shingles or the asphalt used in the traditional asphalt mix design. The PG of extracted asphalt binder (EAB) from RAS was PG 112+2 that was stiffer than that of the PG 64–22 grade, a common asphalt binder used in Illinois [17].

To optimize the benefits of using RAP/RAS in the asphalt mixtures, the interaction between RAP/RAS and virgin asphalt binders (VABs) in the asphalt mixtures needs further investigation. Thus, the effect of using RAP/RAS on the high-temperature rheological properties of EABs from field cores containing PAP/RAS was the main objective of this study. Comparing the effect of RAP and RAS on the high-temperature rheological properties of EABs was another objective.

2. Material and methods

2.1. Materials

Different field mixtures were collected as cores within two weeks after the pavement construction process in 2016, note Table 1. These cores represented 8 mixtures, which either contained RAP, RAS, or both. There was a mixture that contained neither RAP nor RAS (e.g., US 54-5). The asphalt binder replacement (ABR) percentages by RAP-RAS, additives' types, and additives' percentages are depicted in Table 1. The additive's percentage in the job mix formula was specified as a percentage of the net weight of VAB, note Table 1. Different VABs with different PGs were included in these mixtures.

Table 1 Details of field mixtures [8]

No.	Code	County	Route/Dir	Location	Virgin Asphalt PG	Total AC^a (%)	ABR by RAP–RAS (%)	NMAS^b (mm)	Additives
1	MO 13-1-F1	Henry	MO 13 NB	S. of Clinton	64–22H	5.7	17–0	9.5	Morelife T280 0.5%
2	MO 13-1-F2								
3	MO 13-1-F3								
4	US 54-6-F1	Miller	US 54 NB	N. of Osage Beach	58–28	5.1	31–0	12.5	Morelife T280 1%
5	US 54-6-F2								
6	US 54-6-F3								
7	US 54-1-F1	Miller	US 54 SB	N. of Osage Beach	58–28	5.2	0–33	12.5	IPC70 2.5%, PC2106 3.5%, Morelife T280 1.5%
8	US 54-1-F2								
9	US 54-1-F3								
10	US 63-1-F1	Randolph	US 63 SB		58–28	5.1	35–0	12.5	

11	US 63-1-F2			S. of Moberly					Evotherm 0.5%, Evoflex CA 1.75%
12	US 63-1-F3								
13	US 54-3-F1	Miller	US 54	Osage Beach	58–28	5.2	18–15	12.5	Morelife T280 1%
14	US 54-3-F2								
15	US 54-3-F3								
16	US 54-5-F1	Miller	US 54	Osage Beach	64–22H	5.4	0–0	12.5	Morelife T280 1%
17	US 54-5-F2								
18	US 54-4-F1	Miller	US 54	Osage Beach	64–22H	4.8	35–0	12.5	PC2106 3%, Morelife T280 1%
19	US 54-4-F2								
20	US 54-4-F3								
21	US 54-2-F1	Miller	US 54	Osage Beach	58–28	5.3	33–0	12.5	Morelife T280 1%
22	US 54-2-F2								
23	US 54-2-F3								

[a] AC: Asphalt Content and [b] NMAS: Nominal Maximum Aggregate Size; Morelife T280, AD-here HP Plus, LOF 65-00LS1, and IPC-70: anti-stripping agents; Evotherm and PC 2106: warm-mix additives; Evoflex CA: rejuvenator additive

2.2. Methods

2.2.1. Extraction and Recovery of Asphalt Binders from Asphalt Mixtures

Asphalt binders were extracted from the mixtures using the centrifuge extraction process according to ASTM D2172 / D2172M-17e1. The asphalt binders were recovered from the asphalt binder trichloroethylene (TCE) solution, after removing the mineral matter, using a rotavap following the ASTM D5404 / D5404M-12(2017).

2.2.2. Fourier Transform Infrared Spectroscopy Analysis

Fourier transform infrared spectroscopy (FTIR) was utilized to guarantee no TCE traces in the EABs. Attenuated total reflection-FTIR (ATR-FTIR) spectrometer was used by laying the samples on a diamond crystal. The experimental setup was run by applying 32 scans at a resolution of 4 and using wavenumbers ranging from 1000 to 400cm^{-1}.

2.2.3. Short-Term Aging for Virgin Asphalt Binders

Short-term aging was carried out according to ASTM D2872-19 for VABs. Testing was implemented using the rolling thin film oven (RTFO) device.

2.2.4. Rheological Properties of the Asphalt Binders

The VABs, RTFO aged virgin asphalt binders (AVABs), and EABs were analyzed on the dynamic shear rheometer (DSR), following ASTM D7175-15. Samples with a thickness of 1 mm and 25 mm in diameter were tested using temperature sweep and frequency sweep testing. The EABs were treated as RTFO AVABs because the field cores were gathered within two weeks after the construction process.

The temperature sweep testing reflected the changes in EABs' rutting parameters ($|G^*|/\sin\delta$) at different temperatures when compared to RTFO AVABs. Different temperatures were selected for the temperature sweep testing starting at 58 °C and ending with 94 °C with a 6 °C gap. The temperature sweep test was implemented twice for each asphalt binder using two different samples taken from the same can, and the average results were analyzed. For asphalt binders failing before 94 °C ($|G^*|/\sin\delta < 2.2$ kPa), testing was terminated. For the frequency sweep testing, four temperatures were selected—52, 58, 64, and 70 °C—through different frequencies (15.92 to 0.0159 Hz). The frequency sweep testing demonstrated the changes in EABs' $|G^*|/\sin\delta$ values at different temperatures and frequencies when compared to RTFO AVABs. The master curves for RTFO AVABs and EABs were derived from the frequency sweep testing and analyzed at 60 °C as a reference temperature.

The multiple stress creep recovery test (MSCR) test was implemented following ASTM D7405-20 to evaluate the resistance of RTFO AVABs and EABs to rutting. This was achieved by calculating the percentage of recovery ($\%R$) and non-recoverable creep compliance (J_{nr}) at 60 °C by applying ten creep cycles at two different levels of stresses (0.1 and 3.2 kPa). The $\%R$ and J_{nr} reflect the changes that occurred in EABs' elasticities and stiffnesses, respectively, when compared to RTFO AVABs. For each creep cycle, the loading time was 1 sec, and the unloading time (recovery) was 9 sec.

3. Results and discussion

3.1. FTIR Results

Fourier transform infrared spectroscopy test was conducted to confirm that the recovery process was done properly by comparing the TCE and asphalt binders' spectra before and after the extraction and recovery processes. Figure 1 and Figure 2 depict the FTIR spectra—wavenumbers less than 1000 cm^{-1}—for TCE, VABs, RTFO AVABs, and EABs. Two strong sharp peaks were observed for the TCE for wavenumbers 944 and 849 cm^{-1}; these peaks are related to C–Cl stretching in alkyl halide [18]. The EABs' spectra showed no TCE bands, which reflected no TCE traces in EABs.

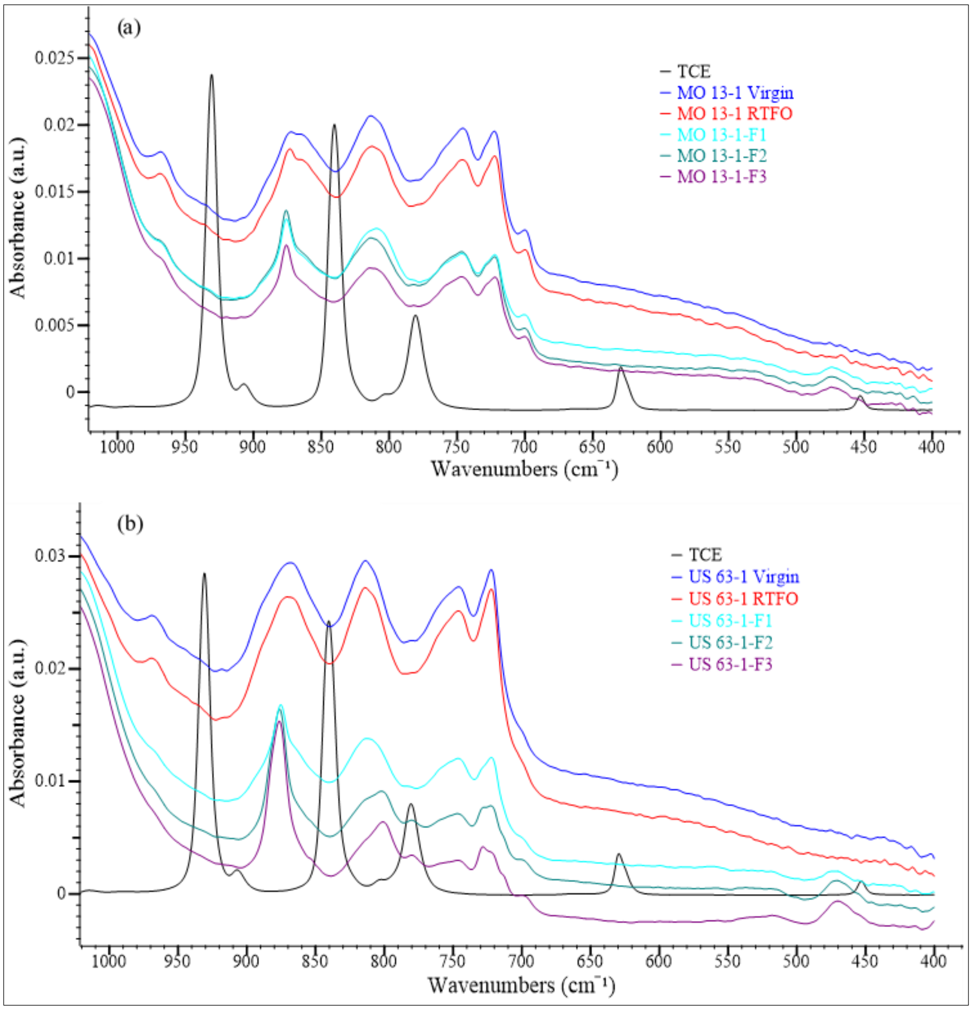

Figure 1 FTIR spectra for TCE, VABs, RTFO AVABs, and EABs from the (a) MO 13-1 and (b) US 63-1 mixtures

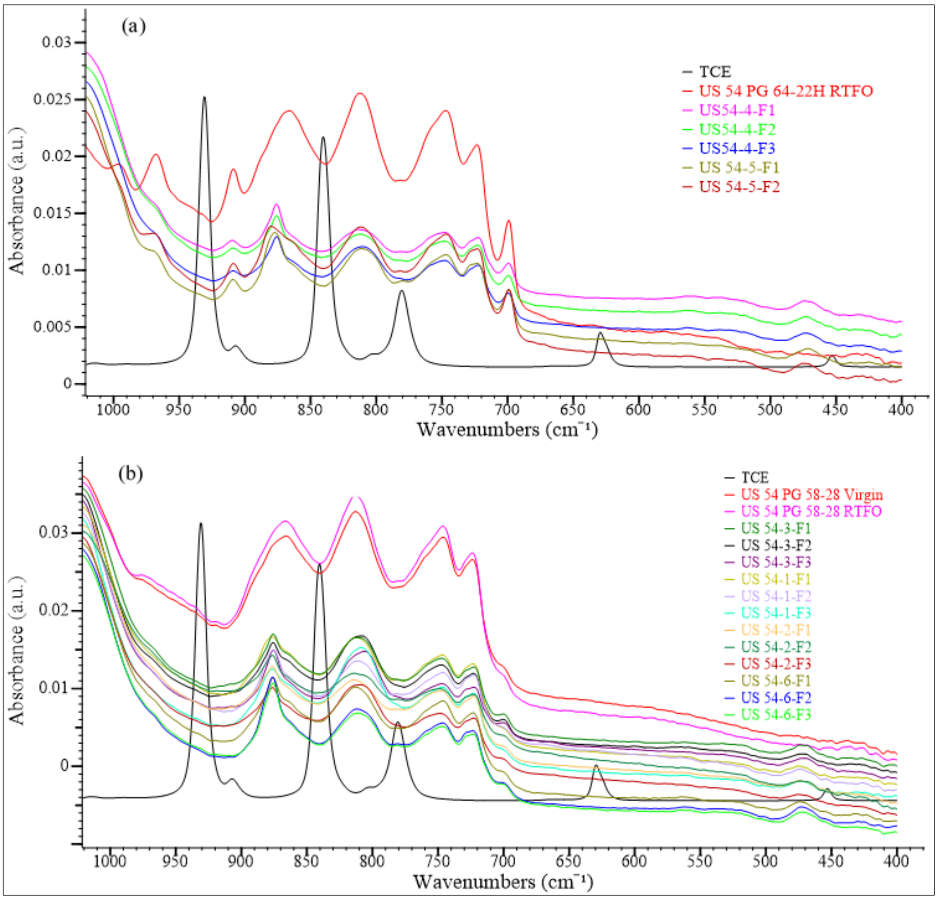

Figure 2 FTIR spectra for TCE, VABs, RTFO AVABs, and EABs from the (a) US 54 PG 64–22H and (b) US 54 PG 58–28 mixtures

3.2. Rheological Results

3.2.1. MSCR Test Results

Figure 3 illustrates the MSCR test results, measured at 60 °C reference temperature and 0.1 & 3.2 kPa stress levels, for RTFO AVAB and EABs from the MO 13-1 mixture containing 17% ABR percentage by RAP and PG 64–22H VAB. The EABs had higher resistance to rutting—higher *%R* and lower J_{nr} values—than RTFO AVAB because of the aged binders included in RAP.

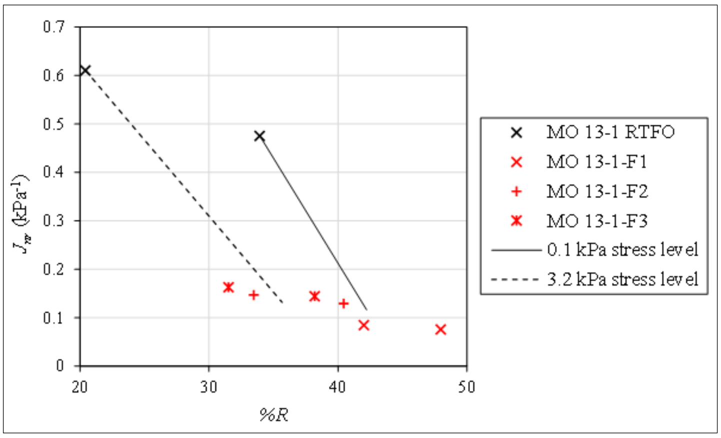

Figure 3 MSCR test results for RTFO AVAB and EABs from the MO 13-1 mixture

Figure 4 depicts the relation between the *%R* and J_{nr}, measured at 60 °C and 0.1 & 3.2 kPa stress levels, for RTFO AVAB and EABs from the US 54 mixtures containing different ABR percentages by RAP, RAS, both, and PG 58–28 VAB. The EABs presented higher *%R* and lower J_{nr} values than RTFO AVAB's values. This reflected the effect of the aged asphalt binders included in RAP/RAS on increasing EABs' stiffnesses and elasticities. The highest *%R* and the lowest J_{nr} values were recorded for EABs from a mixture containing 33% ABR percentage by RAP (US 54-2 EABs). The lowest *%R* and the highest J_{nr} values for EABs were recorded for EABs from a mixture with 31% ABR percentage by RAP (US 54-6 EABs). These findings reflected that increasing the percentage of the recycled materials altered the performance of EABs by increasing the EABs' stiffnesses and elasticities. Another reason was the high variability of the binders' properties included in RAP [19].

For EABs from mixtures containing either 33% ABR percentage by RAS (US 54-1 EABs) or 33% ABR percentage by RAP and RAS, US 54-3 EABs, the EABs had higher rutting resistances than EABs from a mixture containing 31% ABR percentage by RAP and lower resistances than EABs from a mixture with 33% ABR percentage by RAP. The EABs from a mixture containing 33% ABR percentage by RAP had higher stiffnesses and elasticities than EABs from a mixture with the same ABR percentage by RAS. However, the binders included in RAS were air-blown, which were stiffer than the asphalt binders in RAP. This interpreted that RAP binders interacted more readily with VABs than RAS binders, and there was no compatibility occurred between RAS and VABs.

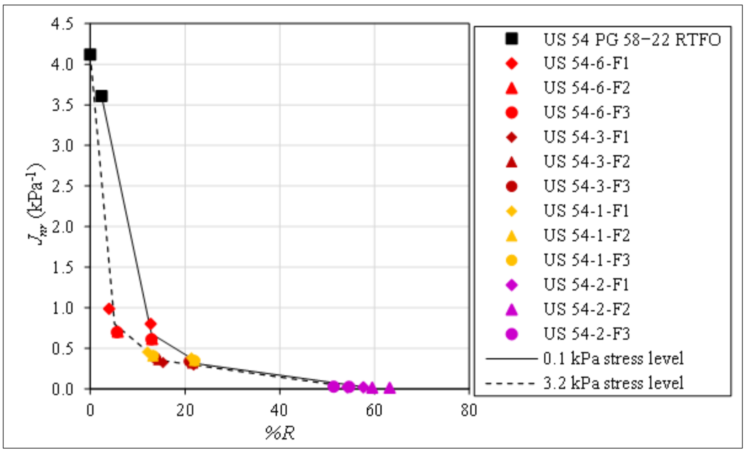

Figure 4 MSCR test results for RTFO AVAB and EABs from the US 54 PG 58–28 mixtures

The MSCR test results at 60 °C for RTFO AVAB and EABs from the US 54 mixtures containing PG 64–22H VAB are presented in Figure 5. The *%R* values increased for the US 54-5-F2 EABs and decreased for the US 54-5-F1 and US 54-4 EABs when compared to RTFO AVAB. For the J_{nr}, EABs introduced lower values than RTFO AVAB's values. The lowest J_{nr} values were recorded for EABs from a mixture containing 35% ABR percentage by RAP (US 54-4 EABs).

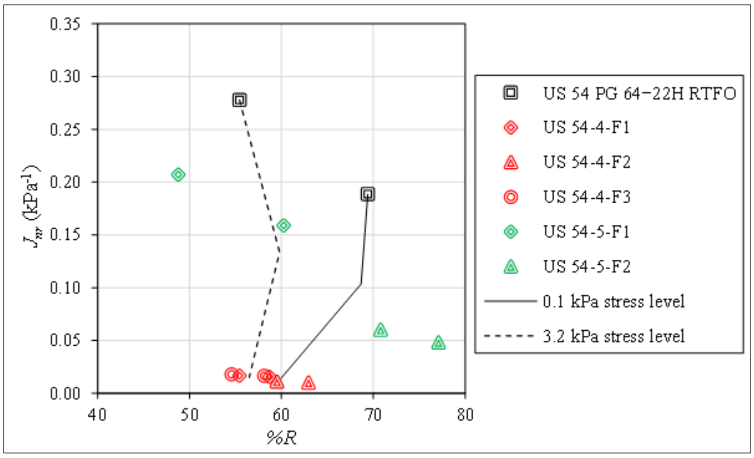

Figure 5 MSCR test results for RTFO AVAB and EABs from the US 54 PG 64–22H mixture

Figure 6 shows the MSCR test results measured at 60 °C for RTFO AVAB and EABs from the US 63-1 mixture containing 35% ABR percentage by RAP and PG 58–28 VAB. The EABs had higher *%R* and lower J_{nr} values than RTFO AVAB's value because of the aged binder in RAP. For the same ABR percentage by RAP (35%), EABs from the US 54-4 mixture had higher *%R* and lower J_{nr} values than those of US 63-1 EABs. This was related to the stiff VAB in the US 54-4 mixture (PG 64–22H); however, the US 63-1 mixture contained a softer VAB with a PG of 58–28. Hence, the PG of VAB and the ABR percentage by RAP/RAS controlled the performance of EABs.

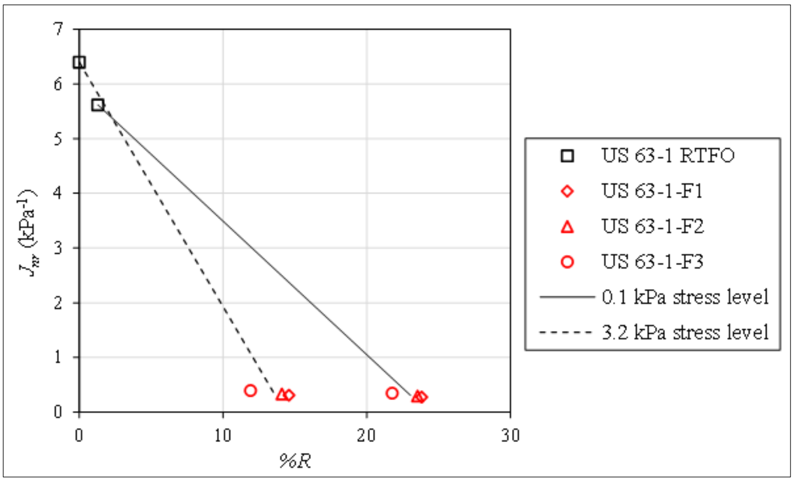

Figure 6 MSCR test results for RTFO AVAB and EABs from the US 63-1 mixture.

Figure 7 illustrates the percentage increase or decrease in the *%R* values for EABs compared to those of RTFO AVABs. The measurements of the MSCR test were conducted at 60 °C and 0.1 & 3.2 kPa stress levels. The EABs presented higher *%R* values than the values of RTFO AVABs. However, some EABs showed a percentage decrease in the *%R* values (e.g., US 54-4 and US 54-5-F1 EABs). These binders were extracted from mixtures with PG 64–22H VAB. The lowest percentage increase in the *%R* values was observed for EABs from the MO 13-1 mixture with PG 64–22H VAB. This reflected that mixtures containing the stiffest VAB, PG 64–22H, had the least improvement in %R values for EABs when compared to those of RTFO AVABs. By using PG 58–28 VAB, the *%R* for EABs enhanced when compared to RTFO AVABs.

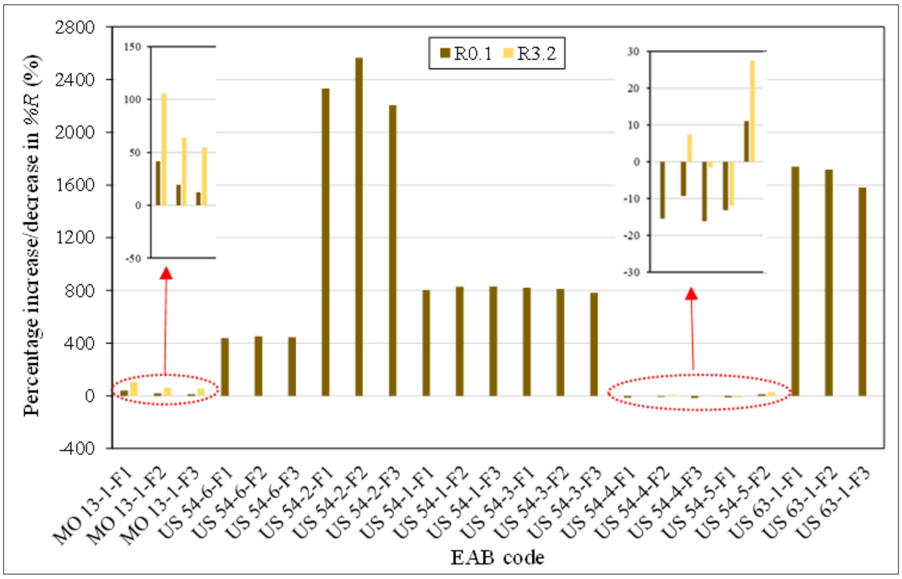

Figure 7 Percentage increase or decrease in the %R values for EABs

The percentages increase in the *%R* values at 3.2 kPa stress level ($R_{3.2}$) for EABs from the US 54 PG 58–28 and US 63-1 mixture were not presented in the figure because the $R_{3.2}$ values for RTFO AVABs were zero. The percentage increase in the $R_{0.1}$ value for EABs from the US 54-6 with 31% ABR percentage by RAP reached above 400%. Increasing the ABR percentage by RAP to 33%, US 54-2, caused a significant increase, more than 2000%, in the percentages increase in the

$R_{0.1}$ value for EABs. These findings reflected that increasing the ABR percentage by RAP altered the performance of EABs by increasing the EABs' stiffnesses. Another reason was the high variability of the binders' properties included in RAP [19].

The EABs from either US 54-1 or US 54-3 mixtures, with 33% percentage ABR percentage by RAS or RAP/RAS, had the same percentage increase in the $R_{0.1}$ value (800%), which was greater than what was obtained for EABs from a mixture contained 31% ABR percentage by RAP and lower than the values obtained for EABs from a mixture contained 33% ABR percentage by RAP. This reflected that there was no compatibility between VABs and RAS. Comparing EABs from the US 54-4 and US 63-1 mixtures, these mixtures had the same ABR percentage by RAP (35%), EABs from a mixture containing PG 58–28 binder VAB (US 63-1) showed a higher increase in the percentage increase in the $R_{0.1}$ value than EABs from a mixture with PG 64–22H stiffer VAB (US 54-4).

Figure 8 displays the percentage decrease in the J_{nr} values for EABs compared to those of RTFO AVABs. The measurements of the MSCR test were conducted at 60 °C and 0.1 & 3.2 kPa stress levels. All EABs presented lower percentages of J_{nr} values than RTFO AVABs' values. The highest percentage decrease in the J_{nr} values was recorded for EABs from a mixture containing 33% ABR percentage by RAP and a VAB having a PG of 58–28 (US 54-2). The EABs from a mixture containing 30% or more ABR percentage by RAP/RAS had a percentage decrease in the J_{nr} values greater than 80%. The lowest percentage decrease in the J_{nr} values was noted for EABs from a mixture containing zero ABR percentage by RAP/RAS (US 54-5-F1).

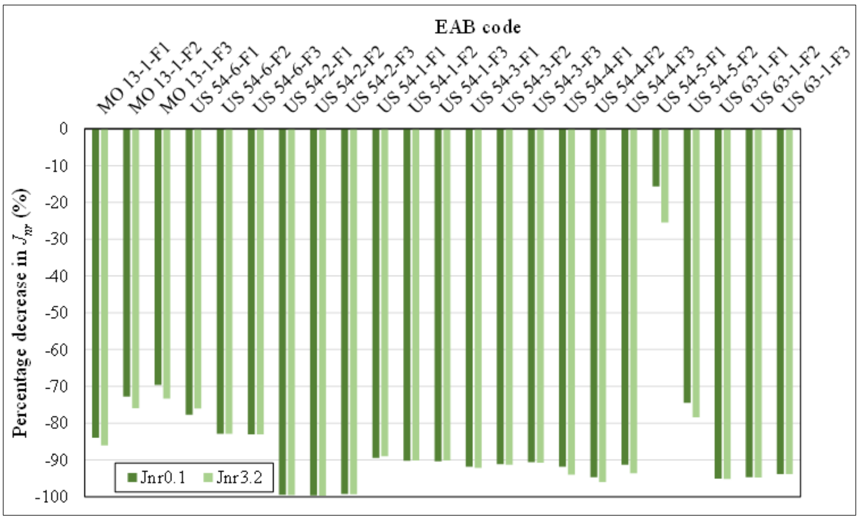

Figure 8 Percentage decrease in the J_{nr} values for EABs

3.2.2. Temperature Sweep and Frequency Sweep Test Results

The temperature sweep test results for RTFO AVAB and EABs from the MO 13-1 mixture, containing 17% ABR percentage by RAP and PG 64–22H VAB, are presented in Figure 9a. Using 17% ABR percentage by RAP increased the $|G^*|/\sin\delta$ for EABs because of the aged binder in RAP. Figure 9b depicts the master curves analyzed at 60 °C for RTFO AVAB and EABs from the MO 13-1 mixture containing 17% ABR percentage by RAP and PG 64–22H VAB. The EABs showed a higher $|G^*|/\sin\delta$ at different frequencies when compared to those of RTFO AVAB. This was attributed to the higher stiffnesses and elasticities of binders in RAP. Therefore, the aged components included in RAP binders increased the EABs' stiffnesses and elasticities, as proven by MSCR testing.

Figure **10**a exhibits the temperature sweep test results for RTFO AVAB and EABs from the US 54 mixtures containing different ABR percentages by RAP and/or RAS and PG 58–28 VAB. The EABs from a mixture containing 31% ABR percentage by RAP (US 54-6) had higher $|G^*|/\sin\delta$ than RTFO AVAB. Increasing the ABR percentage by RAP to 33%, US 54-2, increased the $|G^*|/\sin\delta$ to the highest values. The EABs from a mixture with 33% ABR percentage by RAS (US 54-1) showed higher $|G^*|/\sin\delta$ values than the US 54-6 EABs and lower $|G^*|/\sin\delta$ values than the US 54-2 EABs. The air-blown asphalt binders in RAS were stiffer than the aged binders in RAP. Consequently, it was concluded that there was no compatibility between the RAS binder and VAB. For the same percentage of recycled materials, 33% ABR percentage, EABs from a mixture containing RAP were stiffer than EABs from a mixture containing RAS. Using 33% ABR percentage by RAP and RAS, US 54-3, increased the $|G^*|/\sin\delta$ of EABs than EABs from a mixture containing 33% ABR percentage by RAS (US 54-1). These findings were confirmed by the results obtained in Figure 10b for the master curves. The EABs showed higher $|G^*|/\sin\delta$ values at different frequencies than RTFO AVAB. The highest $|G^*|/\sin\delta$ was obtained for EABs from a mixture containing 33% ABR percentage by RAP (US 54-2).

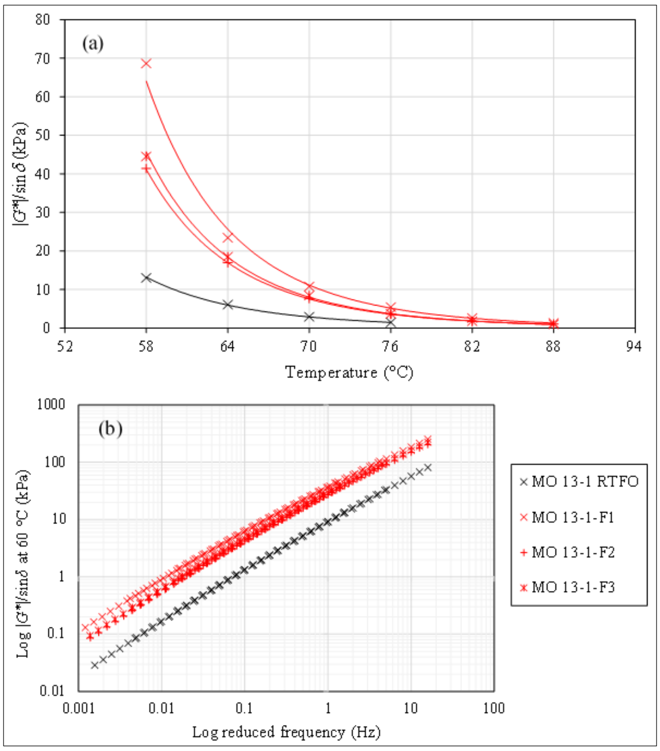

Figure 9 (a) Temperature sweep results and (b) Master curves for RTFO AVAB and EABs from the MO 13-1 mixture

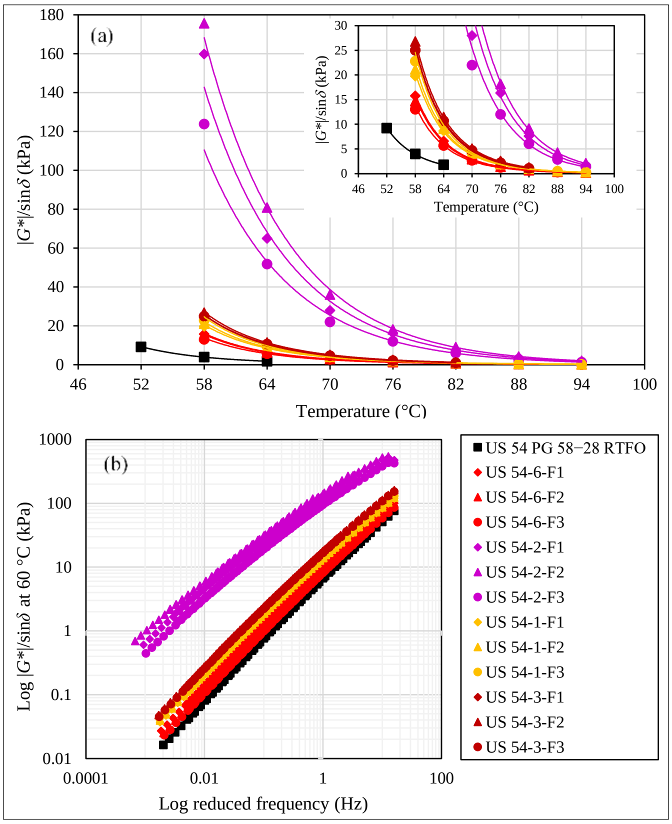

Figure 10 (a) Temperature sweep results and (b) Master curves for RTFO AVAB and EABs from the US 54 PG 58–28 mixtures

Figure 11a depicts the temperature sweep test results for RTFO AVAB and EABs from the US 54 mixtures containing PG 64−22H VAB. The EABs from a mixture without RAP/RAS, US 54-5, showed an increase in stiffnesses by presenting higher $|G^*|/\sin\delta$ values when compared to those of RTFO AVABs. Using 35% ABR percentage by RAP in the US 54-4 mixture increased EABs' $|G^*|/\sin\delta$ to the highest values. Figure 11b displays the master curves for RTFO AVAB and EABs from the US 54 mixtures containing PG 64−22H VAB. The master curves were analyzed at 60 °C and at different frequencies. The EABs had higher $|G^*|/\sin\delta$ values than RTFO AVAB. The highest $|G^*|/\sin\delta$ was for the US 54-4 EABs from a mixture containing 35% ABR percentage by RAP.

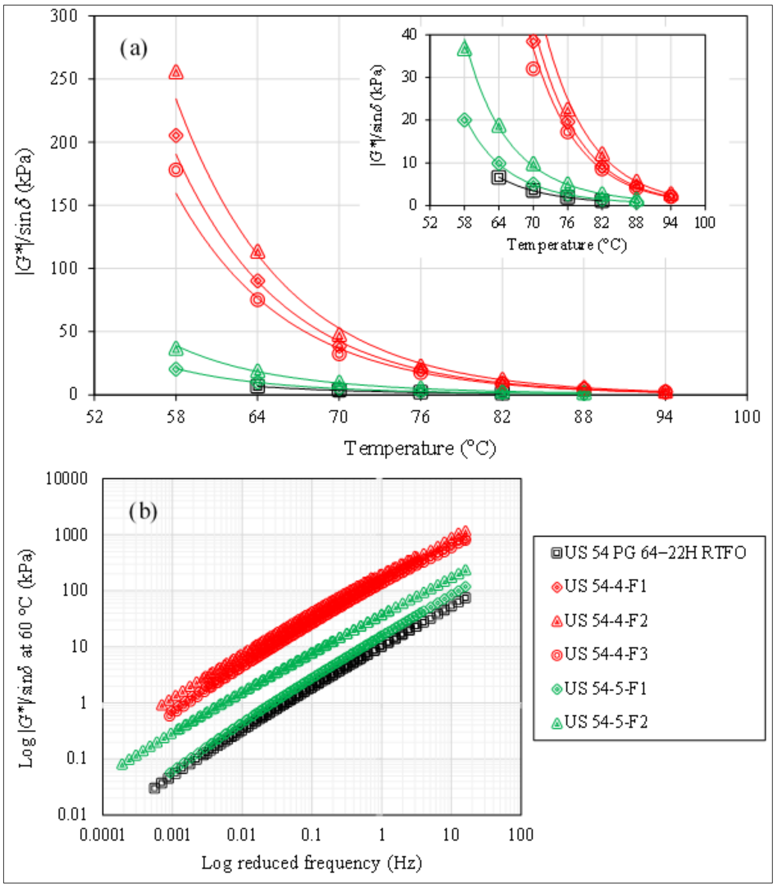

Figure 11 (a) Temperature sweep results and (b) Master curves for RTFO AVAB and EABs from the US 54 PG 64−22H mixtures

Figure 12a exhibits the temperature sweep test results for RTFO AVAB and EABs from the US 63-1 mixture containing 35% ABR percentage by RAP and PG 58−28 VAB. The EABs had an increase in stiffnesses by presenting higher $|G^*|/\sin\delta$ values than RTFO AVAB's values. The master curves for RTFO AVAB and EABs from the US 63-1 mixture at 60 °C and different frequencies are presented in Figure 12b. The EABs depicted higher $|G^*|/\sin\delta$ than RTFO AVAB's values because of the aged binders in RAP that increased the EABs' stiffnesses and elasticities, as proven by MSCR testing.

To compare the EABs and RTFO AVABs, the high PG temperature for each binder is presented in Figure 13. The columns' color indicates the state of the asphalt binder: the black columns represent RTFO AVABs, the red ones indicate EABs from mixtures containing RAP, the green ones reflect EABs from mixtures containing RAS, the purple ones indicate EABs from mixtures containing both RAP and RAS, and the blue ones refer to EABs from mixtures without RAP/RAS. The high PG temperature increased one to two grades, 6 °C per grade, for EABs from a mixture containing 17% ABR percentage by RAP (MO 13-1 EABs). Using 31% ABR percentage by RAP in the US 54-6 mixture and 33% ABR percentage by RAS in the US 54-1 mixture increased the high PG temperatures of EABs by two grades. Increasing the ABR percentage by RAP from 31% to 33% in the US 54-2 mixture increased the high PG temperature by another three grades. Therefore, EABs containing 33% ABR percentage by RAP had a boost in the high PG temperature by five grades when compared to RTFO AVAB. Therefore, increasing the ABR percentage by RAP increased EABs' stiffnesses. Another reason was related to the high variability of the aged binders included in RAP: EABs from RAP could vary from one season and/or stockpile to another [19].

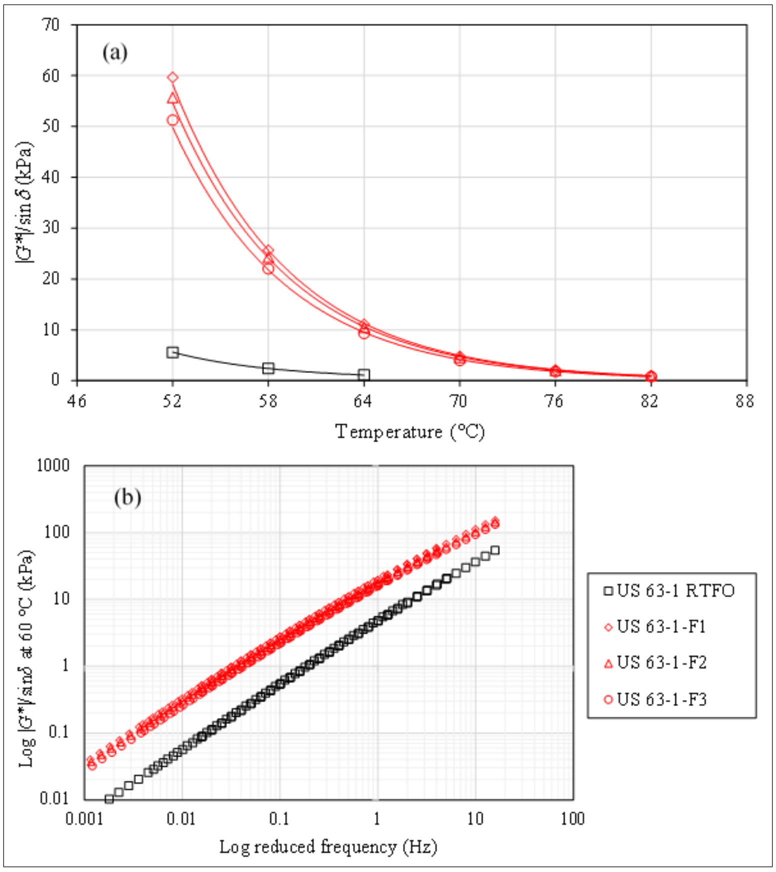

Figure 12 (a) Temperature sweep results and (b) Master curves for RTFO AVAB and EABs from the US 63-1 mixture

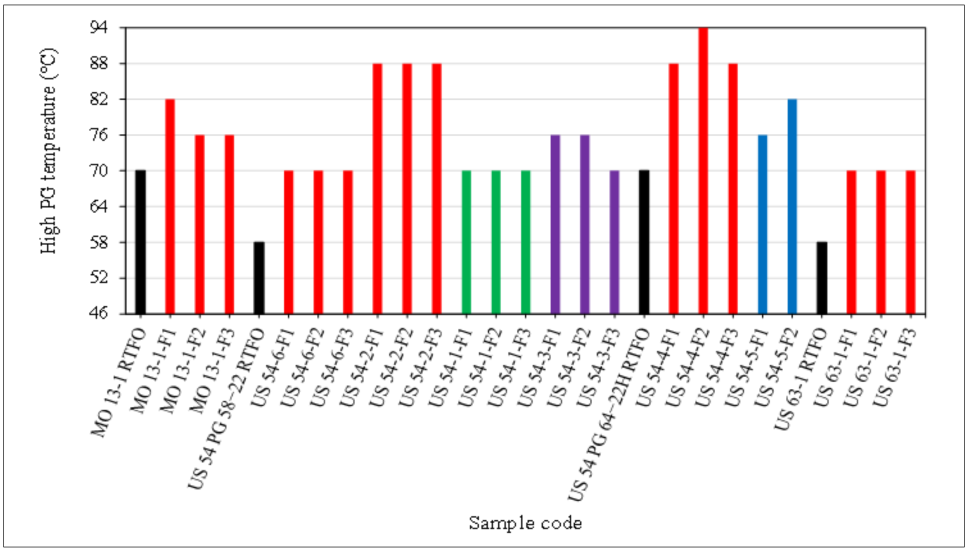

Figure 13 The high PG temperatures for RTFO AVABs and EABs

Using both RAP and RAS in the US 54-3 mixture with a 33% ABR percentage increased the high PG temperature by one grade when compared to the high PG temperature of EABs from a mixture containing the same ABR percentage by RAS, US 54-1 mixture. This finding indicated that using both RAP and RAS in mixtures altered the performance of EABs. This occurred because the asphalt binders in RAP interacted with VABs easier than the interaction between the air-blown asphalt in RAS and the same VABs. The interaction process was different for RAS binders due to the stiff nature of the air-blown asphalt. Thus, there was no compatibility between the binder in RAS and VAB. That's why EABs from a mixture containing 33% ABR percentage by RAP presented higher stiffness values than the values of EABs from a mixture containing the same ABR percentage by RAS and the same VAB.

The EABs from a mixture without RAP/RAS, US 54-5, had an increase in the high PG temperature from one to two grades when compared to RTFO AVAB. Adding 35% ABR percentage by RAP to the US 54-4 mixture increased EABs' high PG temperature from three to four grades when compared to RTFO AVAB. Comparing the high PG temperatures of EABs from the US 54-4 and US 63-1 mixtures, both mixtures contained the same ABR percentage by RAP (35%). However, the US 63-1 mixture contained a softer asphalt binder. Thus, the increase in the high PG temperature of the US 63-1 EABs was two grades, which was lower than the increase for the US 54-4 EABs (three to four grades). Thus, the PG of VAB and ABR percentage by RAP/RAS controlled the high PG temperatures of EABs.

4. Conclusion

Asphalt binders were extracted from 23 field cores that represented eight asphalt mixtures. These mixtures contained different asphalt binder replacement (ABR) percentages by reclaimed asphalt pavement (RAP), recycled asphalt shingles (RAS), both, or none. Different sources of virgin asphalt binders (VABs) with different performance grades (PGs) were included in the asphalt mixtures. The high-temperature rheological temperatures of extracted asphalt binders (EABs) were compared to the corresponding rolling thin film oven aged virgin asphalt binders (RTFO AVABs). Based on this study, the following points were concluded:

- For the same ABR percentage, EABs from mixtures containing RAP were stiffer than EABs from mixtures containing RAS. Thus, no compatibility took place between the RAS binders and VABs.
- The RAP binders interacted more readily with VABs when compared to RAS binders.
- The EABs had higher stiffness and elasticity values than the corresponding RTFO AVABs' values because of the aged binders in RAP/RAS.
- Increasing the ABR percentage by RAP increased EABs' stiffnesses.
- The PG of VAB and ABR percentage by RAP/RAS controlled the high PG temperatures of EABs. For the same ABR percentage by RAP, using a softer VAB decreased stiffnesses of EABs when compared to the stiffnesses of EABs from mixtures with a stiffer VAB.

Compliance with ethical standards

Acknowledgments

The authors acknowledge the technical and funding support of Missouri Department of Transportation (MoDOT) for providing samples and information for this research.

Disclosure of conflict of interest

All authors declare that they have no conflicts of interest.

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