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Interactions between RAP and virgin asphalt binders in field, plant, and lab mixes

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Abstract

Reclaimed asphalt pavement (RAP) has been used in asphalt mixes for several years in the United States. However, the interactions between the RAP binder and the virgin asphalt binder (VAB) need further investigations. Thus, the main objective of this study was to explore the rheological and chemical properties of extracted asphalt binders (EABs) from plant, field, and lab mixes. The plant mixes were collected from behind the paver, reheated to the compaction temperature, and compacted in the lab. The field mixes were collected as cores within two weeks after the end of the construction process. The lab mixes were fabricated in the lab using the same materials used in the plant and field mixes. The mixes contained high asphalt binder replacement percentages by RAP, which were greater than 30%. The EABs were treated as rolling thin film oven aged VABs (RTFO AVABs). The rheological properties of EABs and RTFO AVABs were analyzed using temperature sweep, frequency sweep, and multiple stress creep recovery tests. Chemical investigations of EABs and RTFO AVABs were carried out using Fourier transform infrared spectroscopy and thermogravimetric analysis. The EABs from plant or lab mixes showed higher stiffnesses than EABs from field mixes. This occurred because of the extra heating that was implemented for the plant mixes before the compaction in the lab, which caused more interactions between the RAP binder and VABs. The fabrication mechanism, mixing and short-term aging processes, used in lab mixes caused more interactions between RAP binder and VABs than in the field mixes.

Keywords: RAP; Interaction; Extraction; Recovery; TGA; Rubber; FTIR

1. Introduction

Reclaimed asphalt pavement (RAP), removed and processed pavement materials, contains valuable materials (e.g., asphalt binder and aggregate) [1]. Using RAP in asphalt mixes started in the United States for decades due to the oil embargo in 1973 [1, 2]. However, after the drop in oil prices, the RAP was used in asphalt mixes because of the economic and environmental merits [1]. After years of service, the properties of asphalt binder in the pavement changed [3], and they became more aged. The aging processes of asphalt binders in the RAP deepen with increasing exposed surface—depending on the size of the RAP particles—and exposure time to the atmosphere [4, 5]. Furthermore, RAP storing in the stockpiles increased the RAP binder aging process due to the exposure to air [6, 7]. These aging processes caused the loss of low-molecular-weight fractions by either volatilization or absorption, oxidation that caused changes in composition, and steric hardening that resulted from the molecular structuring [3, 8]. Therefore, the high-temperature performance grade (PG) for extracted asphalt binders (EABs) from different sources of RAP were between 76 and 94°C [9–12].

The interactions between RAP and virgin asphalt binders (VABs) control the performance of the total binder inside the asphalt mixes. McDaniel et al. [13] in the NCHRP D9-12 categorized the interactions between the RAP binder and VAB

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into three categories: no blending, the RAP considered as black rocks, full or 100% blending, and partial blending as occurred in practice (actual practice). Noferini et al. [14] revealed that increasing the RAP percentage in the asphalt mixes caused more interactions between RAP binder and VAB, which increased the stiffnesses of the EABs. The 100% blending, full blending, between RAP binder and VAB did not reach, even so, the researchers [15] tried different RAP percentages and mixing temperatures. Thus, the full blending is a theoretical assumption that was not achieved. Reheating plant mixes—containing 15 to 40% RAP—in the lab before the compaction [16, 17] increased the mixes' stiffness when compared to plant mixes without reheating. The researchers related these findings to the additional aging that occurred to the VABs in the reheated plant mixes. The EABs from plant mixes, containing RAP/reclaimed asphalt shingles (RAS), and lab mixes were compared by Johnson et al. [18]. The EABs from lab mixes were stiffer than EABs from plant mixes because more blending took place between RAP/RAS and VABs in lab mixes than in plant mixes.

Interactions between RAP binder and VAB can be explored by Fourier transform infrared (FTIR) spectroscopy and thermogravimetric analysis (TGA). Fourier transform infrared spectroscopy is used to explore the oxidative functional groups, sulfoxide (S=O) and carbonyl (C=O), in asphalt binders. Poulikakos et al. [19] proved that increasing the aging process of asphalt binders, led to a higher intensity of the oxidative functional groups. Mullapudi et al. [20] mixed different proportions of extracted RAP binders with VABs, and it was found that the oxygenated functional groups' indices—I_{SO} and I_{CO}—increased with increasing RAP binders' percentages. The binder in the RAP contained a high asphaltene fraction [21], thus EABs' maltenes and asphaltenes fractions change based on the interactions between the RAP binder and VAB. The TGA is utilized to examine changes in the components of asphalt binders by monitoring changes in thermograph (TG) parameters: the onset temperature (T_{onset}), endset temperature (T_{endset}), and residue's percentage. The T_{onset} of the mass loss during thermal degradation was used to predict binders' compositional changes [22]. The T_{onset} was defined in the ISO 11358-1 [23] as the point of intersection of the starting-mass baseline and the tangent to the TG curve at the point of the maximum gradient (known as the inflection point). The shape of the derivative of the thermograph (DTG) curve during the thermal degradation reflected the aging condition of asphalt binders [24]. Usually, the DTGs showed three regions for asphalt binders: no mass loss happened in the first region, the thermal degradation initiated in the second region, and the fastest molecules' cracking occurred in the third region [25]. However, Deef-Allah and Abdelrahman [24] found that the second region disappeared for EABs from long-term aged field mixes containing RAP. The asphaltene had one peak in the DTG; however, the maltene presented two peaks [26]. Thus, disappearing the second region in the DTG indicated a decrease in the maltene component of EABs [24].

The main objective of this study was to explore the interactions between RAP binder and VABs. This was achieved by extracting asphalt binders from plant, field, and lab mixes. The plant mixes were collected as loose mixes from behind the paver, reheated to the compaction temperature, and compacted in the lab. The field mixes were gathered as cores within two weeks after the end of the pavement construction processes. The lab mixes were fabricated in the lab using the same materials and proportions used in the field and plant mixes. Different fabrication methods in plant, field, and lab mixes could alter the interactions between RAP binder and VABs, which may affect the performances of EABs. The interactions between RAP binder and VABs reflected on EABs' rheological and chemical properties, which were investigated by this study.

2. Materials and experimental program

2.1. Materials

Asphalt mixes were designed following Superpave and mixed in a drum-mix plant. The plant mixes were collected from behind the paver (six samples representing two mixes). The mixes were reheated to the compaction temperature and compacted in the lab. The mixes contained two different asphalt binder sources; however, they have the same PG (58−28). These mixes contained RAP with two asphalt binder replacement (ABR) percentages, 31 and 35%. For field mixes, the cores were gathered within two weeks after the end of the pavement construction process in 2016. The field cores represented the plant mixes after the construction process; six cores were collected that represented two mixes. Therefore, EABs from plant or field mixes were considered as short-term aged binders. More information about the field and plant mixes is presented in Table 1. The mixes' codes present the road name (e.g., US 54), section number (e.g., 6), and coding system (e.g., F1). Different lab mixes were designed following Superpave using the same original asphalt binders used in the plant mixes, PG 58−28, and the same materials (e.g., aggregate, RAP, and additives) used in plant and field mixes with specific proportions, as explained in the job mix formula (JMF).

Using a softer VAB in mixes containing recycled materials (e.g., RAP) is recommended [27] to increase the workability characteristics because of the aged binders in RAP. Thus, a softer asphalt binder with a PG of 46−34 was used in the lab mixes to evaluate the effect of using a soft asphalt binder in mixes containing RAP when compared to mixes containing the same materials and a stiffer binder (PG 58−28). To promote the sustainability of lab mixes containing RAP, rubber was utilized in these mixes. An engineered crumb rubber (ECR), a type of dry-process ground tire rubber, with three percentages—5, 10, and 20%—by the net weight of total binder were used in the lab mixes. Asphalt binder and ECR were heated to 170°C then blended in a high-shear mixer at 3500 rpm for 30 minutes. After mixing aggregates with binders or modified binders, the mixes were short-term aged in the oven at the compaction temperature, specified in the JMF, for two hours before the compaction process. Finally, the lab mixes were compacted using a Superpave gyratory compactor. The lab mixes' details are presented in Table 2. Figure 1 shows the field, plant, and lab mixes.

Table 1 Field and plant asphalt mixes' information [28]

Field Mixes' Codes	**US 54-6-F1**	**US 54-6-F2**	**US 54-6-F3**	**US 63-1-F1**	**US 63-1-F2**	**US 63-1-F3**
Plant Mixes' Codes	**US 54-6-P1**	**US 54-6-P2**	**US54-6-P3**	**US 63-1-P1**	**US 63-1-P2**	**US 63-1-P3**
Route / Dir	US 54 NB			US 63 SB		
Location	N. of Osage Beach			S. of Moberly		
County	Miller			Randolph		
ABR % by RAP	31			35		
Total AC[a] (%)	5.1			5.1		
Virgin Asphalt PG	58–28			58–28		
NMAS[b] (mm)	12.5			12.5		
Additives	1% Morelife T280[c]			0.5% Evotherm[d] and 1.75% EvoFlex CA[e]		

[a] AC: asphalt content; [b] NMAS: nominal maximum aggregate size; [c] Morelife T280: anti-stripping agent; [d] Evotherm: warm-mix additive; [e] EvoFlex CA: rejuvenator additive

Table 2 Lab asphalt mixes' information [28]

Lab Mixes' Codes	**Total AC (%)**	**Virgin Asphalt PG**	**ECR[a] (%)**	**Additives**
US 54-6 Lab Mixes				
US 54-6-L1	5.1	58–28	0	
US 54-6-L2				
US 54-6-L3				
US 54-6-R[b]-L1				3% Evoflex
US 54-6-R-L2				
US 54-6-SB[c]-L1		46–34		
US 54-6-SB-L2				
US 54-6-SB-E5[d]-L1	5.2		5	
US 54-6-SB-E5-L2				
US 54-6-SB-E5-L3				
US 54-6-SB-E20[e]-L1	5.5		20	
US 54-6-SB-E20-L2				
US 63-1 Lab Mixes				
US 63-1-R-L1	5.1	58–28		1.75% Evoflex & 0.5% Evotherm
US 63-1-R-L2				
US 63-1-R-L3				
US 63-1-SB-L1		46–34		
US 63-1-SB-L2				
US 63-1-SB-L3				
US 63-1-SB-R-L1				1.75% Evoflex & 0.5% Evotherm
US 63-1-SB-R-L2				
US 63-1-SB-R-L3				
US 63-1-SB-E10-L1	5.3		10	

US 63-1-SB-E10-L2				
US 63-1-SB-E20-L1	5.5		20	
US 63-1-SB-E20-L2				

[a] ECR: Engineered Crumb Rubber; [b] R: Rejuvenator; [c] SB: Soft Binder; [d] E5: 5% ECR; and [e] E20: 20% ECR.

Figure 1 Field, plant, and lab mixes [28]

2.2. Experimental Program

2.2.1. Extraction and Recovery of Asphalt Binders from Asphalt Mixes

Asphalt binders were extracted from the mixes using the centrifuge extraction process (Method A) according to ASTM D2172 / D2172M-17e1 [29]. 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) [30].

2.2.2. FTIR Spectroscopy Analysis

Fourier transform infrared spectroscopy was utilized to guarantee no TCE traces in the EABs. Furthermore, it was used to calculate the FTIR aging indices for asphalt binders before and after the extraction and recovery processes. Nicolet iS50 ATR-FTIR spectrometer was used by laying the samples on a diamond crystal. The experimental setup was run using OMNIC 9 software by applying 32 scans at a resolution of 4 and using wavenumbers ranging from 1000 to 400 cm^{-1}.

2.2.3. Short-Term Aging for Virgin Asphalt Binders

Short-term aging was carried out using the rolling thin film oven (RTFO) device according to ASTM D2872-19 [31] for VABs.

2.2.4. Rheological Properties of Asphalt Binders

The VABs, RTFO aged VABs (RTFO AVABs), and EABs were analyzed on a dynamic shear rheometer (DSR), following ASTM D7175-15 [32]. Samples with a thickness of 1 mm and 25 mm in diameter were tested using a temperature sweep test and a frequency sweep test. Both tests were used to identify the changes that occurred in EABs after extracting from different mixes containing RAP. This was achieved by comparing the EABs' and RTFO AVABs' rutting parameters ($|G^*|/\sin\delta$) at different temperatures and through different frequencies.

For field, plant, and lab mixes, the EABs were treated as RTFO AVABs. Different temperatures were selected for the temperature sweep testing starting with the high PG temperature of VAB 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 from the same can and the average results were analyzed. For the frequency sweep testing, four temperatures were selected—52, 58, 64, and 70°C temperatures—through different frequencies (15.92 to 0.0159 Hz). The master curves for RTFO AVABs and EABs were analyzed, using the frequency sweep test results, at 60°C as a reference temperature.

The MSCR test was conducted following ASTM D7405-20 [33] to verify the changes that occurred in EABs' stiffnesses and elasticities, after the extraction from different mixes containing RAP, compared to RTFO AVABs. 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). For each creep cycle, the loading time was 1 sec, and the unloading time (recovery) was 9 sec. The $\%R$ reflected the binders' elasticities, and the J_{nr} indicated the binders' stiffnesses.

2.2.5. Thermal Analysis

Thermal analysis was utilized to monitor the compositional changes that took place in EABs compared to RTFO AVABs and in ECR samples before and after the extraction process. The thermal characteristics of asphalt binders and ECR were analyzed using a Discovery TGA 550 model. The test followed the procedures in the ASTM E1131-20 [34].

Thermal Analysis of Asphalt Binders

The asphalt samples, 15–25 mg, were heated from room temperature to 750°C using a heating rate of 50°C/min, a high-resolution dynamic method, and a nitrogen flow rate of 60 ml/min. The thermal characteristics were analyzed for VABs, RTFO AVABs, and EABs by monitoring the changes in the TG parameters: T_{onset}, T_{endset}, and residue's percentage at 750°C. In addition, the shapes of the DTG curves during the thermal degradation were explored.

Thermal Analysis of ECR

The thermal analysis was conducted on the ECR sample originally received, before using in lab mixes, and the extracted ECR from lab mixes, after extractions of asphalt binders. The ECR samples with 10–20 mg weights were heated from room temperature to 650°C using a heating rate of 50°C/min, a high-resolution dynamic method, and a nitrogen flow rate of 60 ml/min. The mass loss was recorded, and the ECR compositional components were analyzed.

3. Results and discussion

3.1. FTIR Results

3.1.1. FTIR Qualitative Analysis

Fourier transform infrared spectroscopy was used to ensure the recovery process was done properly by comparing the spectra of TCE and asphalt binders before and after the extraction and recovery processes. Figure 2 shows the FTIR spectra—wavenumbers less than 1000 cm^{-1}—for TCE, VABs, RTFO AVABs, and EABs from field and plant mixes. Two strong sharp peaks were observed for the TCE for wavenumbers 944 and 849 cm^{-1}, which were related to C–Cl stretching in alkyl halide [35]. The EABs' spectra showed no TCE bands, which reflected no remaining TCE in EABs from field and plant mixes. The same results were obtained from Figure 3; EABs from lab mixes had no TCE traces.

3.1.2. FTIR Quantitative Analysis

The I_{CO} in carboxylic acid at 1700 cm^{-1} and I_{SO} by sulfoxide at 1030 cm^{-1} were calculated using Equation 1 and Equation 2, respectively. This was achieved by dividing the peaks' areas at 1700 cm^{-1} for the I_{CO} or 1030 cm^{-1} for the I_{SO} by the peaks' areas of the aliphatic groups at 1376 and 1460 cm^{-1}. The peaks at 1376 and 1460 cm^{-1} are related to the C–H bending vibrations in methyl (CH_3) and ethylene (CH_2), respectively [36–38]. It is expected that the intensity of those aliphatic groups' peaks is not changed or affected by aging [39, 40].

$$I_{CO} = \frac{\text{Peak area at 1700 cm}^{-1}}{\text{Peak area at 1376 cm}^{-1} + \text{Peak area at 1460 cm}^{-1}} \quad (1)$$

$$I_{SO} = \frac{\text{Peak area at 1030 cm}^{-1}}{\text{Peak area at 1376 cm}^{-1} + \text{Peak area at 1460 cm}^{-1}} \quad (2)$$

The aging indices (I_{SO} and I_{CO}) were calculated for RTFO AVAB and each EAB. The aging indices were averaged for EABs from the same mix. The CV values for the I_{CO} ranged between zero and 96.47%, and the CV values for the I_{SO} varied between zero and 31.19%. The VABs had a higher I_{SO} than I_{CO}. For RTFO AVABs, the I_{SO} plus I_{CO} increased when compared to VABs. The Rheological Results Section (Section 3.2) showed that although US 54 and US 63-1 mixes had VABs with the same PG (58–28). However, the US 63-1 VAB was softer than the US 54 VAB. This was deduced from Figure 4 because the US 63-1 VAB and RTFO AVAB had lower I_{SO} plus I_{CO} values when compared to those of the US 54 VAB and RTFO AVAB.

The EABs had higher I_{SO} plus I_{CO} values when compared to values of RTFO AVABs because of the aged components in the RAP binder. The EABs from plant mixes had higher values of I_{CO} plus I_{SO} when compared to EABs from field mixes. This was related to the extra heating process that occurred to the plant mixes before the compaction process in the lab. This caused more aging to VAB and more contribution of the aged binders included in RAP to the total EABs. This contribution increased the interactions between the RAP binder and VAB. The EABs from lab mixes had the highest I_{SO} plus I_{CO} when compared to EABs from plant or field mixes.

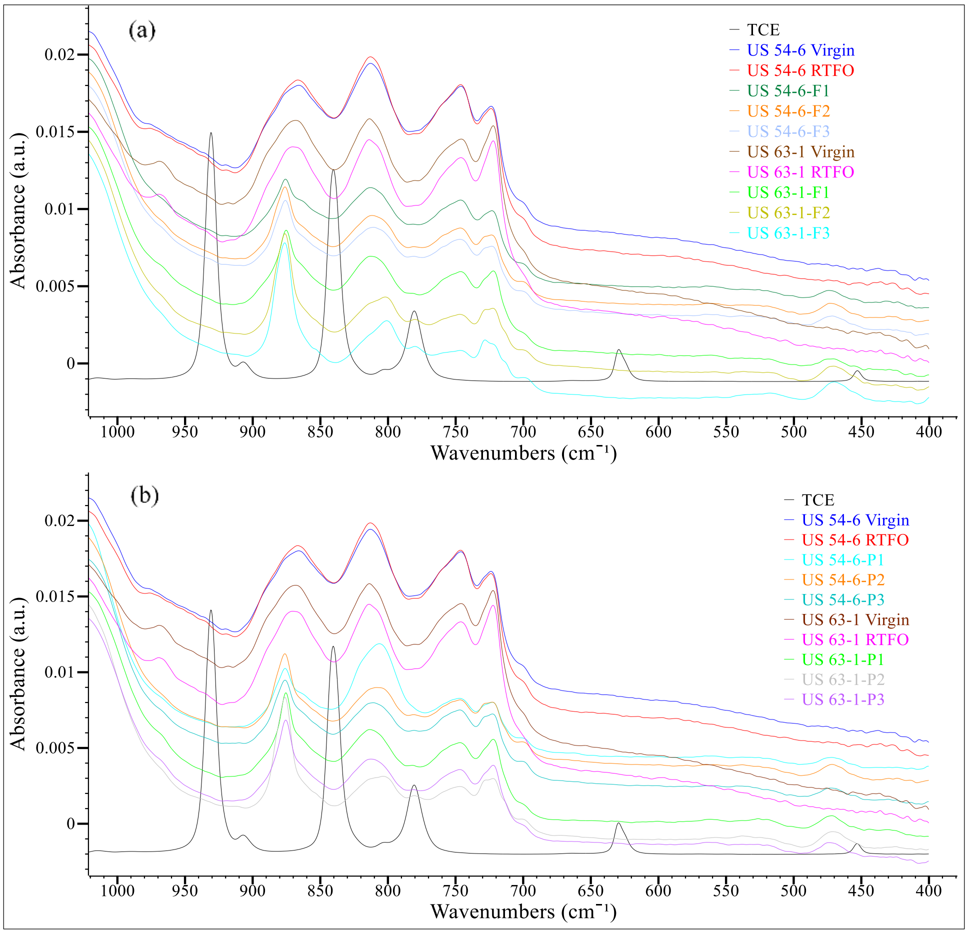

Figure 2 FTIR spectra for TCE, VABs, RTFO AVABs, and EABs from (a) Field and (b) Plant mixes

Using 3% Evoflex, US 54-6-R-L EABs, increased the I_{SO} plus I_{CO} when compared to EABs without Evoflex (US 54-6-L EABs). This illustrated the effect of Evoflex on increasing the contribution of RAP binders in mixes [41], which increased the interactions between RAP binder and VAB. Using a soft binder (SB) with a PG of 46−34 decreased EABs' I_{SO} plus I_{CO} when compared to I_{SO} plus I_{CO} values of EABs from mixes with a stiffer VAB (PG 58−28). Using ECR decreased the I_{SO} plus I_{CO} for EABs when compared to EABs from mixes without ECR, which reflected the ability of rubber particles to decrease binders' aging indices [42].

The I_{SO} plus I_{CO} values for the US 63-1 VAB and RTFO AVAB were lower than the I_{SO} plus I_{CO} values for the US 54-6 VAB and RTFO AVAB. However, the percentage increase in the I_{SO} plus I_{CO} for EABs from the US 63-1 mix (270 to 457%) was higher than that for EABs from the US 54-6 mix (182 to 282%). This was related to the higher ABR percentage by RAP included in the US 63-1 mix (35%) than the ABR percentage by RAP in the US 54-6 mix (31%).

3.2. Rheological Results

3.2.1. MSCR Test Results

The MSCR test results, measured at 0.1 and 3.2 kPa stress levels and 60°C temperature, are illustrated in Figure 5 for RTFO AVAB and EABs from the US 54-6 and US 63-1 field, plant, and lab mixes. The US 54-6 and US 63-1 VABs had the same PG (58−28); however, the US 54-6 RTFO AVAB was stiffer and more elastic than the US 63-1 RTFO AVAB. This was concluded because the US 54-6 RTFO AVAB had lower J_{nr} and higher *%R* values than those of the US 63-1 RTFO AVAB. The EABs had higher *%R* and lower J_{nr} values than the recorded values for the RTFO AVABs due to the stiffness effect of the aged binders in RAP, which agreed with the FTIR quantitative analysis (Section 3.1.2). Furthermore, EABs from the US 63-1 mix revealed lower J_{nr} and higher *%R* values when compared to EABs from the US 54-6 mix. This occurred because the US 63-1 mix contained 4% ABR percentage by RAP higher than the ABR percentage by RAP in the US 54-6 mix. Thus, increasing the ABR percentage by RAP increased the stiffnesses and elasticities of EABs due to the aged binders in RAP. Furthermore, the US 63-1 mix contained Evoflex, as a rejuvenator, that enhanced the contribution of the RAP binder [41] in the mixes and increased the interactions between RAP binder and VAB.

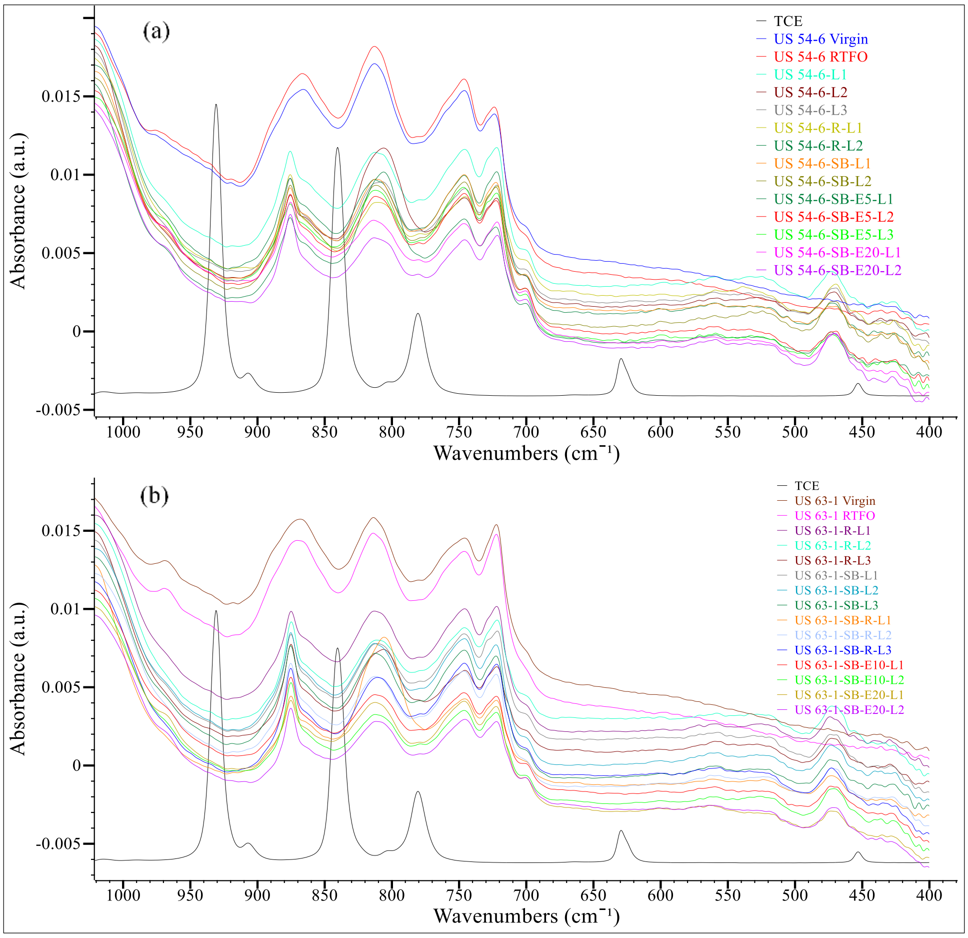

Figure 3 FTIR spectra for TCE, VABs, RTFO AVABs, and EABs from (a) US 54-6 and (b) US 63-1 lab mixes

The EABs from plant mixes showed lower J_{nr} and higher *%R* values when compared to EABs from field mixes. This was related to the extra heating that occurred to plant mixes in the lab before the compaction process, which increased the aging of VAB and the contribution of the RAP binder in the mix. This contribution increased the interactions between RAP binder and VAB, and more aged components were exchanged between RAP and VAB. Moreover, EABs from lab mixes had higher *%R* and lower J_{nr} values when compared to EABs from plant mixes. More interactions processes between RAP binder and VAB happened in lab mixes or plant mixes than in field mixes.

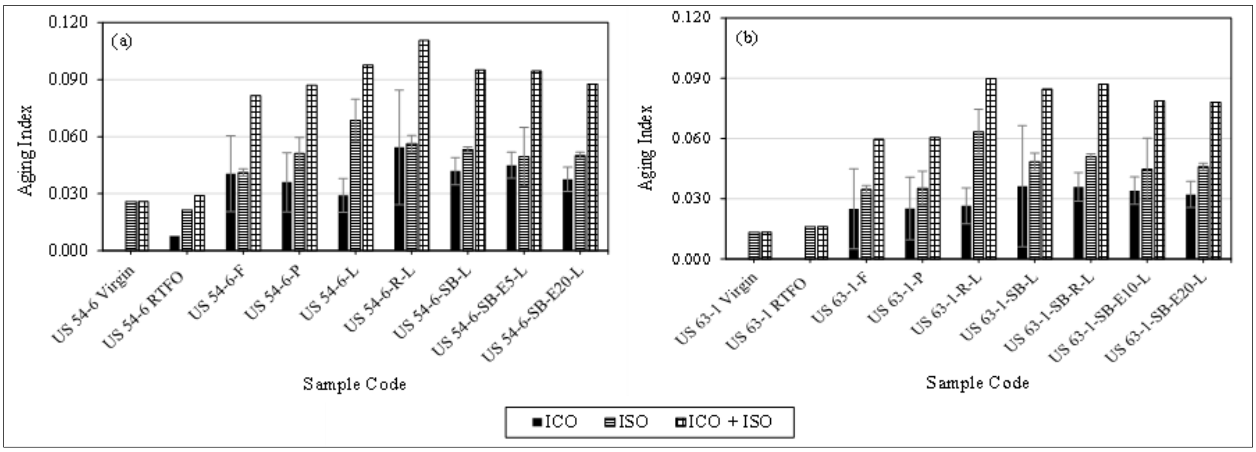

Figure 4 Aging indices for VABs, RTFO AVABs, and EABs from (a) US 54-6 and (b) US 63-1 mixes

Figure 6 shows the MSCR results, measured at 0.1 and 3.2 kPa stress levels and 60°C temperature, for RTFO AVAB and EABs from US 54-6 and US 63-1 lab mixes. The RTFO aged SB, with a PG of 46–34, was softer than RTFO aged US 63-1 virgin binder, with a PG of 58–28, or RTFO aged US 54-6 binder, with a PG of 58–28, because the RTFO aged SB had higher J_{nr} and lower *%R* values. For all lab mixes, EABs had higher stiffnesses and elasticities when compared to RTFO AVABs. This reflected the effect of the aged components in the RAP binder on increasing EABs' stiffnesses and elasticities.

From Figure 6a, adding 3% Evoflex to VAB, by the net weight of VAB, in the US 54-6-R-L2 lab mix increased the *%R* and decreased the J_{nr} for EABs when compared to EABs from a mix without Evoflex (US 54-6-L mix). Evoflex worked as a rejuvenator that enhanced the contribution of the recycled asphalt binders in asphaltic mixes [41]. This contribution increased the interactions between RAP binder and VAB, which increased the aged components in EABs (note the FTIR quantitative analysis in Figure 4). Figure 6b shows that EABs from the US 54-6-SB-L mix—containing a SB with a PG of 46–34—had lower stiffnesses and elasticities by showing higher J_{nr} and lower *%R* values than EABs from the same mix containing PG 58–28 VAB (US 54-6-L). Adding 5% or 20% ECR, by the net weight of the total binder, to VAB of the US 54-6-SB-L mix increased the stiffnesses, lower J_{nr} values, and increased the elasticities, higher *%R* values, of EABs when compared to the US 54-6-SB-L EABs. No significant difference was observed between EABs from US 54-6-SB mixes containing 5% and 20% ECR. Comparing the US 54-6-SB-L and US 63-1-SB-L EABs in Figure 6b and Figure 6d, increasing the ABR by RAP from 31% to 35% caused an increase in the stiffnesses and elasticities of EABs. Figure 6d shows that using a SB with a PG of 46–34 decreased the stiffnesses and elasticities of EABs. Using Evoflex increased the stiffnesses and elasticities of the US 63-1-SB-R-L EABs by increasing the contribution of the RAP binder in the mixes when compared to the US 63-1-SB-L EABs. This contribution increased the interactions between RAP binders and VABs. Using 10% or 20% ECR increased the stiffnesses and elasticities of EABs.

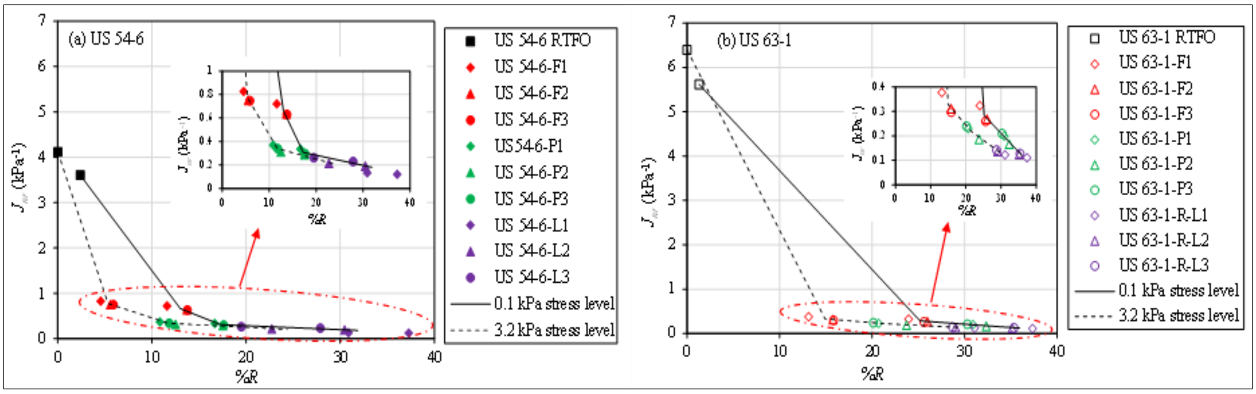

Figure 5 MSCR test results for RTFO AVABs and EABs from field, plant, and lab mixes

3.2.2. Temperature Sweep Test Results

The temperature sweep test results for RTFO AVAB and EABs from the US 54-6 field, plant, and lab mixes containing 31% ABR by RAP are presented in Figure 7a. All EABs showed higher stiffnesses, higher $|G^*|/\sin\delta$ at different temperatures than the RTFO AVABs because of the aged asphalt binder in RAP. It was noted that EABs from lab or plant mixes had higher $|G^*|/\sin\delta$ values than those of EABs from field mixes. The plant mixes were collected from behind the paver, reheated, and compacted in the lab, which increased the aging of VAB and the contribution of the RAP binder in the mix. This contribution increased the interactions between RAP binder and VAB. Furthermore, the fabrication technique, mixing and short-term aging processes, utilized in lab mixes resulted in more interactions between RAP binder and VABs than in the field mixes.

The temperature sweep test results for RTFO AVABs and EABs from US 54-6 lab mixes containing 31% ABR by RAP are illustrated in Figure 7b. Different mixes were fabricated in the lab containing rejuvenator, SB, and/or ECR. The EABs from lab mixes contained ECR had the highest $|G^*|/\sin\delta$ values. This happened because of the effect of the rubber on increasing EABs' stiffnesses and elasticities, which enhanced resistance to rutting. The EABs from mixes containing a SB with a PG of 46–34 had the lowest $|G^*|/\sin\delta$ values; however, they had higher $|G^*|/\sin\delta$ values than RTFO AVAB.

The temperature sweep test results for RTFO AVAB and EABs from the US 63-1 field, plant, and lab mixes containing 35% ABR by RAP are shown in Figure 7c. The EABs showed higher $|G^*|/\sin\delta$ values than RTFO AVAB because of the aged asphalt binder in RAP. The US 63-1 VAB was softer than the US 54-6 VAB; however, EABs from the US 63-1 mix had higher $|G^*|/\sin\delta$ values than EABs from the US 54-6 mix. This took place due to the higher ABR percentage by RAP included in the US 63-1 mix. The EABs from US 63-1 lab mixes had the highest $|G^*|/\sin\delta$ values compared to plant and field EABs. Additionally, EABs from plant mixes were stiffer than EABs from field mixes, which agreed with the MSCR and FTIR results.

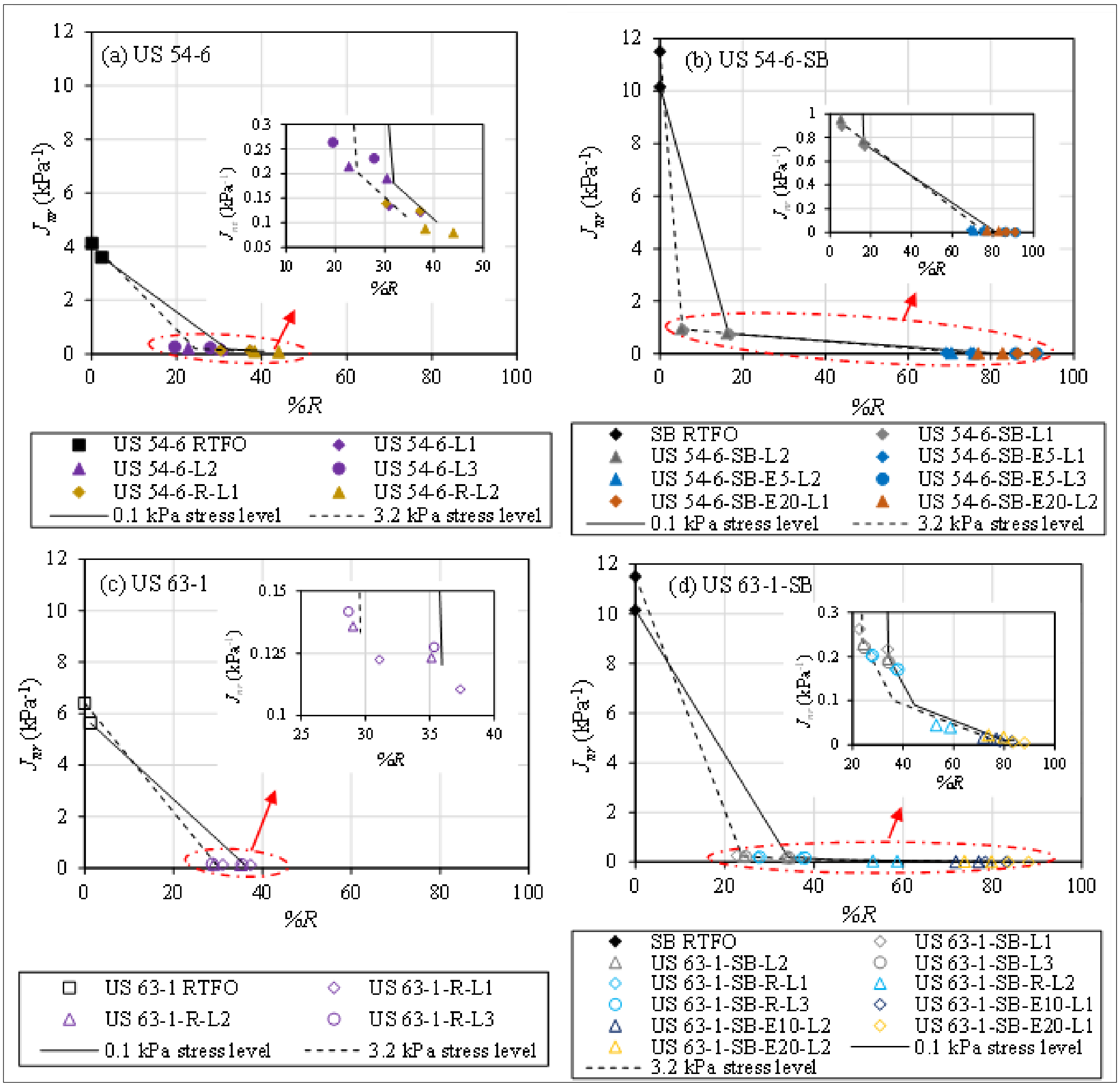

Figure 6 MSCR test results for RTFO AVABs and EABs from lab mixes

The temperature sweep test results for RTFO AVAB and EABs from US 63-1 lab mixes containing 35% ABR by RAP are presented in Figure 7d. Different mixes were fabricated in the lab containing rejuvenator, SB, and/or ECR. Using a SB with a PG of 46–34 decreased the resistance to rutting by showing the lowest $|G^*|/\sin\delta$ values for EABs when compared to EABs from the US 63-1 lab mix with PG 58–28 VAB. Adding 1.75% Evoflex to the SB increased the $|G^*|/\sin\delta$ values, which was related to the effect of the Evoflex on enhancing the RAP binder's contribution in the mix. This contribution increased the interactions between the RAP binder and VAB. Adding 10% or 20% ECR to the SB increased the $|G^*|/\sin\delta$ values due to the role of the rubber in increasing EABs' stiffnesses and elasticities. The enhanced stiffness and elasticity are shown in Figure 8. These photos were taken for EABs from a mix containing ECR (US 63-1-SB-E10-L) after measurements on the DSR. The asphalt binder's connection between the lower and upper plates showed the elastic behavior of these binders. It was difficult to clean the plates after finishing the measurement on the DSR although the temperature was raised to 94°C, which illustrated an increase in the stiffnesses of EABs. Moreover, the enhanced elasticity of EABs was proved using the thermal analysis of the originally received and extracted ECR, as discussed in the Thermal Analysis Results Section (Section 3.3).

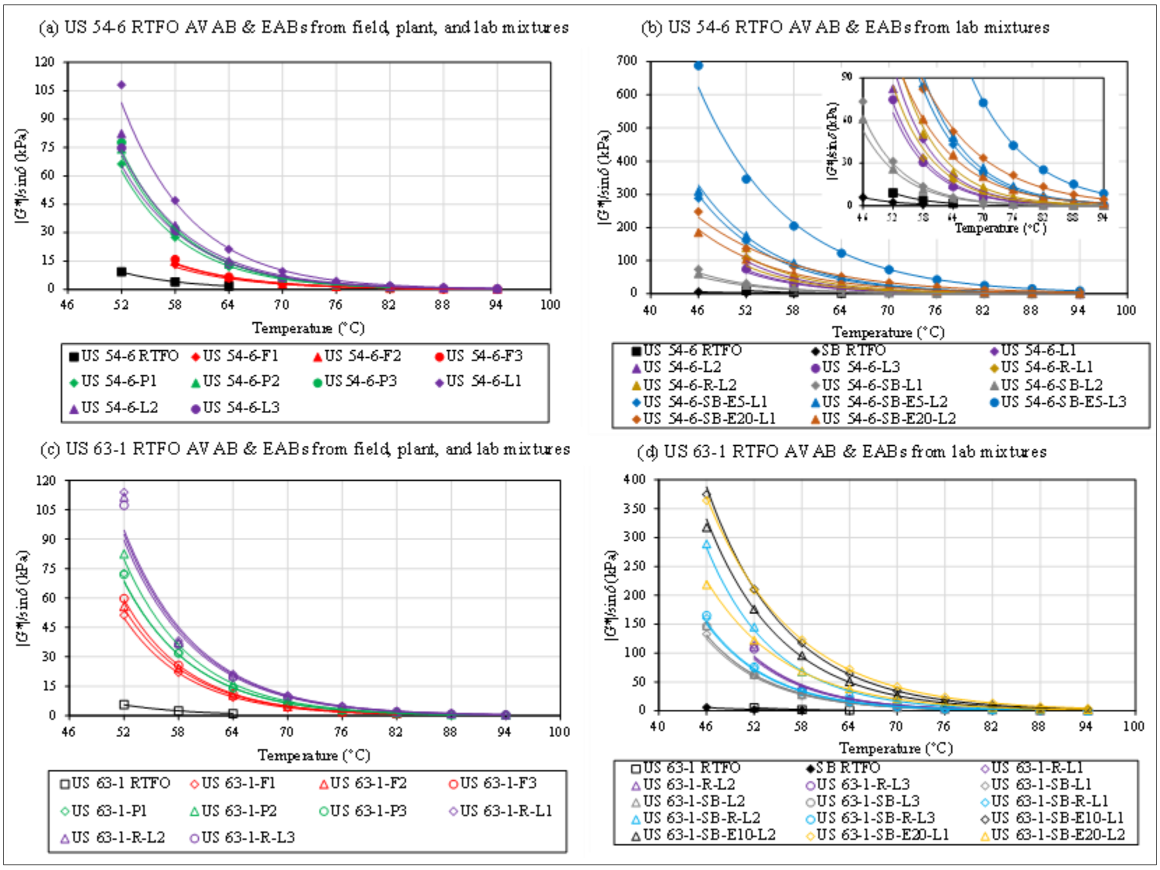

Figure 7 Temperature sweep test results for RTFO AVABs and EABs

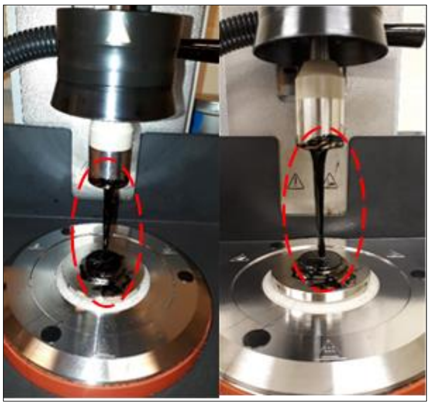

Figure 8 The elasticity of EAB from a mix containing ECR

3.2.3. Frequency Sweep Test Results

The master curves, analyzed at 60°C, for RTFO AVAB and EABs from the US 54-6 field, plant, and lab mixes are presented in Figure 9a. The EABs showed higher $|G^*|/\sin\delta$ values when compared to RTFO AVABs. The EABs from lab or plant mixes showed higher $|G^*|/\sin\delta$ values than those of EABs from field mixes. This was related to more interaction processes that took place between VAB and RAP binder in plant or lab mixes than in field mixes.

The master curves, analyzed at 60°C, for RTFO AVAB and EABs from US 54-6 lab mixes are shown in Figure 9b. The EABs from the US 54-6-L mix showed higher $|G^*|/\sin\delta$ values than RTFO AVAB because of the aged binder included in the RAP. For EABs from the US 54-6-R-L, adding 3% Evoflex to VAB increased the $|G^*|/\sin\delta$ values of EABs because Evoflex increased the interaction processes between VAB and RAP binder. Using a SB, PG 46–34, reduced EABs' $|G^*|/\sin\delta$ values; however, these values were higher than those of RTFO AVAB. Adding 5% or 20% ECR to the SB increased EABs' $|G^*|/\sin\delta$ values. This increase in $|G^*|/\sin\delta$ values occurred because of the effect of the rubber particles on increasing the stiffnesses and elasticities of EABs. The rubber particles released polymeric components in the asphalt binder's matrix [38, 43], which increased the stiffnesses and elasticities of asphalt binders. These findings were proved in the Thermal Analysis Results for ECR Section (Section 3.3.2).

Figure 9c depicts the master curves, analyzed at 60°C, for RTFO AVAB and EABs from the US 63-1 field, plant, and lab mixes. The EABs showed higher $|G^*|/\sin\delta$ values when compared to RTFO AVABs. The EABs from lab or plant mixes had higher $|G^*|/\sin\delta$ values than EABs from field mixes. More interaction processes occurred between the RAP binder and the VAB in plant or lab mixes than in field mixes. The difference in the $|G^*|/\sin\delta$ values between the US 63-1 RTFO AVAB and EABs was higher than that obtained between the US 54-6 RTFO AVAB and EABs because of the higher percentage of ABR by RAP in the US 63-1 mix. However, the US 63-1 VAB was softer than the US 54-6 VAB.

Figure 9d presents the master curves, analyzed at 60°C, for RTFO AVABs and EABs from US 63-1 lab mixes. The EABs from the US 63-1-R-L mix had higher $|G^*|/\sin\delta$ values than those of RTFO AVAB because of the aged asphalt binder in RAP. Using a SB with a PG of 46–34 reduced the $|G^*|/\sin\delta$ values of EABs when compared to EABs from a mix containing VAB with a PG of 58–28. Adding 1.75% Evoflex to SB increased the $|G^*|/\sin\delta$ values of EABs than those of EABs from the same mix without Evoflex. This was related to the effect of the Evoflex on enhancing the contribution of the RAP binder in the mixes, which increased the interactions between the RAP binder and VAB. Adding 10% or 20% ECR to SB increased $|G^*|/\sin\delta$ of EABs to the highest values.

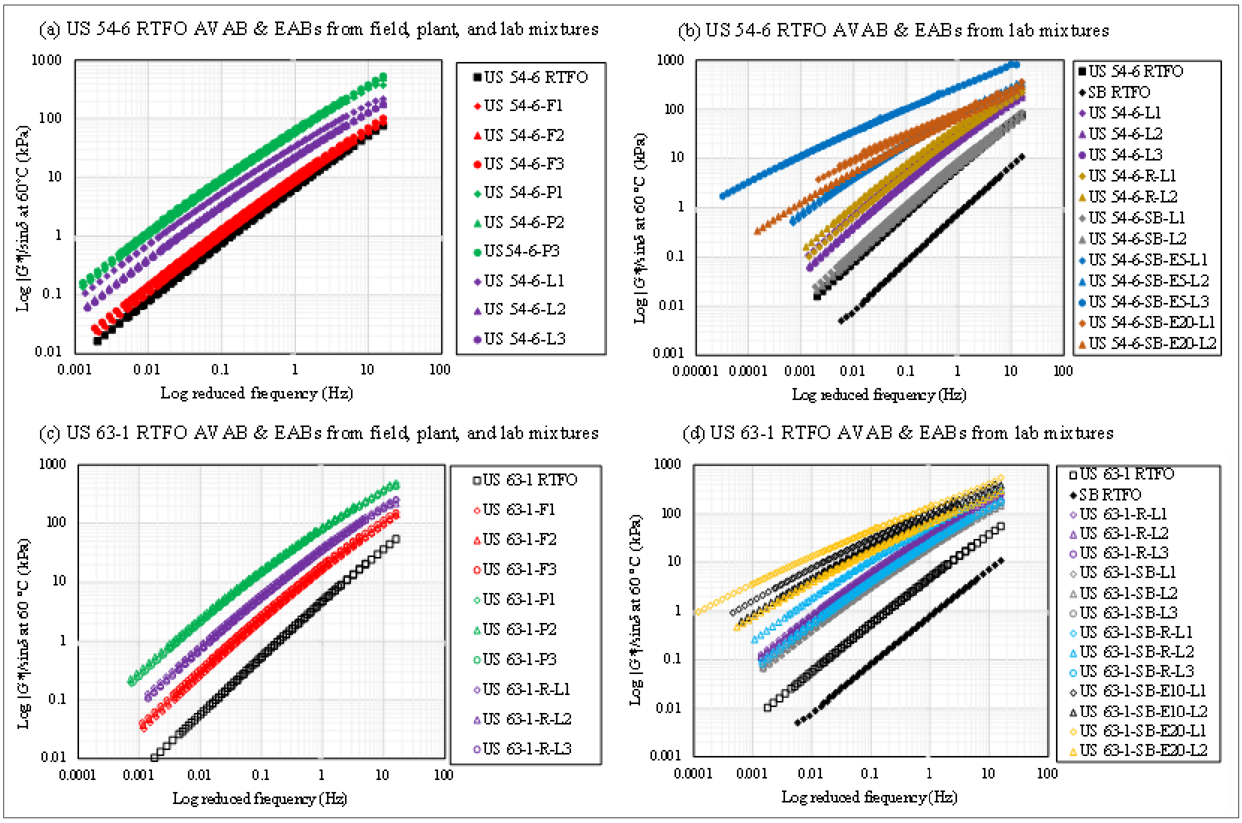

Figure 9 Master curves for RTFO AVABs and EABs

3.3. Thermal Analysis Results

3.3.1. Thermal Analysis Results for Asphalt Binders

The TGA results discussed in this section reflected the TGs and DTGs of VABs, RTFO AVABs, and EABs. Figure 10 depicts TGA results for VAB, RTFO AVAB, and EABs from the US 54-6 lab, plant, and field mixes. Derivative of thermographs showed three regions for the VAB and RTFO AVAB. However, for EABs, the second region started to disappear. As discussed in the introduction, the asphaltene had one peak in the DTG; however, the maltene presented two peaks. Thus, disappearing the second region in the DTG reflected a decrease in the maltene component of EABs [24].

The TGs and DTGs' parameters were estimated and presented in Table 3. All EABs had higher residue percentages than RTFO AVAB, which reflected a higher asphaltene content. The EABs had higher T_{onset} values than the RTFO AVABs, which indicated higher stiffnesses. The highest T_{onset}, T_{endset}, T_1, T_2, and residue percentages were noted for EABs from plant mixes. The EABs from field mixes had the lowest T_{onset}, T_{endset}, T_1, and T_2, when compared to other EABs. These findings agreed with the rheological results: EABs from plant or lab mixes were the stiffest and EABs from field mixes were the softest.

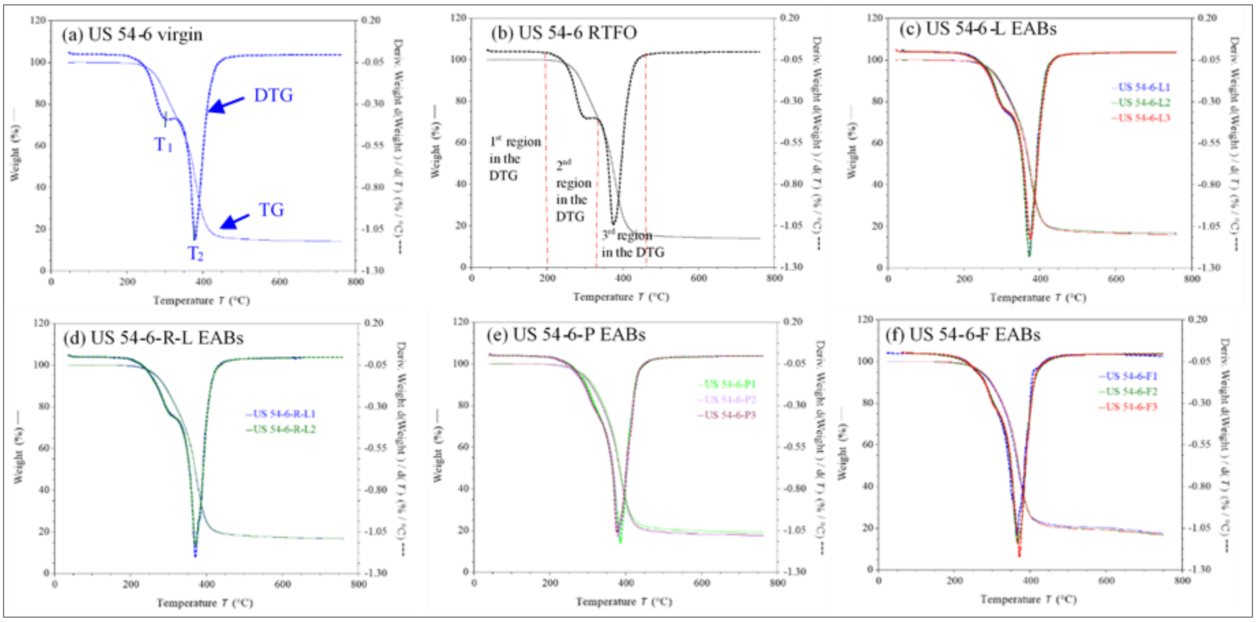

Figure 10 TGs and DTGs of VAB, RTFO AVAB, and EABs from the US 54-6 lab, plant, and field mixes

Table 3 TGs and DTGs analyses for VAB, RTFO AVAB, and EABs from the US 54-6 lab, plant, and field mixes

Binder	TG Parameters			DTG Parameters	
	T_{onset} (°C)	T_{endset} (°C)	Residue at 750°C (%)	T_1^a (°C)	T_2^a (°C)
US 54-6 virgin	326.50	406.73	14.15	298.70	378.96
US 54-6 RTFO	323.03	406.54	13.90	298.59	375.01
US 54-6-L1	328.10	398.51	16.66	299.41	372.83
US 54-6-L2	328.89	398.45	16.71	298.66	372.08
US 54-6-L3	326.75	402.13	15.98	296.59	375.73
US 54-6-R-L1	325.91	398.95	16.67	297.22	371.70
US 54-6-R-L2	324.94	399.92	16.70	302.22	372.02
US 54-6-P1	338.66	413.21	19.10	314.25	385.78
US 54-6-P2	335.82	413.37	17.20	313.44	381.10
US 54-6-P3	334.86	413.17	17.84	314.11	378.11
US 54-6-F1	318.66	394.15	17.65	297.46	365.06
US 54-6-F2	324.30	395.25	16.85	302.11	365.23
US 54-6-F3	326.47	395.03	17.00	299.37	372.82

[a] T_1 and T_2 are the temperatures corresponding to the first and second peaks in DTG, respectively (note Figure 10a)

Figure 11 shows TGA results for SB virgin, SB RTFO, and EABs from US 54-6-SB lab mixes. Derivative of thermograph showed three regions for VAB, RTFO AVAB, and EABs. However, for EABs from the US 54-6-SB-E20-L, the second region started to disappear (note Figure 11e). The high percentage of ECR, 20% by the weight of the total binder, decreased the low aromatic fractions in the asphalt binder. The rubber particles absorbed the low-molecular-weight components in the asphalt binders during the swelling process, then the rubber particles released the polymeric components in the asphalt binder's matrix [38, 43]. These polymeric components increased the binders' stiffnesses and elasticities, which agreed with the MSCR test results. More details were explained in the Thermal Analysis Results for ECR Section (Section 3.3.2). Note that the EABs from lab mixes containing ECR had the lowest T_{onset} when compared to other EABs (see Table 4). These findings agreed with the FTIR results: ECR decreased the FTIR aging indices. Using virgin SB decreased the T_{onset} of EABs than EABs from mixes with a stiffer asphalt binder (PG 58−28). These findings agreed with the rheological results.

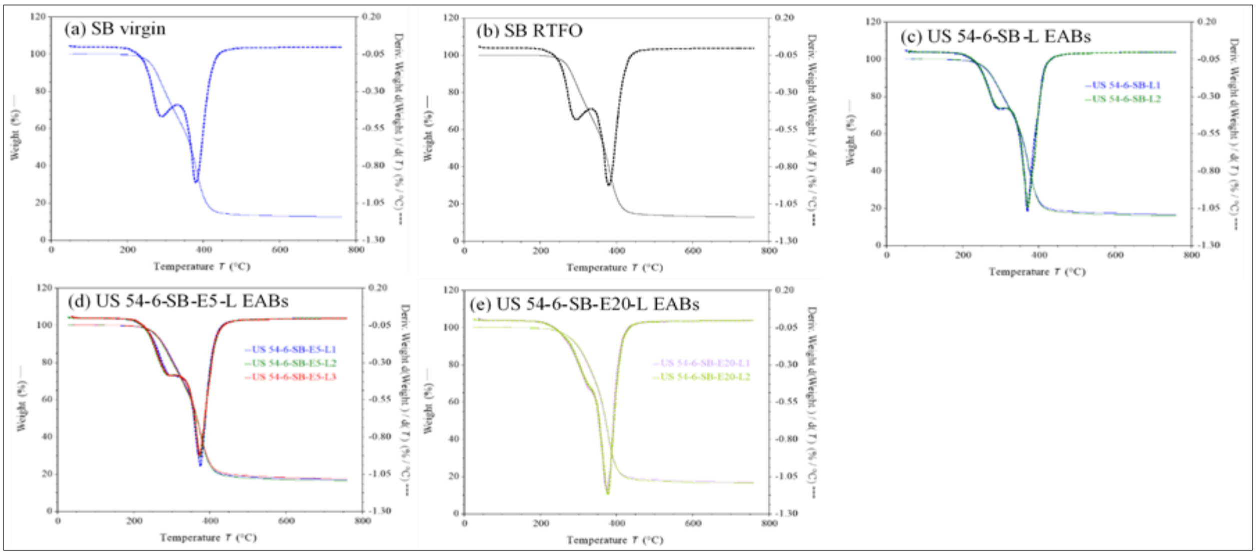

Figure 11 TGs and DTGs of VAB, RTFO AVAB, and EABs from the US 54-6-SB lab mixes.

Table 4 TGs and DTGs analyses for VAB, RTFO AVAB, and EABs from the US 54-6-SB lab mixes

Binder	TG Parameters			DTG Parameters	
	T_{onset} (°C)	T_{endset} (°C)	Residue at 750°C (%)	T_1 (°C)	T_2 (°C)
SB virgin	311.34	409.33	12.50	289.74	380.21
SB RTFO	312.87	408.86	12.99	293.88	380.10
US 54-6-SB-L1	314.99	397.77	16.73	285.60	370.58
US 54-6-SB-L2	315.88	399.65	15.94	285.32	370.63
US 54-6-SB-E5-L1	313.51	400.28	17.06	289.96	374.42
US 54-6-SB-E5-L2	309.38	402.11	16.33	284.73	374.65
US 54-6-SB-E5-L3	309.39	402.18	17.47	287.73	372.45
US 54-6-SB-E20-L1	312.65	399.41	16.96	324.82	375.03
US 54-6-SB-E20-L2	310.25	400.68	16.32	321.90	376.82

Figure 12 displays the TGA results for VAB, RTFO AVAB, and EABs from the US 63-1 lab, plant, and field mixes. Derivative of thermographs showed three regions for VAB, RTFO AVAB, and EABs from lab mixes. However, for EABs from plant and field mixes, the second region disappeared (note Figure 12d and Figure 12e). The strongest manifestation of the second region was noted for the US 63-1-R-L EABs (Figure 12c) due to the existence of Evotherm, a warm mix additive. The highest T_{onset} values were recorded for EABs from plant mixes, which reflected the highest stiffnesses of these binders, note Table 5. The EABs from lab or field mixes had lower T_{onset} values than RTFO AVAB, which was related to the effect of rejuvenators (0.5% Evotherm and 1.75% Evoflex). The T_{onset} values for the Evoflex and Evotherm were 226.75°C and 295.61°C respectively, note Figure 13. However, EABs from lab and field mixes had higher stiffnesses when compared to RTFO AVABs that were returned to the higher residue percentages for EABs, note Table 5. Increasing the residue percentages reflected the increase in the asphaltene fraction of EABs that resulted from the aging components in the RAP binder. The EABs from plant mixes had higher T_{onset} values and residue percentages than RTFO AVAB because the reheating process before compaction in the lab increased the aging process of VAB and interaction processes between RAP binder and VAB.

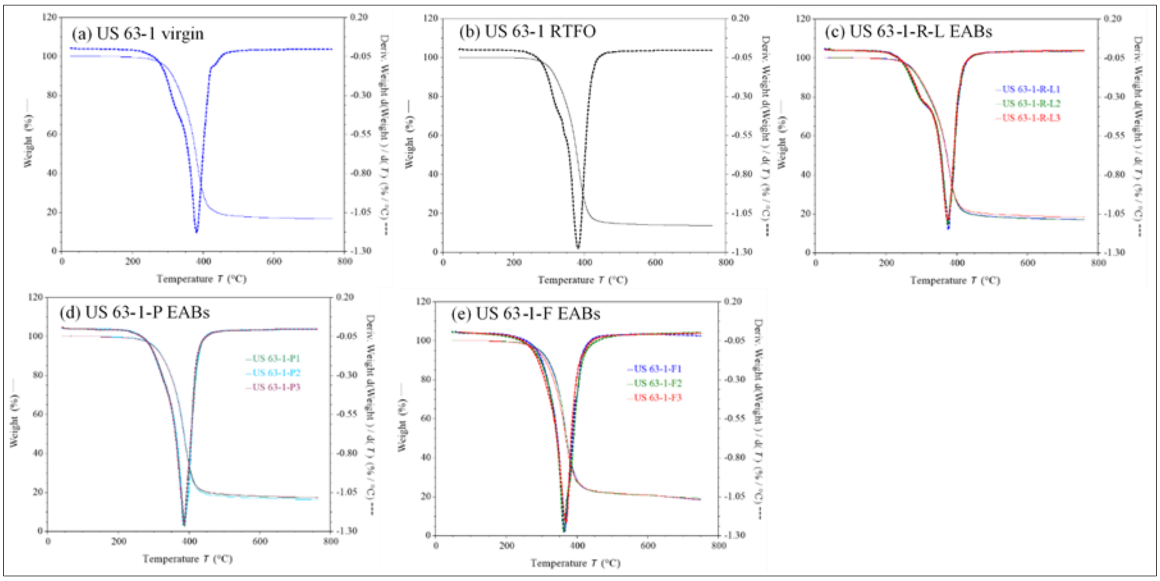

Figure 12 TGs and DTGs of VAB, RTFO AVAB, and EABs from the US 63-1 lab, plant, and field mixes

Table 5 TGs and DTGs analyses for VAB, RTFO AVAB, and EABs from the US 63-1 lab, plant, and field mixes

Binder	**TG Parameters**			**DTG Parameters**	
	T_{onset} (°C)	**T_{endset} (°C)**	**Residue at 750°C (%)**	**T_1 (°C)**	**T_2 (°C)**
US 63-1 virgin	336.45	407.64	16.44	318.53	381.87
US 63-1 RTFO	339.55	407.52	13.69	316.63	382.93
US 63-1-R-L1	326.32	401.25	17.15	299.66	376.93
US 63-1-R-L2	324.78	401.51	16.02	296.59	374.61
US 63-1-R-L3	324.64	400.34	18.38	300.04	374.93
US 63-1-P1	345.22	412.50	17.03	-	387.82
US 63-1-P2	345.54	412.51	16.21	-	384.75
US 63-1-P3	343.85	411.18	17.42	-	386.52
US 63-1-F1	331.38	392.56	18.30	-	364.93
US 63-1-F2	331.28	391.90	19.00	-	363.02
US 63-1-F3	326.90	391.52	18.50	-	368.24

Figure 14 illustrates TGA results for VAB, SB RTFO, and EABs from US 63-1-SB lab mixes. Derivative of thermographs deemed three regions for VAB, RTFO AVAB, and EABs. The VAB and RTFO AVAB had lower T_{onset} values and residue percentages (see Table 6) when compared to those of the US 63-1 VAB and RTFO AVAB, note Table 5. This represented that SB had a higher maltene fraction and a lower asphaltene fraction than those of the US 63-1 VAB. The EABs had higher residue percentages and T_{onset} values than SB RTFO because of the aged binder included in RAP. The US 63-1-SB-R-L EABs had a higher residue percentage than the US 63-1-SB-L EABs because of the Evoflex effect on increasing the interactions between RAP binder and VAB. The lowest T_{onset} values were noted for EABs from the US 63-1-SB-E20-L; however, they contained the highest residue percentages with an average value of 18.25%, as presented in Table 6. The ECR's polymeric components decreased the FTIR aging indices and T_{onset} values; however, the undissolved part of ECR's particles, carbon black and ash, increased the residue percentages detected by TGA. More details were discussed in the Thermal Analysis Results for ECR Section (Section 3.3.2).

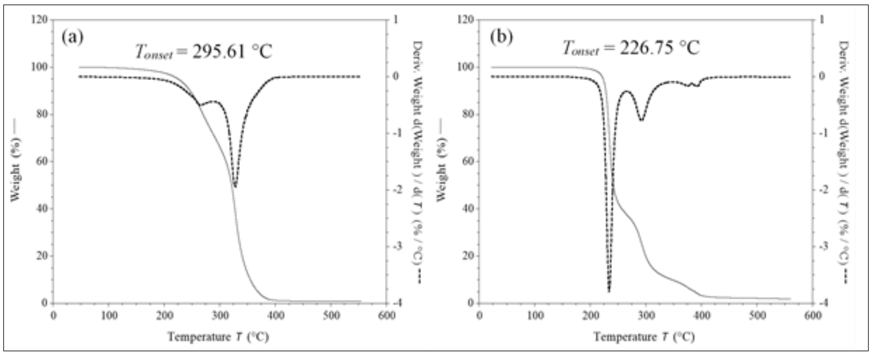

Figure 13 TGs and DTGs of (a) Evotherm and (b) Evoflex

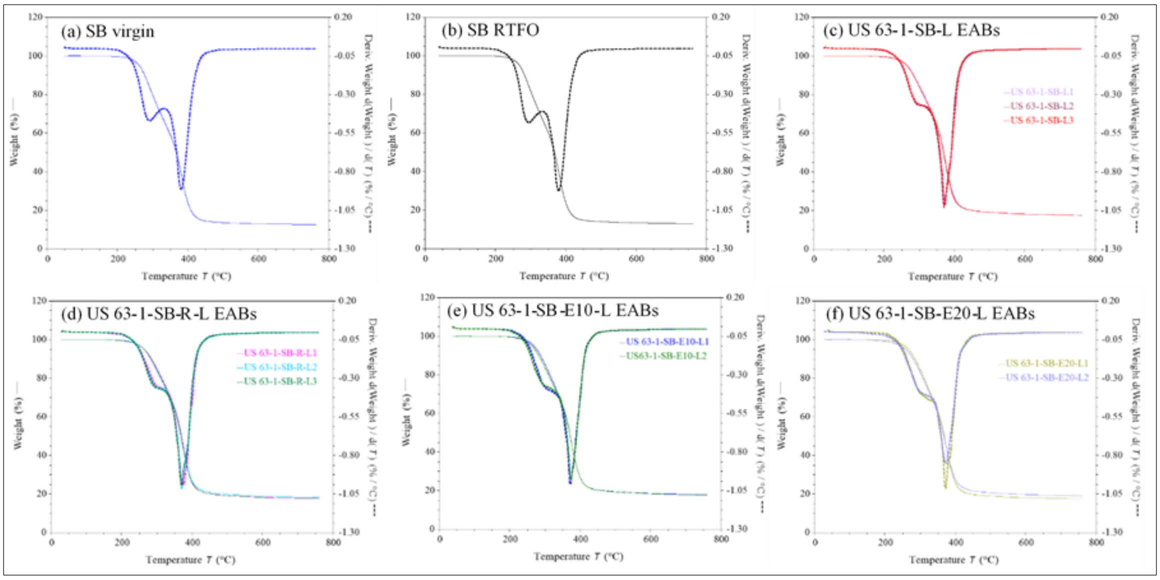

Figure 14 TGs and DTGs of VAB, RTFO AVAB, and EABs from the US 63-1-SB lab mixes

Table 6 TGs and DTGs analyses for VAB, RTFO AVAB, and EABs from the US 63-1-SB lab mixes

Binder	TG Parameters			DTG Parameters	
	T_{onset} (°C)	T_{endset} (°C)	Residue at 750°C (%)	T_1 (°C)	T_2 (°C)
SB virgin	311.34	409.33	12.50	289.74	380.21
SB RTFO	312.87	408.86	12.99	293.88	380.10
US 63-1-SB-L1	316.40	402.44	17.41	288.11	372.91
US 63-1-SB-L2	317.12	400.90	17.57	288.85	370.56
US 63-1-SB-L3	317.44	402.27	17.51	288.26	372.00
US 63-1-SB-R-L1	318.27	402.32	17.79	294.52	372.85
US 63-1-SB-R-L2	315.99	401.08	18.34	290.75	370.63
US 63-1-SB-R-L3	314.62	401.26	17.60	289.20	369.55
US 63-1-SB-E10-L1	317.51	402.33	17.93	294.89	371.78

US 63-1-SB-E10-L2	315.38	403.39	17.71	289.59	373.99
US 63-1-SB-E20-L1	314.88	401.84	17.52	294.64	372.05
US 63-1-SB-E20-L2	306.67	403.10	18.98	296.36	372.69

3.3.2. Thermal Analysis Results for ECR

The ECR's components were investigated using TGA before, originally received, and after the extraction process from lab mixes. The rubber components investigated by other researchers [38, 43–45] were the oily components, natural rubber (NR), synthetic rubber (SR), and filler. Two peaks were observed in the DTG for the originally received ECR, note Figure 15a. The first peak at 314.35°C was related to the natural rubber and the second peak at 357.72°C was for the synthetic rubber. The different decomposition temperature range of each component in the ECR was obtained from other studies [44–46]. The volatiles and oily components decomposed up to 300°C, the NR decomposed from 300°C to the minimum point between the two peaks in the DTG curve (334.47°C), and the SR decomposed from the minimum point between the two peaks in the DTG curve (334.47°C) to 500°C. Finally, the remaining component of the ECR was related to the filler (carbon black and ash).

Figure 15a shows the components of the originally received ECR; these components were 12.30% for the oily components, 23.21% for the NR, 26.44% for the SR, and 38.05% for the filler. Figure 15b depicts a comparison between the originally received and extracted ECR. The extracted ECR were collected from the US 54-6-SB-E20-L and the US 63-1-SB-E20-L; both samples included 20% ECR. The enhanced elasticities of EABs from lab mixes contained ECR was related to the ECR's polymeric components released in the asphalt binder's matrix. Based on the average results in Figure 15b, the extracted ECR had a decrease in the oily components by 88%, a decrease in the NR component by 85%, a decrease in the SR component by 65%, and an increase in the filler component by 126%.

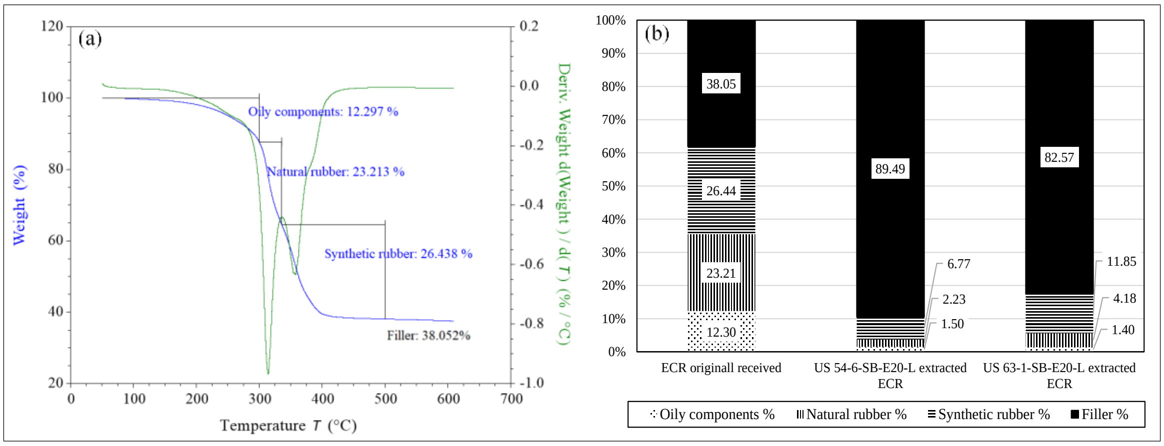

Figure 15 (a) TGA results for the originally received ECR and (b) Components of originally received and extracted ECRs

4. Conclusion

Interactions between reclaimed asphalt pavement (RAP) and virgin asphalt binders (VABs) were investigated in this study. Thus, asphalt binders were extracted from field, plant, and lab mixes containing high asphalt binder replacement (ABR) percentage by RAP, greater than 30%. The plant mixes were collected from behind the paver, reheated to the compaction temperature, and compacted in the lab. The field mixes were collected as cores within two weeks after the end of the construction process. The lab mixes were fabricated in the lab using the same materials and proportions of the plant and field mixes. Variations were followed for some lab mixes by using a softer binder (SB) with a performance grade of 46−34 and additives like engineered crumb rubber (ECR). The extracted asphalt binders (EABs) from these mixes and the corresponding rolling thin film oven aged virgin asphalt binders (RTFO AVABs) were evaluated through rheological testing, Fourier transform infrared (FTIR) spectroscopy analyses, and thermal analysis using thermogravimetric analysis (TGA). Based on this study, the following points were concluded:

- The EABs from plant or lab mixes were stiffer than EABs from field mixes. Reheating plant mixes in the lab to the compaction temperature before the compaction caused additional aging in VABs and increased RAP binder's contribution in the mix, which increased the interactions between RAP binder and VAB. The fabrication process followed in lab mixes revealed more interactions between RAP binder and VAB when compared to interactions that occurred in field mixes.

- Evoflex, a rejuvenator, enhanced the contribution of the RAP binder in the mix by increasing the interaction between the RAP binder and VAB.
- Increasing the ABR percentage by RAP increased the interactions between the RAP binder and VAB.
- Using a SB balanced the effect of aged RAP binder in asphalt mixes, and the ECR promoted the sustainability of mixes containing RAP. The SB reduced the stiffness effect of the aged components in the RAP binder. The ECR absorbed the low-molecular-weight components in the SB, swelled, and released the polymeric components in the asphalt binder's matrix that increased EABs' stiffnesses and elasticities.
- The ECR's released polymeric components decreased the aging indices—detected by FTIR—and reduced onset temperatures, as explored by TGA.

Compliance with ethical standards

Acknowledgments

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Disclosure of conflict of interest

All authors declare that they have no conflicts of interest.

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