07 Mar 2022

Components’ Exchanges between Recycled Materials and Asphalt Binders in Asphalt Mixes

Eslam Deef-Allah

Magdy Abdelrahman
Missouri University of Science and Technology, abdelrahmanm@mst.edu

Mohyeldin Ragab

Recommended Citation

E. Deef-Allah et al., "Components’ Exchanges between Recycled Materials and Asphalt Binders in Asphalt Mixes," *Advances in Civil Engineering Materials*, vol. 11, no. 1, pp. 94 - 114, ASTM International, Mar 2022.
The definitive version is available at https://doi.org/10.1520/ACEM20210105

Advances in Civil Engineering Materials

Eslam Deef-Allah,[1] Magdy Abdelrahman,[2] and Mohyeldin Ragab[3]

DOI: 10.1520/ACEM20210105

Components' Exchanges between Recycled Materials and Asphalt Binders in Asphalt Mixes

VOL. 11 / NO. 1 / 2022

doi:10.1520/ACEM20210105 / Vol. 11 / No. 1 / 2022 / available online at www.astm.org

Eslam Deef-Allah,[1] Magdy Abdelrahman,[2] and Mohyeldin Ragab[3]

Components' Exchanges between Recycled Materials and Asphalt Binders in Asphalt Mixes

Reference

E. Deef-Allah, M. Abdelrahman, and M. Ragab, "Components' Exchanges between Recycled Materials and Asphalt Binders in Asphalt Mixes," *Advances in Civil Engineering Materials* 11, no. 1 (2022): 94–114. https://doi.org/10.1520/ACEM20210105

ABSTRACT

The focus of this study was to explore the components' exchanges between recycled asphalt shingles (RAS) or reclaimed asphalt pavement (RAP) and virgin asphalt binders (VABs) in the asphalt mixes and to establish their effect on the rutting resistance of the extracted asphalt binders (EABs). Twelve plant mixes and twelve field mixes were gathered as examples of four Superpave mixes containing RAP or RAS. The plant mixes were reheated and compacted in the lab. The field mixes were collected as cores within 2 weeks after the ending of the construction process. The exchanged components were investigated using Fourier transform infrared (FTIR) spectroscopy and with the asphalts' components analyses. The FTIR indexes for the EABs from the plant mixes showed more aging components than the FTIR indexes for the EABs from the field mixes. More asphaltenes plus resins and fewer saturates plus aromatics were observed for the EABs from the plant mixes when compared twith the EABs from the field mixes. The FTIR spectra of the EABs from plant mixes containing RAS showed the styrene butadiene styrene (SBS) components, which were not observed for the field mixes' EABs. The SBS polymeric components in the EABs from the plant mixes formed three-dimensional network structures that increased the EABs' stiffness and elasticity characteristics. These components evolved the rutting resistances of EABs. Reheating the plant mixes in the lab before the compaction process increased the blending and components' exchanges between RAP/RAS and VABs.

Keywords

components' exchanges, recycled materials, extraction and recovery, rutting resistance, asphalt components, Fourier transform infrared, RAP, RAS

Manuscript received August 19, 2021; accepted for publication January 31, 2022; published online March 7, 2022. Issue published March 7, 2022.

[1] Department of Civil, Architectural and Environmental Engineering, Missouri University of Science and Technology, Butler-Carlton Hall, 1401 N. Pine St., Rolla, MO 65409, USA (Corresponding author), e-mail: emddkc@mst.edu, https://orcid.org/0000-0003-1405-8257

[2] Department of Civil, Architectural and Environmental Engineering, Missouri University of Science and Technology, Butler-Carlton Hall, 1401 N. Pine St., Rolla, MO 65409, USA

[3] Research and Technology at Pure Asphalt Company, 3455 W. 31st St., Chicago, IL 60623, USA

Introduction

The use of reclaimed asphalt pavement (RAP) or recycled asphalt shingles (RAS) in the asphalt mixes reduced the demand for natural resources and reduced the emissions during the production process.[1,2] RAP consists of aggregates and aged asphalt binders.[3–5] RAS generally contain oxidized air-blown asphalt binder percentages between 19 and 36 % by weight.[6] Typically, a RAS asphalt binder content is five times more than the asphalt binder content in RAP.[7] During the shingles' production process, styrene butadiene styrene (SBS) was added to the asphalt to increase the shingles' durability under various weather conditions.[8,9] The main issue with using RAS in asphaltic mixes was the high stiffness level of the asphalt components.[7] The percentage of asphaltene increased, and the percentages of oil and resin constituents decreased during the air-blown process of the asphalt flux.[10,11] Two basic types of shingles, namely, manufactured waste and tear-off, are allowed to be used in asphalt mixes.[12,13] The oxidation effect in the tear-off shingles caused a stiffer extracted asphalt binder (EAB) property when compared with the EAB from the manufactured waste shingles.[7,14] The average high-performance grade (PG) temperatures for EABs from the manufactured waste and tear-off shingles were 130°C and 178°C, respectively.[6,14]

It was reported that the properties of RAP binders in Massachusetts could not be categorized regionally because they varied between stockpiles and seasons.[15] This variability was due to the aging processes that occurred in the asphalt binders. 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 atmosphere.[3,5] The high PG temperatures for the EABs from different sources of RAP were between 76°C and 94°C.[15,16] Alavi et al.[2] collected three RAP sources from three plants in California and evaluated the properties of the EABs. The high PG temperatures for the extracted RAP binders were between 82°C and 88°C. This indicated that the EABs from RAP were aged, but they were less stiff than the RAS binders. The EABs from asphalt mixes—containing a virgin asphalt binder (VAB) with a PG of 58–28 and recycled binder percentage of 30–35 % by RAP—yielded a high PG temperature of 70°C.[17] For mixes that included recycled binder percentages of 30–35 % by RAP and RAS, the EABs yielded increased high PG temperature, reaching 76°C. This illustrated that using both RAP and RAS increased the stiffness of the EABs when compared with EABs from mixes containing the same percentages by RAP only.[17]

The components exchanged between recycled materials and VABs altered the performances of modified asphalt binders as demonstrated in previous studies.[18–21] However, the components' exchanges between RAP/RAS and VABs were not understood; therefore, the main objective of this paper was to explore the effect of the components' exchanges in the asphalt mixes on the rutting resistance of the EABs. The goal was met by conducting Fourier transform infrared (FTIR) analyses for the EABs and by evaluating the high-temperature performances of these binders. This objective's outcome was realized by comparing the high-temperature performance of the EABs from mixes containing RAP or RAS with the short-term aged virgin asphalt binders (AVABs). Furthermore, the interrupted shear flow test was conducted to identify the effect of the components' exchanges on the three-dimensional (3-D) network structures' formations. The components' exchanges could alter the EABs' compositions when compared with the compositions of binders before extraction. Thus, the asphalts' compositions were analyzed before and after the extraction.

Materials and Experimental Program

MATERIALS

Four asphalt mixes were designed following Superpave, and each mix was mixed in a drum-mix plant. The plant was located near the intersection of Lakeside Rd. and US 54, near Lakeland, Missouri. Twelve plant mixes were sampled from behind the paver during the construction process; these plant mixes represented four asphalt mixes, as shown in **Table 1**. The plant mixes were reheated to 100°C±5°C in the lab before separation, then they were reheated to the compaction temperature specified in the job mix formula (JMF) and compacted using Superpave gyratory. The compaction temperatures were 130°C, 135°C, and 154°C for the US 63-1, US 54, and MO 13-1 mixes, respectively.

TABLE 1

Asphalt mixes information

Mix Number	Plant Mixes' Codes	Field Mixes' Codes	Route/ Dir	Location (County)	ABR % by RAP-RAS	Total AC, %	VABs' PG	NMAS, mm	Additives
1	MO 13-1-A-P MO 13-1-B-P MO 13-1-C-P	MO 13-1-I-F MO 13-1-II-F MO 13-1-III-F	MO 13 NB	S. of Clinton (Henry)	17-0	5.7	64–22H	9.5	0.5 % Morelife T280[a]
2	US 54-6-A-P US 54-6-B-P US54-6-C-P	US 54-6-I-F US 54-6-II-F US54-6-III-F	US 54 NB	N. of Osage Beach (Miller)	31-0	5.1	58–28	12.5	1.0 % Morelife T280[a]
3	US 54-1-A-P US 54-1-B-P US 54-1-C-P	US 54-1-I-F US 54-1-II-F US 54-1-III-F	US 54 SB		0-33	5.2			2.5 % IPC-70,[b] 3.5 % PC 2106,[c] and 1.5 % Morelife T280[a]
4	US 63-1-A-P US 63-1-B-P US 63-1-C-P	US 63-1-I-F US 63-1-II-F US 63-1-III-F	US 63 SB	S. of Moberly (Randolph)	35-0	5.1	58–28	12.5	0.5 % Evotherm[d] and 1.75 % Evoflex CA[e]

Note: [a,b] Anti-stripping agents. [c,d] Warm-mix additives. [e] Rejuvenator additive. Dir-direction; S.-south; and N.-north.

Twelve field mixes were collected as cores within 2 weeks after the ending of the construction process; the field mixes represented the same four asphalt mixes shown in Table 1. The four asphalt mixes contained either RAP or RAS; three mixes contained RAP, and one mix contained RAS. The asphalt binder replacement (ABR) by RAP or RAS is presented in Table 1. Additionally, the total asphalt content (AC) percentage by total mass including the VABs and binders in recycled materials (as expressed in the JMF), VABs' PG, nominal maximum aggregate size (NMAS), and additives used in these mixes are illustrated in Table 1. The PG of the VAB used in the US 54 and US 63-1 mixes was 58–28. The viscosity of the US 63-1 VAB (0.215 Pa.s) was lower than that of the US 54 VAB (0.293 Pa.s) at 135°C. The MO 13-1 mix contained VAB with a PG of 64–22H and a viscosity of 0.661 Pa.s at 135°C. The mixes' codes used the road names (e.g., MO 13), section numbers (e.g., 1), coding systems (e.g., A, B, and C for plant and I, II, and III for field mixes), and mix types (e.g., F: field and P: plant).

EXPERIMENTAL PROGRAM

Extraction and Recovery of Asphalt Binders from Asphaltic Mixes

The centrifuge extraction process for asphalt binders from mixes was performed according to ASTM D2172/D2172M-17e1, discussed as method A, *Standard Test Methods for Quantitative Extraction of Asphalt Binder from Asphalt Mixtures*.[22] The trichloroethylene (TCE) solvent was used to extract the asphalt binder from the asphaltic mixes using a centrifuge extractor. Asphalt binders were recovered from the asphalt binder-TCE solutions using a rotavap following ASTM D5404/D5404M-12(2017), *Standard Practice for Recovery of Asphalt from Solution Using the Rotary Evaporator*.[23]

Short-Term Aging Process for VABs

The process of short-term aging was carried out according to ASTM D2872-19, *Standard Test Method for Effect of Heat and Air on a Moving Film of Asphalt (Rolling Thin-Film Oven Test)*,[24] for the VABs using a rolling thin-film oven (RTFO) device. The VABs were collected from the plant before adding additives. These binders had different PGs (e.g., PG 58–28 or PG 64–22H), note Table 1.

FTIR Spectroscopy Analysis

A Nicolet iS50 FTIR spectrometer was used to analyze molecules' vibrations in TCE and asphalt binders. The components' exchanges between RAP/RAS and VABs were explored by qualitative and quantitative FTIR analyses. Attenuated total reflection mode was used by laying the samples on a diamond crystal. The experimental

setup was implemented by applying 32 number scans at a resolution of 4 and using wavenumbers ranging from 4,000 to 400 cm^{-1}.

Evaluating the Asphalt Binders' Rutting Resistance

A dynamic shear rheometer (DSR) was used to evaluate the rutting resistance of the RTFO AVABs and EABs. The EABs were treated as RTFO aged asphalt binders. Therefore, asphalt binder samples with thicknesses of 1 mm and 25 mm in diameter were investigated.

High PG and Continuous Grade Temperatures

The high PG and continuous grade temperatures were evaluated for the RTFO AVABs and EABs. The ASTM D7175-15 specification, *Standard Test Method for Determining the Rheological Properties of Asphalt Binder Using a Dynamic Shear Rheometer*,[25] was followed for RTFO AVABs and EABs from the US 54 and US 63-1 mixes. AASHTO M 332, *Standard Specification for Performance-Graded Asphalt Binder Using Multiple Stress Creep Recovery (MSCR) Test*,[26] was followed for RTFO AVAB and EABs from the MO 13-1 mix because the VAB included in this mix presented the PG using multiple stress creep and recovery (MSCR) tests.

Frequency Sweep Testing

Various temperatures (58°C, 64°C, and 70°C) were used with various frequencies (15.9 to 0.016 Hz) to measure the rutting parameter ($|G^*|/\sin\delta$) for the RTFO AVABs and EABs. The master curves were analyzed at 60°C as a reference temperature.

MSCR Test

The MSCR test was carried out following ASTM D7405-20, *Standard Test Method for Multiple Stress Creep and Recovery (MSCR) of Asphalt Binder Using a Dynamic Shear Rheometer*.[27] The test was conducted to explore the resistances of the RTFO AVABs and the EABs to rutting. This was achieved by calculating the percentages of recovery (%R) and nonrecoverable creep compliance (J_{nr}) at 60°C, as a reference temperature, and by applying ten creep cycles at two different stress levels (0.1 and 3.2 kPa). For each creep cycle, the loading time was 1 s and the unloading time (recovery) was 9 s.

Interrupted Shear Flow Test

The interrupted shear flow measurements were conducted using the DSR on 25-mm diameter and 1-mm thickness RTFO AVABs and EABs. The test aimed to explore the presence of 3-D polymeric network structures and their development after shearing.[28,29] The formation of 3-D polymeric network structures was based on the components' exchanges between RAP/RAS and VABs. Shingles contain polymers; however, the presence of polymeric components in RAP depends on the RAP binders' composition. The testing temperatures were 70°C and 90°C for the RTFO AVABs and EABs, respectively. The asphalt samples were sheared, using the parallel plates, at a steady rate of 2 s^{-1} for 15 s. The shearing period was followed by rest periods—15, 30, and 220 s—before the shearing initiated at the same shear rate for 15 additional seconds.[28,29]

Asphalts' Components

The exchanged components between RAP/RAS and VABs could alter the composition of EABs, which would support the FTIR quantitative analysis. Therefore, asphalt binders' fractionation was conducted to assess changes in the EABs' compositions when compared with the compositions of binders before extraction. The test was carried out using thin-layer chromatography (TLC) and the hydrogen flame ionization detector (FID) approach by employing a TLC-FID Iatroscan. A 0.5-g sample of asphalt was dissolved in 20 mL of high-performance liquid chromatography grade dichloromethane (HPLCDCM). Once a sample was completely dissolved in HPLCDCM, 1 μL of the sample was spotted on a chromarod (thin-layer quartz rod). For each sample, a total of ten chromarods were spotted. The chromarods were then placed in three development tanks. The first development tank contained 100 % HPLC Hexane as a mobile phase. The second development tank contained 100 % HPLC Toluene as a mobile phase, whereas the third development tank contained 95 % HPLCDCM : 5 % HPLC Methanol as a mobile phase. Chromarods were air-dried before transference from one development tank to the other.

Once development was completed, samples were then transferred to the TLC-FID Iatroscan for flame ionization detection.[30,31] The average chromarods results were then reported for each sample.

Results and Discussion

FTIR RESULTS

FTIR Qualitative Analysis

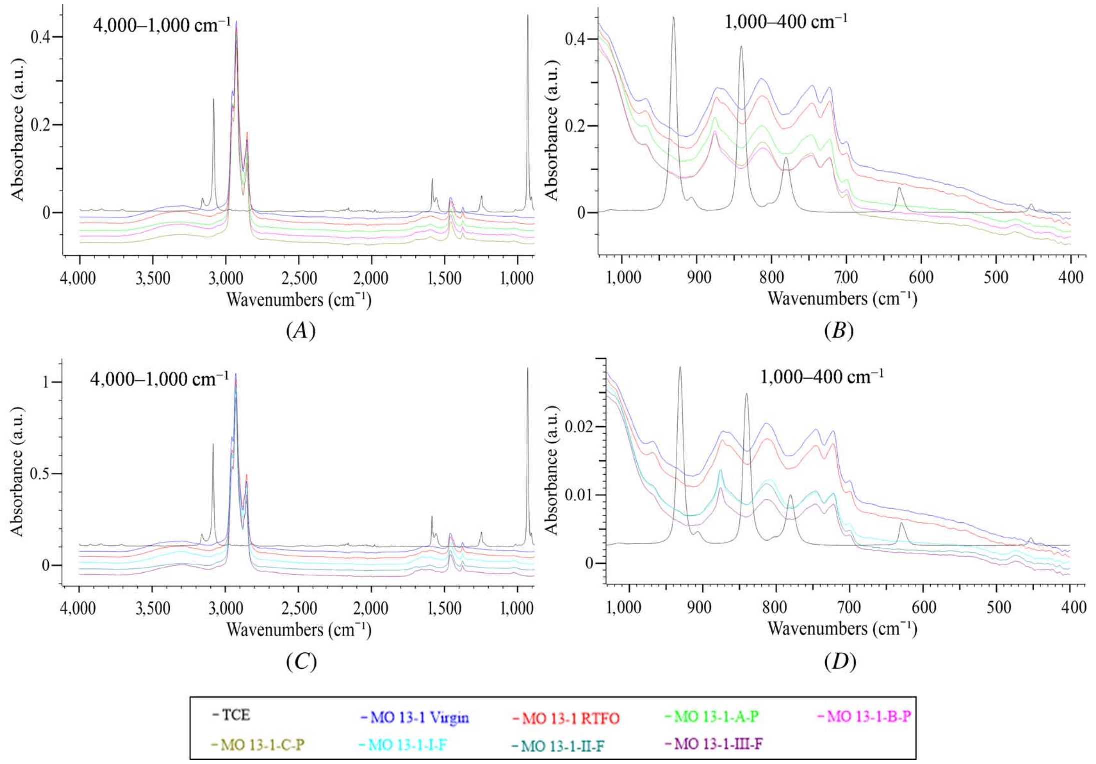
To ensure no TCE traces were in the EABs, the FTIR was used to compare the bands of the TCE and asphalt binders. **Table 2** shows the FTIR characteristic bands for the asphalt binder and TCE.[32–37] **Figure 1** presents the FTIR spectra for the TCE and MO 13-1 asphalt binders. Two strong sharp peaks were observed for the TCE for wavenumbers 944 and 849 cm^{-1}; these peaks are related to C–Cl stretching in alkyl halide (note **Table 2**).[37] By comparing the spectra of the TCE and EABs for wavenumbers less than 1,000 cm^{-1}, as in **figure 1*B*** and **1*D***, the TCE and the EABs did not share the same peaks. For wavenumbers greater than 1,000 cm^{-1}, the TCE had a medium peak at 3,083 cm^{-1}. This peak was not detected for MO 13-1 EABs, and this peak was related to the alkene C-H stretching (note **Table 2**).[36] The same observations were made by analyzing the spectra for US 54 and US 63-1 binders in **figures 2** and **3**, respectively.

In **figure 2*B***, for wavenumbers between 1,000 and 400 cm^{-1}, three new FTIR peaks were observed for the EABs from plant mixes containing 33 % ABR by RAS. The three peaks were located at 966, 911, and 699 cm^{-1}, and they were related to the polymeric components of SBS. The peaks at 966 and 911 cm^{-1} were related to the C–H bending of trans- and terminal-alkene in polybutadiene (PB), respectively.[38] The peak at 699 cm^{-1} was associated with the out-of-plane bending of the C–H group in the monosubstituted aromatic ring in the polystyrene (PS).[38,39] This reflected that reheating to the compaction temperature, as carried out in the lab for the plant mixes, caused components' exchanges between the RAS and the VABs; more details are included in the MSCR Test Results Section. No polymeric components were explored for EABs from mixes containing RAP. However, Deef-Allah and Abdelrahman[40] demonstrated PS and PB polymeric components in EABs from RAP-containing mixes due to the modification of the VABs in these mixes with SBS.

TABLE 2
Infrared characteristic bands for asphalt binder and TCE[32–37]

Asphalt Binder Bands	
Band Position, cm^{-1}	Band Assignment
3,800–2,700	O–H stretching[32]
3,100–3,000	C–H stretching for aromatic (sp^2 hybrids)[33,34]
3,000–2,850	C–H stretching for aliphatic (sp^3 hybrids)[33,34]
1,750–1,730	C=O stretching in the ester[33,34]
1,700	C=O stretching in the carboxylic acid[33,34]
1,600 (1,635–1,538)	C=C stretching vibrations for aromatic[33]
1,465 (1,538–1,399)	C–H bending vibrations in CH_2[33]
1,376 (1,399–1,349)	C–H bending vibrations in CH_3[33]
1,300	C–O stretching[34,35]
1,030 (1,082–980)	S=O stretching[33]
900–600	C–H out-of-plane bending vibration[33]
722	$(CH_2)_n$ rock, $n \geq 4$[33]
TCE Bands	
Band Position, cm^{-1}	Band Assignment
3,010–3,100	=C–H stretching in alkene[36]
1,620–1,680	C=C stretching in alkene[36]
944 and 849	C–Cl stretching in alkyl halide[37]
783	=C–H bending in alkene[37]

FIG. 1 FTIR spectra for TCE and the MO 13-1 binders. (*A*, *B*) Plant mixes' binders and (*C*, *D*) field mixes' binders.



FTIR Quantitative Analysis

The FTIR quantitative analysis was used in this section to identify the effects of the components' exchanges on the EABs' FTIR indexes (I_{CO}, I_{SO}, I_{CC}, and I_{CH}). If the FTIR indexes of RTFO AVABs are comparable with those of EABs, this reflects that no components' exchanges occurred between RAP/RAS and VABs. By contrast, if the FTIR indexes of EABs are different from those of RTFO AVABs, this indicates that blending occurred between RAP/RAS and VAB, and the components' exchanges took place. The area around the peak was calculated between a baseline with limits, defined by the TG5 group of RILEM,[41] and the curved line. While comparing FTIR indexes, these limits should be identical for all binders.[33]

The I_{CO} reflected aging due to carbonyl (C=O) at 1,700 cm^{-1}; see equation (1). The I_{SO} indicated aging because of sulfoxide (S=O) at 1,030 cm^{-1}; note equation (2).[19,33,42] The areas near 1,460 and 1,376 cm^{-1} represented the C–H bending vibrations in the CH_2 and CH_3 aliphatic groups, respectively. These aliphatic groups were not changed by aging.[33] The I_{CO} and I_{SO} indexes were direct measurements of the binder's aging.[19,33,42] The following equation represents the I_{CO}:

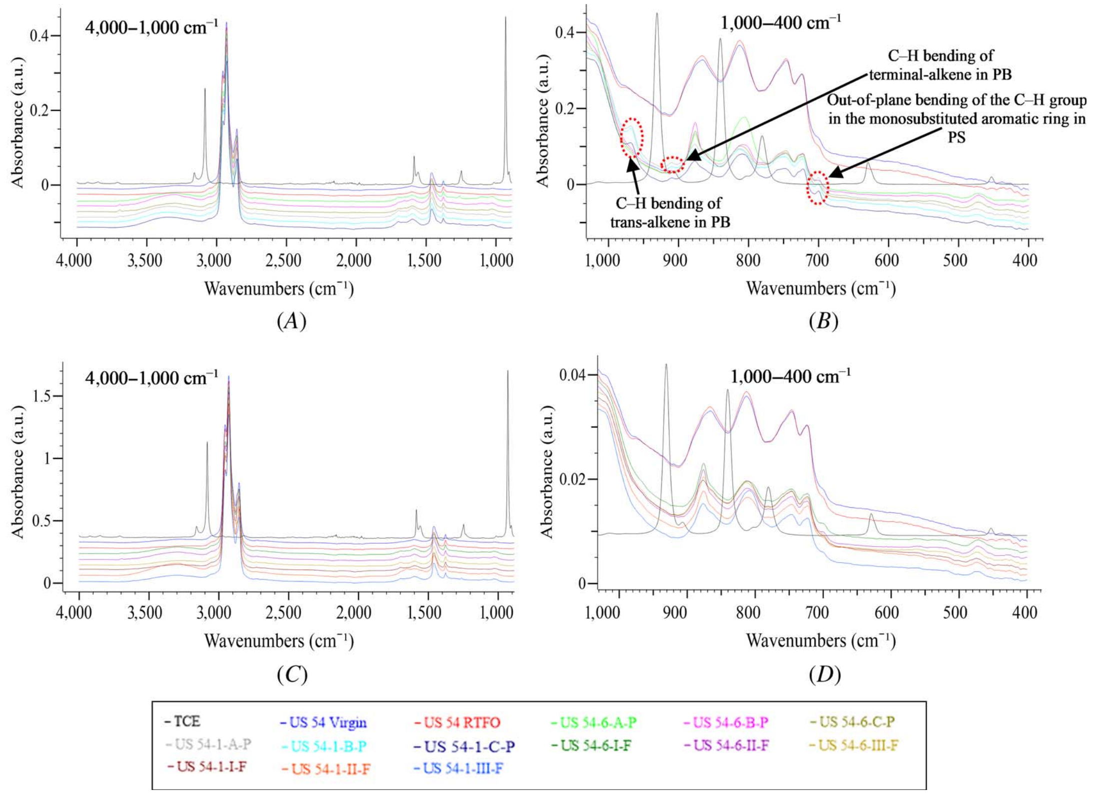
$$I_{CO} = \frac{Area\, around\; 1{,}700\; cm^{-1}}{Area\, around\; 1{,}460\; cm^{-1} + Area\, around\; 1{,}376\; cm^{-1}} \tag{1}$$

The next equation exemplifies the I_{SO}:

$$I_{SO} = \frac{Area\, around\; 1{,}030\; cm^{-1}}{Area\, around\; 1{,}460\; cm^{-1} + Area\, around\; 1{,}376\; cm^{-1}} \tag{2}$$

The C=C stretching in the aromatic index (I_{CC}) and the C–H bending in the aliphatic index (I_{CH}) were calculated using equation (3) and equation (4), respectively.[43,44] Changes in the I_{CC} and I_{CH} indexes interpreted the changes in the binder's aging.[43,44] The I_{CC} is defined by the subsequent equation:

FIG. 2 FTIR spectra for TCE and the US 54 binders. (*A*, *B*) Plant mixes' binders and (*C*, *D*) field mixes' binders.



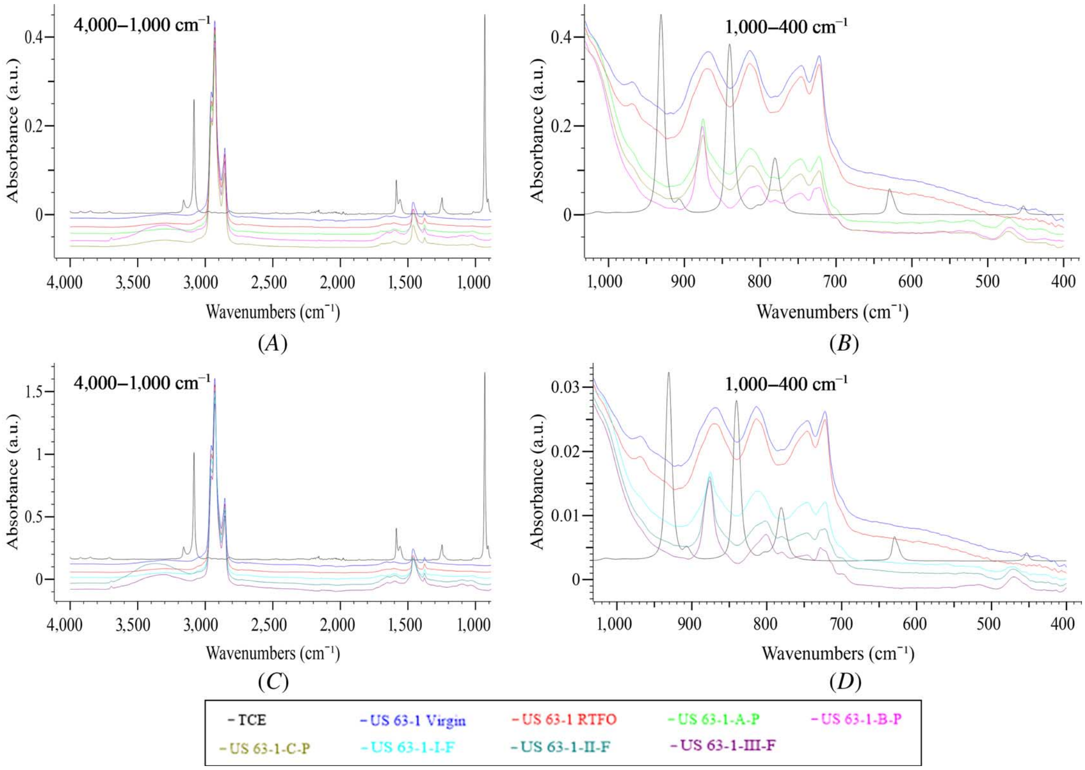
$$I_{CC} = \frac{Area\ around\ 1{,}600\ cm^{-1}}{\sum Area\ around\ 1{,}460,\ 1{,}376,\ 1{,}030,\ 1{,}700,\ and\ 1{,}600\ cm^{-1}} \quad (3)$$

The I_{CH} is illustrated by the following equation:

$$I_{CH} = \frac{Area\ around\ 1{,}460\ cm^{-1} + Area\ around\ 1{,}376\ cm^{-1}}{\sum Area\ around\ 1{,}460,\ 1{,}376,\ 1{,}030,\ 1{,}700,\ and\ 1{,}600\ cm^{-1}} \quad (4)$$

FTIR indexes were calculated for each EAB separately, and the results were averaged for EABs from the same mixture. The coefficient of variation (CV) values ranged between 0 and 96.47 % for I_{CO}, 0 and 16.49 % for I_{SO}, 0 and 18.00 % for I_{CC}, and 0 and 4.53 % for I_{CH}. Figure 4*A* illustrates the FTIR indexes for the MO 13-1 binders. The VAB and RTFO AVAB did not show the I_{CO}, and the I_{SO} was the same for both binders. Amounts of the sulfoxide group were found to be produced in higher quantities than those of the carbonyl group, which agreed with the results of a previous study.[45] The VAB did not show a carbonyl peak at 1,700 cm^{-1}, which agreed with previous results.[46,47] This happened because the carbonyl is associated with a high level of oxidation[47]; the carbonyl peak does not visibly increase with the aging of RTFO.[45] The obvious increase in carbonyl peak can be visible after the pressure aging vessel process.[45] After the RTFO aging process, the I_{CH} decreased, and the I_{CC} increased. The EABs yielded higher I_{CO} and I_{SO} indexes than the values recorded for the VAB and RTFO AVAB because aged components included in RAP were exchanged with VABs. The EABs from the plant mixes showed higher I_{CO}, I_{CC}, and lower I_{CH} than the EABs from the field mixes. The aliphatic molecules with lower molecular weights were converted into aromatics with higher molecular weights with aging. Therefore, increasing the aromatics and decreasing the aliphatic indexes

FIG. 3 FTIR spectra for TCE and the US 63-1 binders. (*A*, *B*) Plant mixes' binders and (*C*, *D*) field mixes' binders.



reflected increases in the asphalt binders aging processes.[43] This reflected more components' exchanges that occurred in plant mixes when compared to those in field mixes.

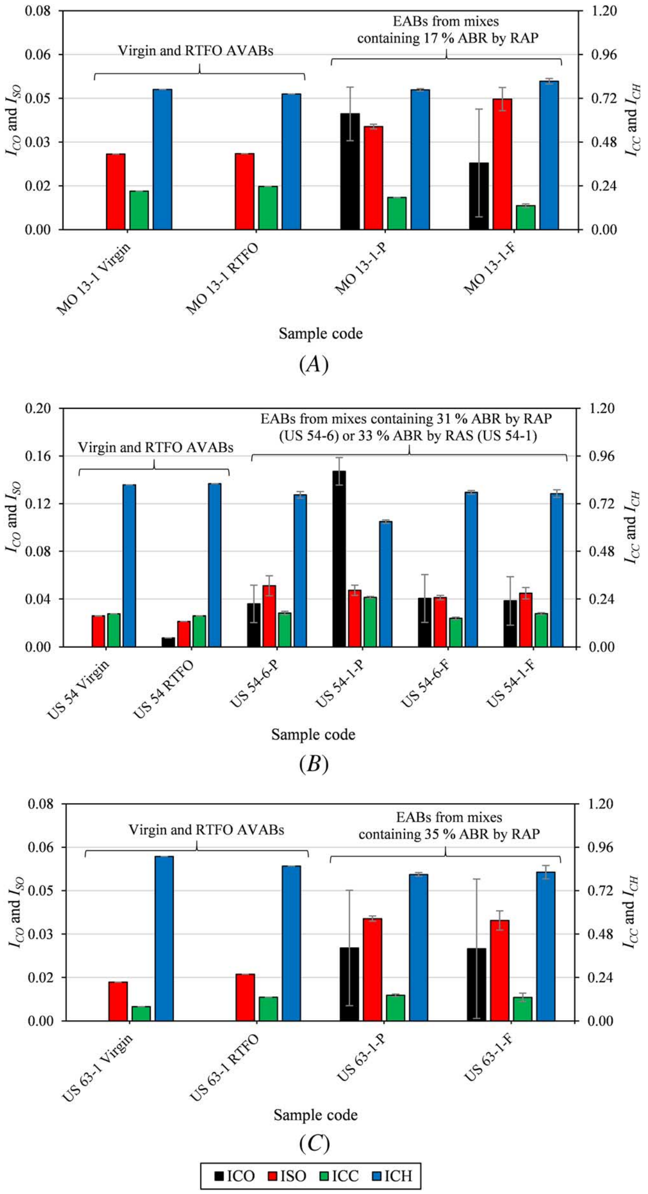
Figure 4*B* shows the FTIR indexes for the US 54 binders. No significant differences were observed between the I_{SO}, I_{CC}, and I_{CH} for the VAB and RTFO AVAB. However, the RTFO AVAB presented I_{CO} that was not observed in the VAB. The EABs illustrated higher I_{CO} and I_{SO} indexes than the indexes observed for the VAB and RTFO AVAB. This was related to the aged components in the RAP/RAS that were exchanged with VABs. The EABs from the US 54-1 mix containing 33 % ABR by RAS showed lower I_{CH} and higher I_{CC} than the EABs from the US 54-6 mix containing 31 % ABR by RAP. This illustrated the effects of oxidized binders in the RAS on increasing aging components when compared with binders included in the RAP. The EABs from the plant mixes showed higher I_{SO}, I_{CO}, I_{CC}, and lower I_{CH} than the EABs from the field mixes. The highest aging components were recorded for EABs from the US 54-1 plant mix; these binders showed the highest I_{CO}, I_{CC}, and the lowest I_{CH}. The RAS contained air-blown asphalt that was stiffer than the asphalt binders in the RAP. Therefore, reheating the plant mixes in the lab increased the blending of RAS and VAB, which caused more aged components' exchanges.

Comparing the FTIR indexes for the US 54-6-F and US 54-1-F EABs, no significant difference was observed. However, the US 54-1 mix included 2 % ABR by RAS higher than the ABR by RAP in the US 54-6 mix. The difference in the FTIR indexes was more pronounced for US 54-6-P and US 54-1-P EABs. This revealed that reheating the plant mixes in the lab to the compaction temperature prior to compaction increased the blending of the RAP/RAS and VAB, which increased the components exchanged in the plant mixes.

Figure 4*C* shows the FTIR indexes for the US 63-1 binders. The RTFO AVAB had higher I_{SO}, I_{CC}, and lower I_{CH} than the VAB. The EABs showed higher I_{CO}, I_{SO}, I_{CC}, and lower I_{CH} than those yielded by VAB and RTFO

FIG. 4

FTIR quantitative analysis for the (*A*) MO 13-1, (*B*) US 54, and (*C*) US 63-1 binders.



AVAB. This occurred because of the aged components included in the RAP that were exchanged with VABs. The EABs from the plant mixes presented higher I_{SO}, I_{CO}, I_{CC}, and lower I_{CH} than the EABs from the field mixes. Reheating the plant mixes to compaction temperature in the lab caused more components' exchanges between the RAP and the VAB; more details are discussed in the MSCR Test Results section.

RUTTING RESISTANCE

High PG and Continuous Grade Temperatures

Table 3 illustrates high PG and continuous grade temperatures for the RTFO AVABs and EABs. Two samples were inspected for each binder, and the average values were recorded. The CV values were found to be between

TABLE 3
High PG and continuous grade temperatures for asphalt binders

			High PG/Continuous Grade Temperature		
Mix Number	Plant Sample Code	Field Sample Code	RTFO AVABs	Plant EABs	Field EABs
1	MO 13-1-A-P	MO 13-1-I-F	64H/72.53	64E/88.79	64E/80.57
	MO 13-1-B-P	MO 13-1-II-F		64E/91.23	64E/80.02
	MO 13-1-C-P	MO 13-1-III-F		64E/87.76	64E/83.29
2	US 54-6-A-P	US 54-6-I-F	58/62.18	76/76.25	70/71.00
	US 54-6-B-P	US 54-6-II-F		76/77.12	70/71.83
	US54-6-C-P	US54-6-III-F		76/77.15	70/72.14
3	US 54-1-A-P	US 54-1-I-F		106/111.7	70/74.21
	US 54-1-B-P	US 54-1-II-F		106/111.4	70/74.61
	US 54-1-C-P	US 54-1-III-F		106/108.6	70/75.22
4	US 63-1-A-P	US 63-1-I-F	58/58.58	76/77.59	70/75.74
	US 63-1-B-P	US 63-1-II-F		76/78.77	70/75.42
	US 63-1-C-P	US 63-1-III-F		76/77.86	70/74.14

0.25 and 6.51 %. Using 17 % ABR by RAP in the MO 13-1 mix changed the asphalt binder's high PG temperature from 64 high (H) for the RTFO AVAB to 64 extremely high (E) for the EABs. However, the EABs from the MO 13-1 plant mix showed higher continuous grade temperatures than the EABs from the MO 13-1 field mix. This occurred because there were more components' exchanges between the RAP and the VAB in the plant mixes.

Using 31 % or 35 % ABR by RAP increased the asphalt binder's high PG temperatures by three grades (6°C per grade) for the EABs from the US 54-6 and US 63-1 plant mixes when compared with the RTFO AVABs. However, the EABs from the US 54-6 and US 63-1 field mixes increased two grades. The same observations were noted for the continuous grade temperatures: the EABs from the plant mixes had higher continuous grade temperatures than the EABs from the field mixes. The US 54 and US 63-1 mixes contained binders with the same PG (58−28); however, the binder included in the US 63-1 was softer than that used in the US 54 binder. This was concluded from the continuous grade temperatures of both binders: the US 63-1 RTFO AVAB showed a lower continuous grade temperature than the US 54 RTFO AVAB. Nevertheless, the EABs from the US 63-1 mix yielded higher continuous grade temperatures than the EABs from the US 54-6 mix for two reasons: the first was the higher percentage of RAP included in the US 63-1 mix, and the second was the Evoflex additive in the US 63-1 mix. The Evoflex increased the contribution of the binders, including in the recycled materials, by increasing their mobilization inside the asphalt mixes, thereby increasing the components' exchanges. For EABs from the US 54-1 plant mix containing 33 % ABR by RAS, the high PG temperatures were 106°C with eight increase grades when compared with the high PG temperature for the US 54 RTFO AVAB. By contrast, the increase was only two grades for the EABs from the US 54-1 field mix containing 33 % ABR by RAS. This occurred due to the increase in the components' exchanges within the plant mixes when compared with the field mixes.

The EABs from the US 54-6 plant mix containing 31 % ABR by RAP and the US 54-1 plant mix containing 33 % ABR by RAS were compared. These mixes contained the same VAB. The high PG temperatures for the EABs from the US 54-6 plant mix increased three grades beyond the RTFO AVAB. Conversely, the high PG temperatures for the EABs from the US 54-1 plant mix increased eight grades when compared with the RTFO AVAB. This illustrated that the exchanged components between the recycled materials and the VAB yielded higher stiffness levels for the EABs from mixes containing RAS as opposed to the mixes containing RAP. Nevertheless, no significant difference was seen between the EABs from the US 54-1 and US 54-6 field mixes. These results agreed with the FTIR analyses.

Frequency Sweep Test Results

The rutting parameters derived from master curves for the field mixes' binders at a reference temperature of 60°C and reduced frequencies ranging from 0.001 to 15.9 Hz are presented in figure 5. The EABs from the field mixes presented higher $|G^*|/\sin\delta$ values than the RTFO AVABs because of the stiff nature of the binders included in the recycled materials, which exchanged their aged components with the VAB. From the FTIR results, there were no SBS polymeric components exchanged between the RAS and the VAB in the US 54-1 field mix containing 33 % ABR by RAS. Moreover, this was concluded because the highest rutting resistance was noted for the EABs from the MO 13-1 mix containing 17 % ABR by RAP. The MO 13-1 mix contained the lowest levels of recycled materials; however, it contained the stiffest asphalt binder.

Figure 6 presents the master curves for the plant mixes' binders at a reference temperature of 60°C and with reduced frequencies ranging from 0.0006 to 15.9 Hz. The EABs showed higher rutting parameters than the corresponding RTFO AVABs. The highest rutting parameter values were obtained for EABs from the US 54-1 mix containing 33 % ABR by RAS. For mixes containing RAP, the highest resistance to rutting was observed for the

FIG. 5 Master curves measured at 60°C for the field mixes' binders.

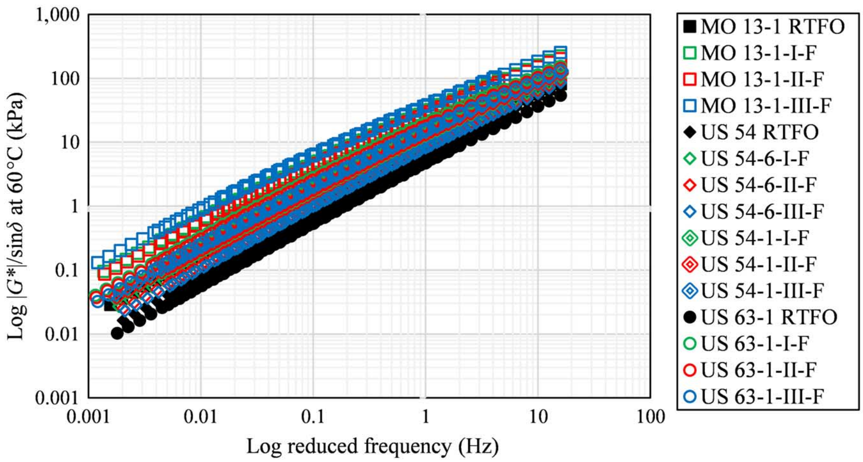
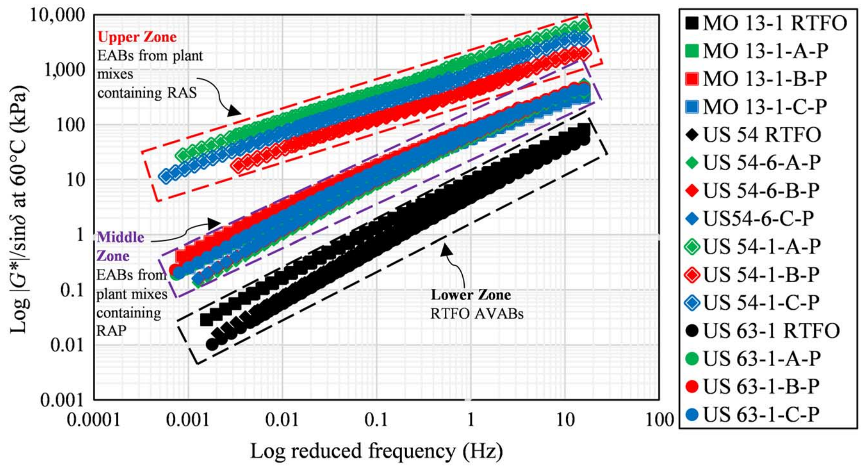


FIG. 6 Master curves measured at 60°C for the plant mixes' binders.



MO 13-1 EABs. The components' exchanges were higher in the plant mixes than in the field mixes because reheating to the compaction temperature was implemented in the lab for the plant mixes; more discussions are included in the MSCR Test Results Section. This appears in figure 6 by showing three zones: the lower zone for the RTFO AVABs, the middle zone for the EABs from mixes containing RAP, and the upper zone for the EABs from mixes containing RAS. The upper zone presented binders with the highest rutting resistance, and the lower zone depicted binders with the lowest resistance to rutting.

MSCR Test Results

Two samples were tested for each binder, and the average %R and J_{nr} values were analyzed. The CV values were found to be between 0.90 and 9.58 % for %R and between 0.09 and 13.89 % for J_{nr}. Figure 7 presents the MSCR test results—%R and J_{nr} values—for the MO 13-1 binders at 60°C. Increasing the stress levels from 0.1 to 3.2 kPa decreased the %R and increased the J_{nr} values. The RTFO AVAB had the lowest %R and the highest J_{nr} values. The EABs from the plant mixes presented higher %R and lower J_{nr} values than the EABs from the field mixes. This illustrated that more components' exchanges were achieved in the plant mixes when compared with those in the field mixes.

Figure 8 shows the %R and J_{nr} values for the US 54 binders at 60°C. The RTFO AVAB had the lowest %R and the highest J_{nr} values at various stress levels. The EABs from the US 54-6 mix containing 31 % ABR by RAP (fig. 8*A*) yielded lower %R and higher J_{nr} values than the EABs from the US 54-1 mix containing 33 % ABR by RAS (fig. 8*B*). This occurred because the binders included in the RAS were stiffer than the binders inside the RAP.

The EABs from the MO 13-1 mix containing 17 % ABR by RAP—presented in figure 7—showed higher %R and lower J_{nr} values than the EABs from the US 54-6 mix containing 31 % ABR by RAP, see figure 8*A*. However, the US 54-6 mix contained 1.82 times greater ABR percentage by RAP than the MO 13-1 mix. This happened because the VAB included in the MO 13-1 mix was stiffer than the VAB that was in the US 54-6 mix. Another reason could be the variability of properties of the asphalt binders included in the RAP.[15] The EABs from the MO 13-1 field mix showed higher %R and lower J_{nr} values than the EABs from the US 54-1 field mix containing 33 % ABR by RAS (fig. 8*B*). The MO 13-1 mix contained 0.52 times lesser ABR percentages by RAP than the ABR by RAS in the US 54-1 mix. This illustrated that the polymeric components' exchanges were not achieved for the US 54-1 field mix, which agreed with the FTIR results.

Other researchers[48,49] evaluated the effect of reheating on plant mixes—containing 15 to 40 % RAP—in the lab prior to compaction. The performance of these mixes was compared with that of plant mixes compacted after the production process without reheating. The results deemed that the plant mixes without reheating had lower stiffness than the reheated plant mixes. The researchers concluded that more aging occurred in the VABs present in the reheated plant mixes when compared with the VABs in the plant mixes without reheating. Johnson et al.[13]

FIG. 7

MSCR test results for the MO 13-1 mixes' binders, measured at 60°C.

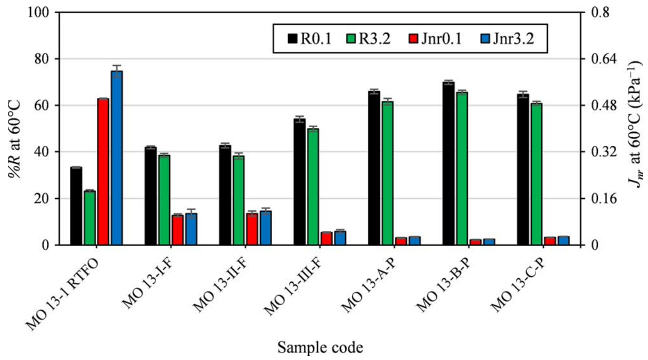
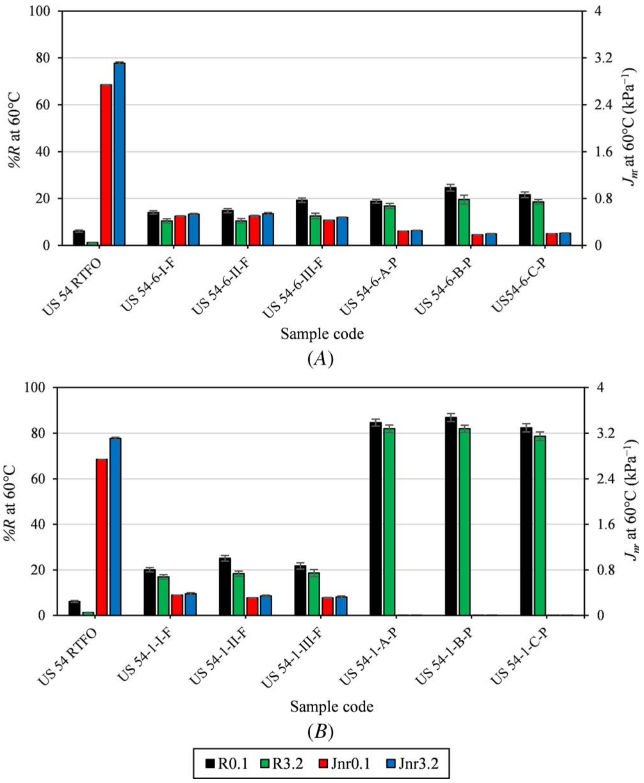


FIG. 8

MSCR test results for the (*A*) US 54-6 mixes' binders and (*B*) US 54-1 mixes' binders, measured at 60°C.



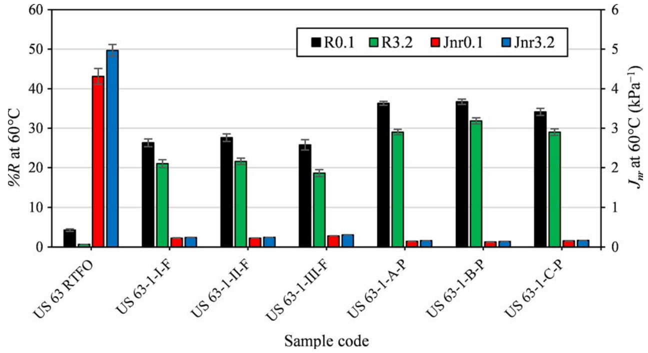
compared EABs from plant mixes and simulated lab mixes containing RAP/RAS. The plant mixes' EABs were softer than the lab mixes' EABs. The researchers[13] explicated that more blending occurred between the RAP/RAS and VABs in the lab mixes when compared with the plant mixes. This was related to the shorter mixing time in the plant compared with the lab.

The EABs from the plant mixes yielded higher *%R* and lower J_{nr} values than the EABs from the field mixes. However, the difference between the MSCR results for the EABs from the US 54-6 plant and field mixes containing 31 % ABR by RAP was smaller than the difference between the MSCR results for the EABs from the US 54-1 plant and field mixes containing 33 % ABR by RAS. Note that the US 54-6 and US 54-1 mixes contained the same VAB. Thus, the aging process of the VAB during reheating the plant mixes to the compaction temperature was not the primary control of the EAB's performances. The FTIR results showed that the spectra of the EABs from the US 54-1 plant mix presented the shingles' SBS polymeric components. These polymeric components were not detected in the spectra of the EABs from the same mix gathered from the field. Therefore, the reheating to the compaction process in the lab of the plant mixes increased the blending between the RAP/RAS and VABs. This increased the exchanged components between RAP/RAS and VABs. Note that the binders inside the RAP interacted more readily with the VABs when compared with the binders in the RAS.

Figure 9 shows the MSCR test results for the US 63-1 binders at 60°C. The EABs from the field mixes showed lower %*R* and higher J_{nr} values than the EABs from the plant mixes. This happened because more components were exchanged between the RAP and the VAB of the plant mixes than those of the field mixes. The US 63-1 RTFO AVAB presented lower %*R* and higher J_{nr} values than the MO 13-1 and US 54 RTFO AVABs. However, the EABs from the US 63-1 mix containing 35 % ABR by RAP showed higher %*R* and lower J_{nr} values

FIG. 9

MSCR test results for the US 63-1 mixes' binders, measured at 60°C.



than the EABs from the US 54-6 mix containing 31 % ABR by RAP. This was achieved because the US 63-1 mix was composed of a higher ABR percentage by RAP than the US 54-6 mix. Furthermore, the US 63-1 mix contained the Evoflex additive that increased the contribution and mobilization of the binders included in the recycled materials inside the mix. This increased the components' exchanges in the US 63-1 mix. The EABs from the US 63-1 mix had lower %*R* and higher J_{nr} values than the EABs from the MO 13-1 mix containing 17 % ABR by RAP. Nevertheless, the US 63-1 mix contained two times greater ABR percentage by RAP than the ABR percentage in the MO 13-1 mix. This occurred because the VAB included in the MO 13-1 mix was stiffer than the VAB in the US 63-1 mix, and the variability of the asphalt binders' properties in the RAP could be another reason.[15] Therefore, the percentage of the recycled materials and the PGs of the VABs in the asphalt mixes controlled the high-temperature performance of the EABs.

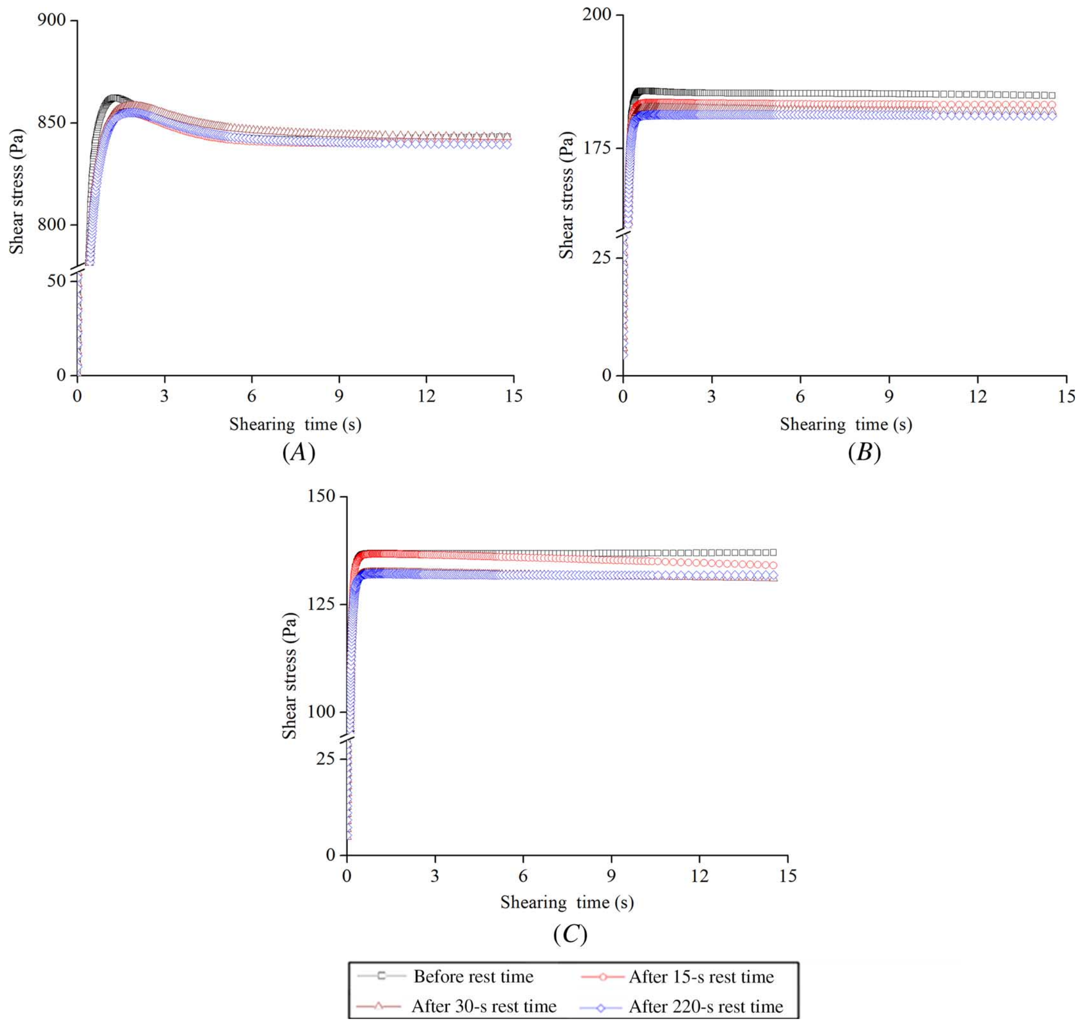
The EABs from the US 54-1 field mix containing 33 % ABR by RAS showed lower %*R* and higher J_{nr} values than the EABs from the US 63-1 field mix containing 35 % ABR by RAP. However, the EABs from the US 54-1 plant mix had higher %R and lower J_{nr} values than the EABs from the US 63-1 plant mix. Thus, the components' exchanges were more pronounced in the plant mixes than in the field mixes. For the field mixes, the VABs interacted more readily with the RAP binders than with the RAS binders. Therefore, the EABs from the field mixes containing RAP (e.g., the US 63-1 and MO 13-1) yielded higher %*R* and lower J_{nr} than EABs from the US 54-1 field mix containing RAS.

Interrupted Shear Flow Test Results

Figure 10 shows the interrupted shear flow test results for the RTFO AVABs. No stress overshoot was observed for the RTFO AVABs. Wekumbura, Stastna, and Zanzotto[28] stated that no stress overshoot was recorded for neat asphalt binders without additives because of weak associations inside the asphalt network (e.g., hydrogen bonding and bipolar attractions). These bonds were easy to be broken by varying stress or temperature.[28,29]

Figure 11 depicts the interrupted shear flow test results for the EABs from the plant mixes. Stress overshoot was observed for the EAB from the US 54-1-C plant mix containing 33 % ABR by RAS (**fig. 11*B***). Stress overshoot reflected the disturbance of the material's structure network under flow,[50–52] which occurred in the form of segment orientation, segment stretch, and in the decrease of the chains' entanglement densities.[50,53] For polymers, it was reported that elasticity was necessary for the occurrence of stress overshoot.[50,54] This agreed with the MSCR test results; the EABs from the US 54-1 mix showed the highest elasticity (the highest %*R*) when compared with the other EABs. Increasing the rest time from 30 to 220 s, as presented in **figure 11*B***, caused an increase in the magnitude of the stress overshoot, which was attributed to the re-entanglement of chains disentangled during previous shearing.[50,53] For asphalt binders modified with polymers, the stress overshoot was attributed to the

FIG. 10 Interrupted shear flow test results, measured at 70°C temperature and 2 s^{-1} shear rate, for the (*A*) MO 13-1, (*B*) US 54, and (*C*) US 63-1 RTFO AVABs.

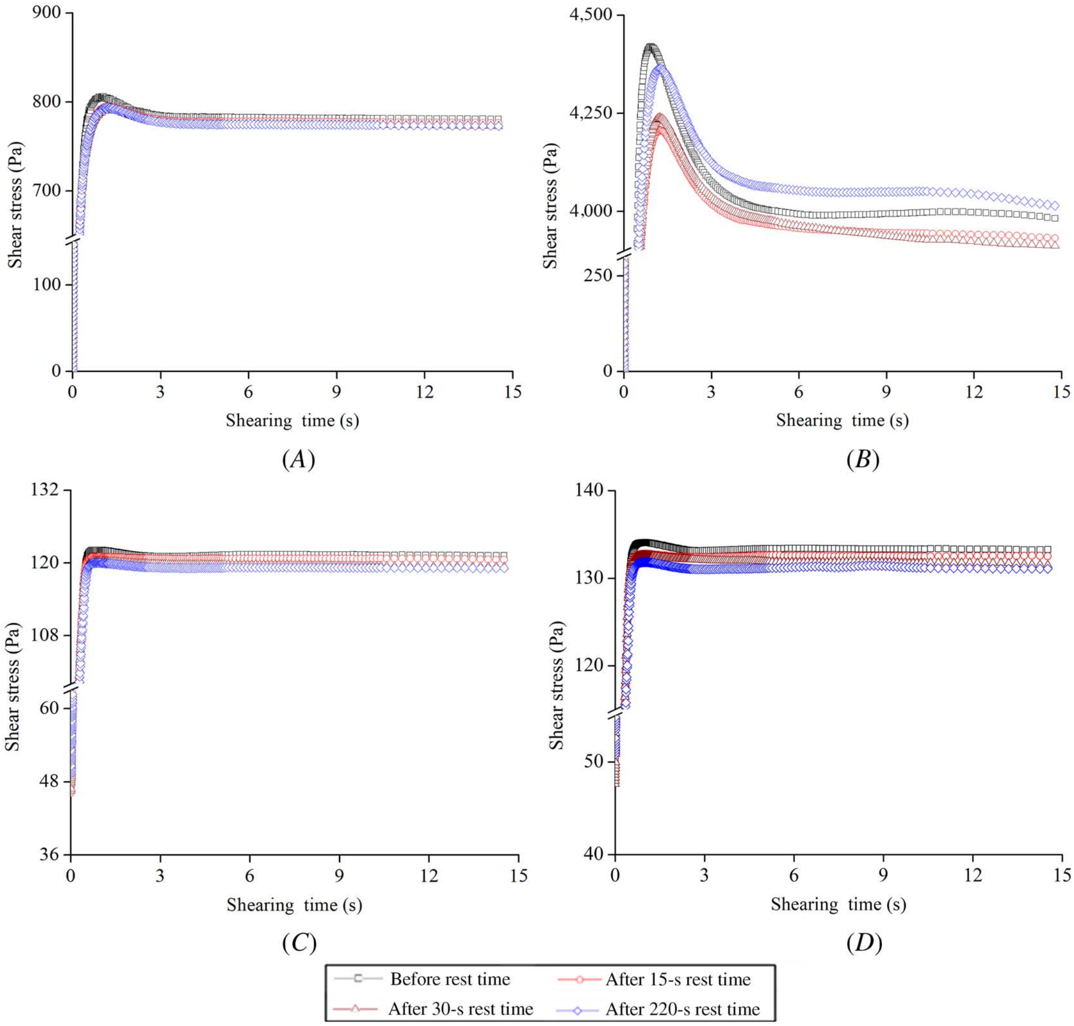


existence of 3-D network structures in the modified binders.[28,29] After shearing, the disturbed structure reformed and self-healed.[28] The SBS polymeric components, explored by the FTIR, in the US 54-1-C-P EAB formed 3-D network structures that caused the stress overshoot. No stress overshoot was observed for the EABs from the plant mixes containing RAP (**fig. 11*A***, **11*C***, and **11*D***).

Figure 12 demonstrates the interrupted shear flow test results for the EABs from the field mixes. No stress overshoot was observed for the EABs from the field mixes containing RAP (**fig. 12*A***, **12*C***, and **12*D***). For EABs from the US 54-1-I field mix containing RAS (**fig. 12*B***), no stress overshoot was observed. The SBS polymeric components were not detected by the FTIR for the EABs from US 54-1 field mix; therefore, no 3-D network structures formed in these EABs.

The process of reheating increased the SBS polymer swelling by absorbing more low molecular weight fractions from the asphalt binders (aromatic oils), thus decreasing the maltene fraction and increasing stiffness. These results are exemplified in detail in the Asphalt's Components Results section. The swollen polymer strands formed a crystalline-like domain PS and were connected by other PB segments.[28,29] This created 3-D network

FIG. 11 Interrupted shear flow test results, measured at 90°C temperature and 2 s^{-1} shear rate, for the (*A*) MO 13-1-B-P, (*B*) US 54-1-C-P, (*C*) US 54-6-A-P, and (*D*) US 63-1-A-P plant mixes' EABs.

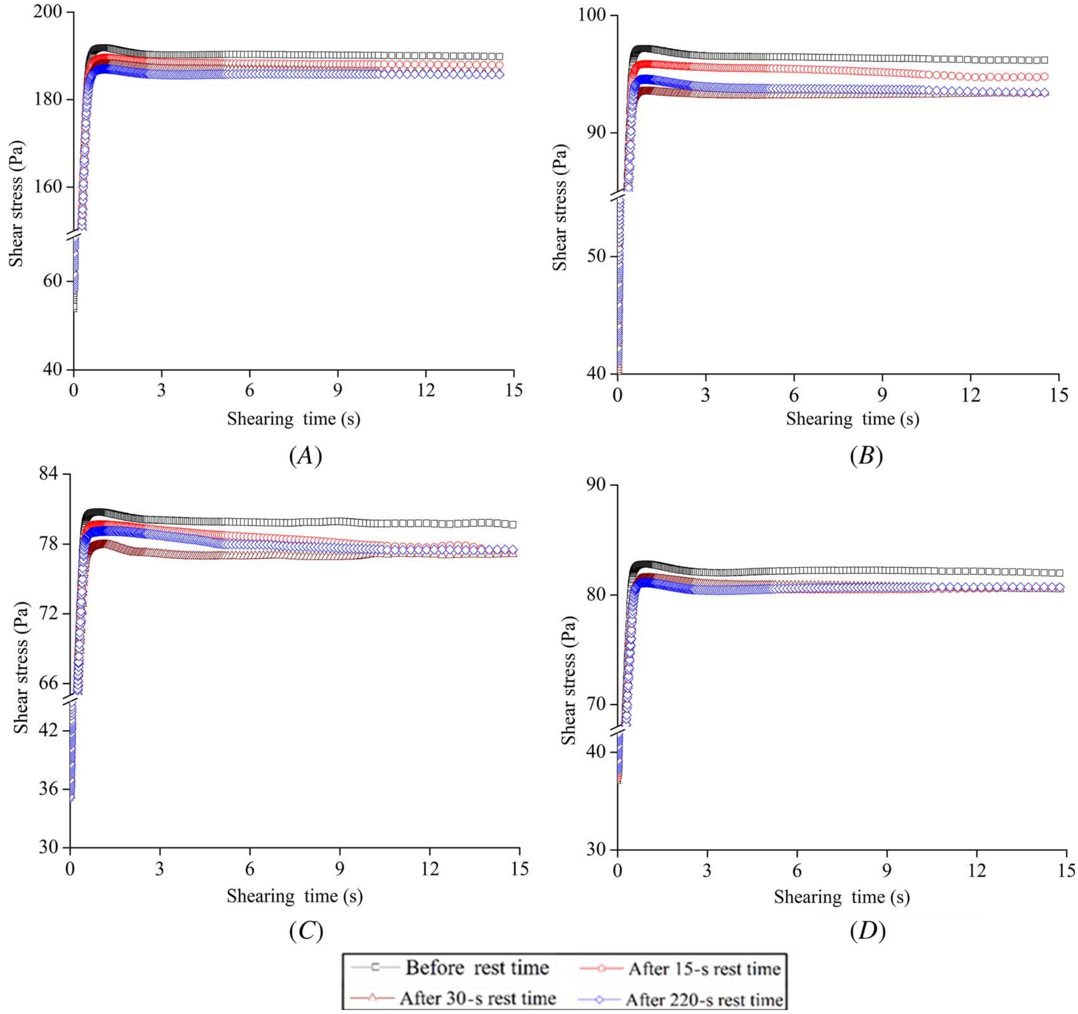


structures with certain degrees of entanglement that increased the binders' stiffness, elasticity, and resistance to rutting. However, the 3-D network structures were not formed in the same mixes collected from the field as cores.

Asphalt's Components Results

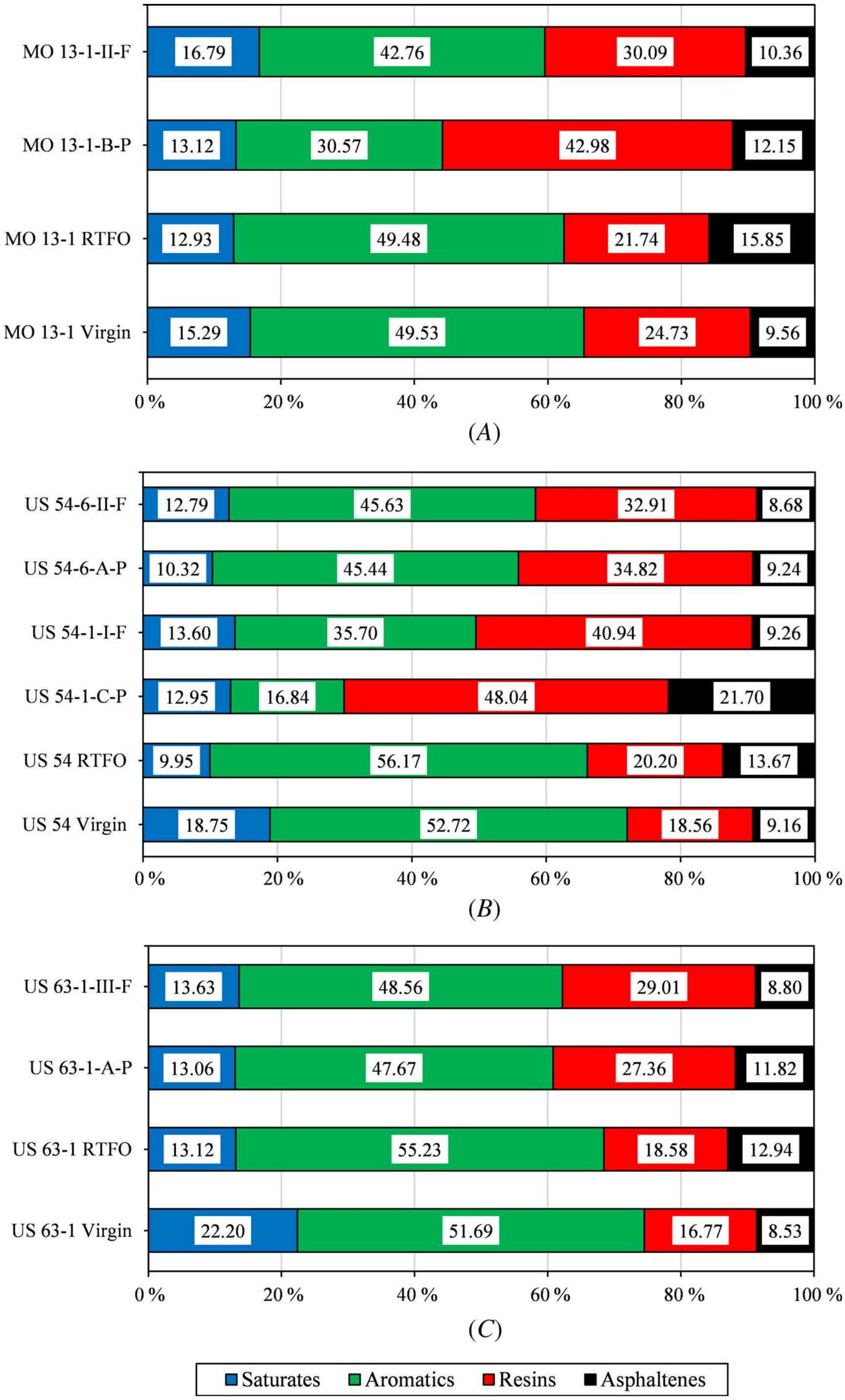
The asphalt binders' compositional analyses are deemed in **figure 13**. Ten samples were tested for each binder, and the average results were analyzed. The CV ranged between 2.05 and 19.15 % for saturates, 1.43 and 8.02 % for aromatics, 0.96 and 16.23 % for resins, and 4.11 and 33.44 % for asphaltenes. By analyzing VABs and RTFO AVABs, the US 63-1 binder had the lowest asphaltenes plus resins percentage, and it had the highest saturates plus aromatics percentage. The MO 13-1 binder had the highest asphaltenes plus resins percentage, and it had the lowest saturates plus aromatics percentage. This agreed with the previous results. The US 63-1 binder was the softest, and MO 13-1 binder was the stiffest.

FIG. 12 Interrupted shear flow test results, measured at 90°C temperature and 2 s^{-1} shear rate, for the (*A*) MO13-1-II-F, (*B*) US 54-1-I-F, (*C*) US 54-6-II-F, and (*D*) US 63-1-III-F field mixes' EABs.



The EABs depicted higher asphaltenes plus resins percentages and lower saturates plus aromatics percentages when compared with the RTFO AVABs. Furthermore, the EABs from the plant mixes had higher asphaltenes plus resins percentages and lower saturates plus aromatics percentages than the field mixes' EABs. This illustrated the effect of the aged binders in the RAP/RAS on changing the composition of the EABs by increasing the aging components' exchanges, which agreed with the previous results. For US 54 binders, the EABs from the mix containing RAS had the highest asphaltenes plus resins percentages and the lowest saturates plus aromatics percentages. Therefore, the EABs from the mix containing RAS were stiffer than the EABs from the mix containing RAP. Additionally, the EABs from plant mix containing RAS had the lowest aromatics, highest asphaltenes, and highest resins. This occurred because reheating to the compaction temperature that occurred for the plant mix in the lab resulted in increased the components' exchanges. Moreover, the polymeric components in the RAS (e.g., SBS) absorbed more aromatics, and their swelling process increased. This led to a decrease in the maltene fraction and increase in the binders' stiffness and elasticity levels.

FIG. 13 Components for the (*A*) MO 13-1, (*B*) US 54, and (*C*) US 63-1 binders.



Conclusions

To evaluate the effect of the components' exchanges between recycled materials and VABs in asphalt mixes, asphalt binders were extracted from the field and plant asphalt mixes containing RAP or RAS. The field mixes were collected within 2 weeks after the construction process. The plant mixes were reheated and compacted in the lab. Each mix contained a different percentage of RAP or RAS, different VABs' PGs, and different additives. Based on this study, the following conclusions were drawn:

- More component exchanges between RAP/RAS and VABs took place in plant mixes—compacted in the lab—than in field mixes. This happened because the plant mixes were reheated before compaction in the lab.
- The EABs from the plant mixes showed higher FTIR aging and aromatics, and they yielded lower aliphatic indexes than the EABs from the field mixes.
- For the EABs from plant mixes containing RAS, the SBS polymeric component peaks were noted in the FTIR spectra. These FTIR peaks were not recorded for the EABs from the same mixes collected from the field.
- The EABs from the plant mixes had higher asphaltenes plus resins percentages and lower saturates plus aromatics percentages than the EABs from the field mixes.
- The EABs from the plant mixes had higher rutting resistance than the EABs from the field mixes because more components' exchanges occurred between the recycled materials and the VABs inside the plant mixes.
- For the EABs from the plant mixes containing RAS, the SBS polymeric components formed 3-D network structures. These structures increased the EABs' stiffness and elasticity. However, these 3-D network structures were not formed in the EABs from the same mixes collected from the field.
- The EABs had higher rutting resistance than the short-term aged VABs. The EABs had higher asphaltenes plus resins percentages and lower saturates plus aromatics percentages than the short-term aged VABs.
- The PGs of the VABs and the percentages of recycled materials in the asphalt mixes controlled the high-temperature performance of the EABs.
- The Evoflex additive increased the components exchanged between the RAP and the VAB.

ACKNOWLEDGMENTS

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

References

1. R. West, N. Tran, A. Kvasnak, B. Powell, and P. Turner, "Construction and Field Performance of Hot Mix Asphalt with Moderate and High RAP Contents" in *Bearing Capacity of Roads, Railways and Airfields (BCR2A'09) Eighth International Conference* (Leiden, the Netherlands: CRC Press/Balkema, 2009), 1373–1381.
2. M. Z. Alavi, D. Jones, Y. He, P. Chavez, and Y. Liang, *Investigation of the Effect of Reclaimed Asphalt Pavement and Reclaimed Asphalt Shingles on the Performance Properties of Asphalt Binders: Phase 1 Laboratory Testing, UCPRC-RR-2016-06* (Sacramento, CA: California Department of Transportation, 2016).
3. Z. Wang, P. Wang, H. Guo, X. Wang, and G. Li, "Adhesion Improvement between RAP and Emulsified Asphalt by Modifying the Surface Characteristics of RAP," *Advances in Materials Science and Engineering* 2020 (April 2020): 4545971, https://doi.org/10.1155/2020/4545971
4. W. G. Buttlar, M. Abdelrahman, H. Majidifard, and E. Deef-Allah, *Understanding and Improving Heterogeneous, Modern Recycled Asphalt Mixes, cmr 21-007* (Jefferson City, MO: Missouri Department of Transportation, 2021).
5. R. R. de Lira, D. D. Cortes, and C. Pasten, "Reclaimed Asphalt Binder Aging and Its Implications in the Management of RAP Stockpiles," *Construction and Building Materials* 101, Part 1 (December 2015): 611–616, https://doi.org/10.1016/j.conbuildmat.2015.10.125
6. J. R. Willis and P. Turner, *Characterization of Asphalt Binder Extracted from Reclaimed Asphalt Shingles, NCAT Report 16-01* (Auburn, AL: National Center for Asphalt Technology, 2016).
7. A. Alvergue, "Laboratory Evaluation of Asphalt Mixtures and Binders with Reclaimed Asphalt Shingle Prepared Using the Wet Process" (master's thesis, Louisiana State University and Agricultural and Mechanical College, 2014).

8. J. Davis, "Modified Asphalt Strengthens Roofing Shingles," *Asphalt: The Magazine of the Asphalt Institute*, 2016, http://web.archive.org/web/20210127184142/http://asphaltmagazine.com/modified-asphalt-strengthens-roofing-shingles/
9. B. Klutz, E. Dutton, and J. Davis, "Modified Asphalt Use in Roofing Applications," *Asphalt: The Magazine of the Asphalt Institute*, 2017, http://web.archive.org/web/20210803084132/http://asphaltmagazine.com/modifiedasphaltuseroofing/
10. L. R. Kleinschmidt and H. R. Snoke, "Changes in the Properties of an Asphalt during the Blowing Operation," *Journal of Research of the National Bureau of Standards* 60, no. 3 (March 1958): 169–172, https://doi.org/10.6028/jres.060.021
11. National Institute for Occupational Safety and Health (NIOSH), *Asphalt Fume Exposures during the Manufacture of Asphalt Roofing Products: Current Practices for Reducing Exposures, DHHS (NIOSH) 2001–127* (Cincinnati, OH: National Institute for Occupational Safety and Health (NIOSH), 2001).
12. G. W. Maupin Jr., *Investigation of the Use of Tear-Off Shingles in Asphalt Concrete, FHWA/VTRC 10-R23* (Charlottesville, VA: Virginia Transportation Research Council, 2010).
13. E. Johnson, G. Johnson, S. Dai, D. Linell, J. McGraw, and M. Watson, *Incorporation of Recycled Asphalt Shingles in Hot-Mixed Asphalt Pavement Mixtures, MN/RC 2010-08* (Maplewood, MN: Minnesota Department of Transportation, 2010).
14. F. Zhou, H. Li, R. Lee, T. Scullion, and G. Claros, "Recycled Asphalt Shingle Binder Characterization and Blending with Virgin Binders," *Transportation Research Record* 2370, no. 1 (January 2013): 33–43, https://doi.org/10.3141/2370-05
15. A. J. Austerman, W. S. Mogawer, and K. D. Stuart, "Variability of Reclaimed Asphalt Pavement (RAP) Properties within a State and Its Effects on RAP Specifications," *Transportation Research Record* 2674, no. 6 (January 2020): 73–84, https://doi.org/10.1177/0361198120917679
16. J. S. Daniel, J. L. Pochily, and D. M. Boisvert, "Can More Reclaimed Asphalt Pavement Be Added?" *Transportation Research Record* 2180, no. 1 (January 2010): 19–29, https://doi.org/10.3141/2180-03
17. C. Rodezno and G. Julian, *Asphalt Binder Extraction Protocol for Determining Amount & PG Characteristics of Binders Recovered from Asphalt Mixtures, WHRP 0092-16-02* (Madison, WI: Wisconsin Department of Transportation, 2018).
18. E. Deef-Allah, M. Abdelrahman, and A. Hemida, "Improving Asphalt Binder's Elasticity through Controlling the Interaction Parameters between CRM and Asphalt Binder," *Advances in Civil Engineering Materials* 9, no. 1 (May 2020): 262–282, https://doi.org/10.1520/ACEM20190204
19. E. Deef-Allah and M. Abdelrahman, "Effect of Used Motor Oil as a Rejuvenator on Crumb Rubber Modifier's Released Components to Asphalt Binder," *Progress in Rubber, Plastics and Recycling Technology* 37, no. 2 (May 2021): 87–114, https://doi.org/10.1177/1477760620918600
20. E. Deef-Allah and M. Abdelrahman, "Balancing the Performance of Asphalt Binder Modified by Tire Rubber and Used Motor Oil," *International Journal of Recent Technology Engineering* 8, no. 4 (November 2019): 5501–5508, https://doi.org/10.35940/ijrte.D8893.118419
21. E. Deef-Allah, M. Abdelrahman, M. Fitch, M. Ragab, M. Bose, and X. He, "Balancing the Performance and Environmental Concerns of Used Motor Oil as Rejuvenator in Asphalt Mixes," *Recycling* 4, no. 1 (February 2019): 11, https://doi.org/10.3390/recycling4010011
22. *Standard Test Methods for Quantitative Extraction of Asphalt Binder from Asphalt Mixtures*, ASTM D2172/D2172M-17e1 (2017) (West Conshohocken, PA: ASTM International, approved April 1, 2017), https://doi.org/10.1520/D2172_D2172M-17E01
23. *Standard Practice for Recovery of Asphalt from Solution Using the Rotary Evaporator*, ASTM D5404/D5404M-12(2017) (West Conshohocken, PA: ASTM International, approved October 1, 2017), https://doi.org/10.1520/D5404_D5404M-12R17
24. *Standard Test Method for Effect of Heat and Air on a Moving Film of Asphalt (Rolling Thin-Film Oven Test)*, ASTM D2872-19(2019) (West Conshohocken, PA: ASTM International, approved June 15, 2019), https://doi.org/10.1520/D2872-19
25. *Standard Test Method for Determining the Rheological Properties of Asphalt Binder Using a Dynamic Shear Rheometer*, ASTM D7175-15(2015) (West Conshohocken, PA: ASTM International, approved July 1, 2015), https://doi.org/10.1520/D7175-15
26. *Standard Specification for Performance-Graded Asphalt Binder Using Multiple Stress Creep Recovery (MSCR) Test*, AASHTO M 332 (2020) (Washington, DC: AASHTO Provisional Standards, 2020).
27. *Standard Test Method for Multiple Stress Creep and Recovery (MSCR) of Asphalt Binder Using a Dynamic Shear Rheometer*, ASTM D7405-20 (2020) (West Conshohocken, PA: ASTM International, approved March 1, 2020), https://doi.org/10.1520/D7405-20
28. C. Wekumbura, J. Stastna, and L. Zanzotto, "Destruction and Recovery of Internal Structure in Polymer-Modified Asphalts," *Journal of Materials in Civil Engineering* 19, no. 3 (March 2007): 227–232, https://doi.org/10.1061/(ASCE)0899-1561(2007)19:3(227)
29. M. Ragab, M. Abdelrahman, and A. Ghavibazoo, "Performance Enhancement of Crumb Rubber–Modified Asphalts through Control of the Developed Internal Network Structure," *Transportation Research Record* 2371, no. 1 (January 2013): 96–104, https://doi.org/10.3141/2371-11
30. G. Holleran and I. Holleran, "Bitumen Chemistry Using Cheaper Sources - An Improved Method of Measurement by TLCFID and the Characterisation of Bitumen by Rheological and Compositional Means" (paper presentation, 24th ARRB Conference, Melbourne, Australia, October 12–15, 2010).
31. C. Jiang, S. R. Larter, K. J. Noke, and L. R. Snowdon, "TLC–FID (Iatroscan) Analysis of Heavy Oil and Tar Sand Samples," *Organic Geochemistry* 39, no. 8 (August 2008): 1210–1214, https://doi.org/10.1016/j.orggeochem.2008.01.013

32. R. M. Silverstein, F. X. Webster, and D. J. Kiemle, *Spectrometric Identification of Organic Compounds,* 7th ed. (Hoboken, NJ: John Wiley and Sons, 2005).
33. W. van den Bergh, "The Effect of Ageing on the Fatigue and Healing Properties of Bituminous Mortars" (PhD diss., Delft University of Technology, 2011).
34. P. Beauchamp, "Spectroscopy Tables: Infrared Tables (Short Summary of Common Absorption Frequencies)," California State Polytechnic University, 2011, http://web.archive.org/web/20210803084143/https://www.cpp.edu:443/~psbeauchamp/pdf/spec_ir_nmr_spectra_tables.pdf
35. H. Yao, Q. Dai, and Z. You, "Fourier Transform Infrared Spectroscopy Characterization of Aging-Related Properties of Original and Nano-modified Asphalt Binders," *Construction and Building Materials* 101, Part 1 (December 2015): 1078–1087, https://doi.org/10.1016/j.conbuildmat.2015.10.085
36. D. Ge, Z. You, S. Chen, C. Liu, J. Gao, and S. Lv, "The Performance of Asphalt Binder with Trichloroethylene: Improving the Efficiency of Using Reclaimed Asphalt Pavement," *Journal of Cleaner Production* 232 (September 2019): 205–212, https://doi.org/10.1016/j.jclepro.2019.05.164
37. H. Nishikiori, M. Hayashibe, and T. Fujii, "Visible Light-Photocatalytic Activity of Sulfate-Doped Titanium Dioxide Prepared by the Sol–Gel Method," *Catalysts* 3, no. 2 (April 2013): 363–377, https://doi.org/10.3390/catal3020363
38. J.-F. Masson, L. Pelletier, and P. Collins, "Rapid FTIR Method for Quantification of Styrene-Butadiene Type Copolymers in Bitumen," *Journal of Applied Polymer Science* 79, no. 6 (February 2001): 1034–1041, https://doi.org/10.1002/1097-4628(20010207)79:6<1034::AID-APP60>3.0.CO;2-4
39. Q. Zhou, H. Liang, W. Wei, C. Meng, Y. Long, and F. Zhu, "Synthesis of Amphiphilic Diblock Copolymers of Isotactic Polystyrene-Block-Isotactic Poly(p-Hydroxystyrene) Using a Titanium Complex with an [OSSO]-Type Bis(Phenolate) Ligand and Sequential Monomer Addition," *RSC Advances* 7, no. 32 (April 2017): 19885–19893, https://doi.org/10.1039/C7RA01450C
40. E. Deef-Allah and M. Abdelrahman, "Investigating the Relationship between the Fatigue Cracking Resistance and Thermal Characteristics of Asphalt Binders Extracted from Field Mixes Containing Recycled Materials," *Transportation Engineering* 4 (June 2021): 100055, https://doi.org/10.1016/j.treng.2021.100055
41. C. de la Roche, M. van de Ven, J.-P. Planche, W. van den Bergh, J. Grenfell, T. Gabet, V. Mouillet, L. Porot, F. Farcas, and C. Ruot, "Hot Recycling of Bituminous Mixtures," in *Advances in Interlaboratory Testing and Evaluation of Bituminous Materials*, ed. M. N. Partl, H. U. Bahia, F. Canestrari, C. de la Roche, H. di Benedetto, H. Piber, and D. Sybilski (Dordrecht, the Netherlands: Springer Netherlands, 2013), 361–428, https://doi.org/10.1007/978-94-007-5104-0
42. D. Singh and D. Sawant, "Understanding Effects of RAP on Rheological Performance and Chemical Composition of SBS Modified Binder Using Series of Laboratory Tests," *International Journal of Pavement Research and Technology* 9, no. 3 (May 2016): 178–189, https://doi.org/10.1016/j.ijprt.2016.06.002
43. R. S. Mullapudi and K. S. Reddy, "An Investigation on the Relationship between FTIR Indices and Surface Free Energy of RAP Binders," *Road Materials and Pavement Design* 21, no. 5 (July 2020): 1326–1340, https://doi.org/10.1080/14680629.2018.1552889
44. M. Gong, J. Yang, H. Yao, M. Wang, X. Niu, and J. E. Haddock, "Investigating the Performance, Chemical, and Microstructure Properties of Carbon Nanotube-Modified Asphalt Binder," *Road Materials and Pavement Design* 19, no. 7 (October 2018): 1499–1522, https://doi.org/10.1080/14680629.2017.1323661
45. B. Hofko, L. Porot, A. Falchetto Cannone, L. Poulikakos, L. Huber, X. Lu, K. Mollenhauer, and H. Grothe, "FTIR Spectral Analysis of Bituminous Binders: Reproducibility and Impact of Ageing Temperature," *Materials and Structures* 51, no. 2 (March 2018): 45, https://doi.org/10.1617/s11527-018-1170-7
46. M. Sá da Costa, F. Farcas, L. F. Santos, M. I. Eusébio, and A. C. Diogo, "Chemical and Thermal Characterization of Road Bitumen Ageing," *Materials Science Forum* 636–637 (January 2010): 273–279, https://doi.org/10.4028/www.scientific.net/MSF.636-637.273
47. W. H. Daly, I. I. Negulescu, and S. S. Balamurugan, *Chemical Characterization of Asphalts Related to Their Performance, FHWA/LA.15/560* (Baton Rouge, LA: Louisiana Transportation Research Center, 2019).
48. J. S. Daniel, M. Corrigan, C. Jacques, R. Nemati, E. V. Dave, and A. Congalton, "Comparison of Asphalt Mixture Specimen Fabrication Methods and Binder Tests for Cracking Evaluation of Field Mixtures," *Road Materials and Pavement Design* 20, no. 5 (July 2019): 1059–1075, https://doi.org/10.1080/14680629.2018.1431148
49. W. Mogawer, T. Bennert, J. S. Daniel, R. Bonaquist, A. Austerman, and A. Booshehrian, "Performance Characteristics of Plant Produced High RAP Mixtures," *Road Materials and Pavement Design* 13, no. S1 (June 2012): 183–208, https://doi.org/10.1080/14680629.2012.657070
50. P. G. Santangelo and C. M. Roland, "Interrupted Shear Flow of Unentangled Polystyrene Melts," *Journal of Rheology* 45, no. 2 (February 2001): 583–594, https://doi.org/10.1122/1.1349711
51. D. De Kee and C. F. Chan Man Fong, "Rheological Properties of Structured Fluids," *Polymer Engineering and Science* 34, no. 5 (March 1994): 438–445, https://doi.org/10.1002/pen.760340510
52. M. Whittle and E. Dickinson, "Stress Overshoot in a Model Particle Gel," *Journal of Chemical Physics* 107, no. 23 (July 1997): 10191–10200, https://doi.org/10.1063/1.474155
53. Y. Masubuchi, Y. Doi, and T. Uneyama, "Primitive Chain Network Simulations for the Interrupted Shear Response of Entangled Polymeric Liquids," *Soft Matter* 16, no. 28 (June 2020): 6654–6661, https://doi.org/10.1039/D0SM00654H
54. M. A. Lockyer and K. Walters, "Stress Overshoot: Real and Apparent," *Rheologica Acta* 15, no. 3 (March 1976): 179–188, https://doi.org/10.1007/BF01526065