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TECHNICAL PAPER

Thermal, chemical and rheological properties of asphalt binders extracted from field cores

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Abstract
The intermediate-temperature performance of extracted asphalt binders (EABs) is altered when recycled asphalt shingles (RAS) and/or reclaimed asphalt pavement (RAP) are included in asphalt mixes. This happened as a result of the RAP’s aged asphalt binder and the RAS’s oxidized air-blown asphalt. Thus, the rheological properties of EABs from field cores were examined at intermediate temperatures. The fatigue life and the Superpave fatigue cracking parameter were among the rheological properties. Thermogravimetric analysis and Fourier transform infrared were used to analyze EABs’ thermal and chemical characteristics, respectively. The relationships between EABs’ fatigue cracking resistance, thermal, and chemical characteristics were scrutinized. Ages of mixes, percentages of RAP and/or RAS, and intermediate performance grade (PG) temperatures of virgin asphalt binders (VABs) controlled the resistance of EABs to fatigue cracking. Considering VABs with the same intermediate PG temperatures, EABs from older mixes with higher RAS percentages had higher resistance to fatigue cracking than those from younger mixes with lower RAP percentages. When RAP percentages in asphalt mixes were increased, EABs’ resistance to fatigue cracking deteriorated. Thermal and chemical analyses along with rheological characteristics are suggested as indicators of EABs’ intermediate-temperature performance.

Keywords Fatigue cracking · Thermal analysis · Chemical analysis · TGA · FTIR · Residue

Introduction
Recycled asphalt shingles (RAS) and reclaimed asphalt pavement (RAP) have essential components that make them more appropriate for usage in asphalt mixtures [1]. RAP is typically produced by milling old asphalt pavement, and it can be created at the asphalt plant as leftover hot mix asphalt materials [2]. Aggregates and aged asphalt binders make up RAP [3–5]. RAS is derived from two sources: post-consumer (tear-off) and post-manufactured shingles. Post-manufactured shingles are waste products of the single manufacturing process, such as factory scraps and tab cut-outs, whereas post-consumer shingles are shingles that mainly come from residential and business building roofs after their life span has ended, which include damage from inclement weather [6]. RAS includes 19–36% by weight oxidized air-blown asphalt binder, 20–38% by weight granules (e.g., sand-sized natural aggregate or ceramic-coated), 8–40% by weight mineral filler/stabilizer, and 2–20% by weight fibers (e.g., fiberglass or cellulose backing) [7, 8]. The use of RAP and/or RAS in asphalt mixes offers both economic and environmental advantages [9–11]. The use of 20% RAP in asphalt mixes reduced energy consumption by 5.0–7.5% [9]. Using 35% RAP in a 1-mile-long overlay section cut costs by 25% [10]. The addition of 5% RAS in asphalt mixes resulted in cost savings ranging from $1.00 to $2.80 per ton [11].

The incorporation of RAS and/or RAP into asphalt mixes influences the performance of the total binders in the mixes, including virgin asphalt binders (VABs) and aged binders in RAS and/or RAP [4]. At high temperatures, utilizing RAS and/or RAP in asphalt mixes boosted the rutting resistance of extracted asphalt binders (EABs) due to the stiff binders in RAP and RAS [12–14] based on the exchanged components between RAP or RAS and VAB [14]. At low temperatures, it was reported that mixing RAS binder with a
performance grade (PG) 58–28 binder resulted in a low-temperature change of 0.4 °C per 1% of asphalt binder replacement (ABR) [15]. Compared to EABs extracted from mixes that did not contain RAP and/or RAS, the inclusion of RAP and/or RAS in asphalt mixes harmed the low-temperature capabilities of EABs [16]. Additionally, utilizing RAS in asphalt mixes worsened the low-temperature characteristics of EABs when compared to EABs extracted from RAP-containing mixes [16]. At intermediate temperatures, increasing the percentage of ABR by RAP in asphalt mixes deteriorated the fatigue resistance of EABs [17–19]. The addition of ground RAS to asphalt binders improved resistance to fatigue cracking and led to higher fatigue life (Nf) values. The Superpave fatigue cracking parameter (G*|sinδ| values), on the other hand, increased, indicating a reduced resistance to fatigue cracking [20]. Another research, executed by Abbas et al. [21], found that employing various percentages of RAS binder, 5, 7, and 10% by weight, with VAB had no effect on G*|sinδ| values when compared to the G*|sinδ| value of VAB.

Fatigue cracking resistance is assessed using the G*|sinδ| parameter in the Superpave grading system [22]. More elastic asphalt binders with lower δ values and less stiff asphalt binders with lower G* values are advised to withstand fatigue cracking [23]. The G*|sinδ| parameter, according to Johnson [24], was a measure of undamaged linear viscoelastic characteristics premised on the concept of dissipated energy and did not indicate damage during cyclic loading. Another test, the linear amplitude sweep (LAS), which relies on viscoelastic continuum damage (VECD) analysis, has been proven to be more accurate in predicting the Nf of asphalt binders [24–26]. However, the LAS test was not included in the Superpave testing. Kim et al. [27] examined the G*|sinδ| of a styrene butadiene styrene (SBS) polymer-modified binder, as a VAB, blended with various percentages of RAP EAB, and discovered that including RAP binder and increasing its percentage in the VAB impaired the fatigue cracking resistance compared to VAB. Other studies [28, 29] reported the same observations: Blending RAP EABs with VAB decreased the Nf when compared to the value of VAB, and increasing the ABR by RAP reduced the Nf value. These variations in EABs’ performance tracked changes in these binders’ compositions [14].

To anticipate binders’ compositional changes and their fatigue resistance, the onset temperature (T_onset) for mass loss during the pyrolysis process by thermogravimetric analysis (TGA) is adopted [17, 30]. T_onset is defined by ISO 11358-1 [31] as the point at which the thermograph (TG) beginning-mass baseline intersects with the tangent to the TG curve at the highest gradient. Furthermore, the shapes of the derivative of thermograph (DTG) during thermal degradation reflect the asphalt binders’ compositions [17, 32]. Because the RAP binder contains a high content of asphaltene [33], the components of EABs—maltenes and asphaltene—alter depending on how the RAP binder and VAB interact. These interactions and related changes in asphalt fractions can be explored through TGA. Nciri et al. [34] found that using waste pig fat as a rejuvenator with RAP binders increased fatigue cracking resistance—by having G*|sinδ| lower values—and decreased the T_onset and percentage of residue (%R) or char at the end of the pyrolysis process.

The aging components included in RAP and/or RAS exchanged with VABs in asphalt mixes caused more stiffness by altering the binders’ chemical composition [12–14, 17]. Hence, the aging components exchanged between RAP or VAB and RAS altered the Fourier transform infrared (FTIR) aging indices [carbonyl index (I_C), aromatic index (I_A), and aliphatic index (I_CH)] [12, 13]. Deef-Allah and Abdelrahman [17] correlated FTIR indices with G*|sinδ| for EABs from field cores; direct relationships were noted between I_C, I_A, and G*|sinδ|. However, inverse relationships were noticed between G*|sinδ|, I_SO or I_CH. The long-term aging processes in the field caused an increase in the I_C, I_A, and a decrease in the I_CH for EABs. However, the sulfoxide degraded, and the I_SO decreased. These findings were accompanied by an increase in the G*|sinδ| values. A direct relationship was observed between T_onset and G*|sinδ|; however, an inverse relationship was found between T_onset and Nf at 2.5% strain. Hence, direct relationships between I_C, I_A, and T_onset have been recorded, and inverse relationships between T_onset and I_SO or I_CH have been observed. In addition, inverse relationships were noticed between I_C, I_A, and Nf, and direct relationships were noted between Nf and I_SO or I_CH. Based on these relationships, the lowest G*|sinδ|, T_onset, I_C, I_A, I_CH, the highest Nf, I_SO, and I_CH were found in EABs from field cores with the highest resistance to fatigue cracking.

The characteristics of the asphalt binder in the pavement alter over years of use, and the pavement stiffens [35]. Moreover, storing RAP in stockpiles accelerates the aging process of the RAP binder due to air exposure [36, 37]. RAS binders stiffen throughout manufacture and after years of oxidative aging in service, and as a result, RAS binders become substantially stiffer than binders commonly used in pavements [6]. Besides the highly oxidized air-blown asphalt in RAS, the in-service and storage aging processes in RAP and RAS result in the loss of low-molecular-weight fractions owing to oxidation—oxidation that causes compositional changes—or volatilization—as well as steric hardening due to molecular structuring [35, 38]. Hence, the EABs from field cores were assessed as long-term aged binders in this study. Furthermore, owing to the aging components in RAP and/ or RAS, the EABs’ main concerns were thermal cracking.
and fatigue cracking at low and intermediate temperatures, respectively. In a previous study [16], the EABs’ thermal cracking resistance was assessed. Therefore, the primary objective of this study was to evaluate the fatigue cracking resistance of EABs from field mixes. The objective of this study was achieved by establishing relationships between EABs’ fatigue resistance, thermal, and chemical analysis. In a previous study [17], the relationships between the resistance to fatigue cracking [(|G*|.sinδ) and Nf at 2.5% strain], T_onset, and FTIR indices were investigated. Further investigations were explored in this study on the relationships between resistance to fatigue cracking [(|G*|.sinδ) and Nf at 2.5% and 5% strain levels], T_onset, %R, and FTIR indices.

Materials and methods

Materials

Field cores were sampled from several Missouri roads. The asphalt mixes in the collected cores contained different ABR% by RAS and/or RAP and various PGs of VABs. The asphalt mixes’ ages ranged between 4 and 14 years during the coring process. Therefore, EABs from those mixes were classified as long-term aged binders. Two mixes—US 54-7 and MO 94—did not include RAS or RAP. Detailed information on asphalt mixes is presented in Table 1. Representative samples from field cores are deemed in Fig. 1.

Methods

The experimental program involved six phases, as represented in Fig. 2. The first phase included coring the field samples, gathering information on the asphalt mixes in these cores, as indicated in Table 1, and preparing the mixes before extraction by heating them in the oven at 100 °C for 1–1.5 h. The second phase was achieved by extracting asphalt binders from the mixes using a centrifuge extractor. Then, in the third phase, the asphalt binders were recovered from the extracted binder-solvent solutions using a rotavap. Rheological, chemical, and thermal tests were implemented for each EAB from each field core, and the results were averaged for EABs from field cores representing the same asphalt mix. Rheological testing at intermediate temperatures for EABs was conducted through a dynamic shear rheometer (DSR) as a fourth phase. The chemical and thermal properties of EABs are good indicators of the fatigue resistance of EABs [17]. Therefore, the fifth phase, the chemical properties of EABs, contained the FTIR qualitative and quantitative analyses for EABs. Finally, following the sixth phase, the thermal properties of EABs were examined using TGA.

Table 1 Field cores’ details

| Mix code | Route-direction | Virgin asphalt PG† | Total ACb (%) | ABRc by RAPd,RAS e (%) | Construction year | Coring year | Number of collected cores | Agef (years) |
|----------|-----------------|--------------------|---------------|------------------------|------------------|-------------|--------------------------|-------------|
| US 54-1  | US 54-WB        | 64−22              | 6.2           | 0–0                    | 2003             | 2016        | 3                        | 13          |
| US 54-2  | US 54           | 70−22 g           | 5.6           | 9–0                    | 2006             | 3           | 10                       |
| US 50    | US 50           | 64−22              | 5.0           | 25–0                   | 2011             | 3           | 5                        |
| MO 52    | MO 52           | 64−22              | 4.8           | 0–34                   | 2010             | 3           | 6                        |
| US 63    | US 63-SB        | 64−22              | 5.6           | 20–10                  | 2008             | 3           | 8                        |
| MO 94    | MO 94           | 64−22              | 5.6           | 0–0                    | 2005             | 3           | 14                       |
| US 54-3  | US 54-E         | 70−22 g           | 5.7           | 12–0                   | 2010             | 3           | 9                        |
| US 36    | US 36-E         | 64−22              | 5.1           | 25–0                   | 2011             | 3           | 8                        |
| MO 6     | MO 6-W          | 58−28              | 5.9           | 30–0                   | 2015             | 5           | 4                        |
| US 61    | US 61-N         | 64−22H             | 5.3           | 30–0                   | 2013             | 3           | 6                        |
| MO 151   | MO 151          | 64−22              | 4.7           | 16–15                  | 2014             | 5           | 5                        |

†PG: performance grade
‡AC: asphalt content
§ABR: asphalt binder replacement
∥RAP: reclaimed asphalt pavement
¶RAS: recycled asphalt shingles
§Age: age of mix during the coring process
#Styrene butadiene styrene was included in these binders
Fig. 1 Representative samples from field cores collected in a 2016 and b 2019

Fig. 2 Experimental program

1st Phase
Collecting Field Cores and Preparing them before the Extraction Process by Warming them in the Oven at 100 °C for 1–1.5 hr

2nd Phase
Extracting Asphalt Binders from Loose Field Mixes using a Centrifuge Extractor

3rd Phase
Recovery of Asphalt Binders from Extracted Binder-Solvent Solution using Rotavap

4th Phase
Rheological Properties of EABs using a DSR at Intermediate Temperatures

5th Phase
Chemical Properties of EABs using FTIR

6th Phase
Thermal Properties of EABs using TGA
Extraction and recovery of asphalt binders from field cores

Asphalt binders were extracted from field cores according to ASTM D2172/D2172M-17el [39], discussed as method A, using a centrifuge extractor and trichloroethylene (TCE) solvent. Asphalt binders were recovered from the extracted solution (asphalt binders dissolved in TCE) using a rotavap according to ASTM D5404/D5404M-21 [40].

Rheological properties of EABs

Asphalt binders were extracted from mixtures cored from the field. During the coring time, the asphalt mixes’ ages ranged between 4 and 14 years. Thus, EABs were considered long-term aged binders, and the main concerns for these binders were fatigue cracking and thermal cracking at intermediate and low temperatures, respectively. Another study [16] assessed the low-temperature rheological properties of EABs. The focus of this study was the intermediate-temperature rheological properties of EABs that were analyzed using a DSR. The intermediate-temperature rheological properties of EABs reflected EABs’ resistance to fatigue cracking. Unfortunately, VABs used in these mixes were not available for comparison with EABs. Samples of EABs with an 8-mm diameter and a 2-mm thickness were tested. The $|G^*|\sin \delta$ parameter was calculated for EABs at 1.59 Hz frequency [41], 1% shear strain to remain within the linear viscoelastic region [41, 42], and 22 °C as the reference temperature. The LAS test was performed according to AASHTO TP 101-14 [43] at a reference temperature of 22 °C. There were two stages to the LAS test. To analyze the damage, the first stage required running a frequency sweep test with a 0.1% strain load and a frequency range of 0.2 Hz to 30 Hz (containing 12 frequencies); to minimize accumulated deformation, the amplitude sweep test—the second stage of the LAS test—was performed at a constant frequency of 10 Hz in a strain-control mode. A linearly increasing strain load from 0 to 30% was applied for 3100 loading cycles at 10 cycles/second to accelerate damage. EABs’ $N_f$ values were calculated at 2.5% and 5% strain values using Eq. (1) [41]. The strain of the asphalt binder is estimated to be 50 times that of the bulk mixture strain [44, 45]. Strong pavement with a thickness of more than 4 inches is estimated to have a 500 μm strain, meaning the binder’s strain is 2.5%. The strain in a weak pavement with a thickness of less than 4 inches is predicted to be 1000 μm, thereby the binder’s strain is 5% [45, 46]. The $N_f$ is characterized by the following equation [43]:

$$N_f = A(r_{max})^{-B}$$

(1)

where $r_{max}$ is the maximum expected asphalt binder strain (%) for a given pavement structure, and $A$ and $B$ are parameters that are calculated using Eqs. (2) and (3), respectively, using the VECD principle [43]. The following equation represents the $A$ parameter [43]:

$$A = \frac{f(D_i)^k}{k(\pi C_1 C_2)^\alpha}$$

(2)

The next equation reflects the $B$ parameter [43]:

$$B = 2\alpha$$

(3)

where $f$ is 10 Hz loading frequency,

$$k = 1 + (1 - C_2)\alpha,$$

$$\alpha = 1/m$$

$\alpha$ is the damage analysis parameter, and $m$ is the slope of the linear relationship between elastic modulus $G'(\omega)$ and log $(\omega)$,

$$G'(\omega) = |G*| (\omega) \cos \delta(\omega),$$

where $|G*| (\omega)$ is the complex shear modulus, $\delta(\omega)$ is the phase angle, $\omega$ is the angular frequency, and $D_i$ is the value of the damage accumulation $[D(t)]$ at failure, as represented by Eq. (4), and it corresponds to the decrease in starting $|G*|$ at the highest shear stress. The $D_i$ is simplified by the following equation [43]:

$$D_i = \left(\frac{C_0 - C}{C_1}ight)^{1/C_2}$$

(4)

The $D(t)$, adopted by Kim et al. [47], is estimated using Eq. (5), as represented by the following equation [43]:

$$D(t) = \frac{\sum_{i=1}^{N} \left[\pi \gamma^2 e(C_{i-1} - C_i)\right]}{t^{1/\gamma}} (t - t_{i-1})^{1/\gamma}$$

(5)

where $D$ is the damage intensity, $C$ is the integrity parameter of material, $t$ is the testing time in s,

$$C(t) = \frac{G*_{0}}{|G*|_{initial}}$$

where $|G*|$ is the complex shear modulus in MPa, and $|G*|_{initial}$ is the undamaged value of $|G*|$.

The $C(t)$ and $D(t)$ values are recorded, and Eq. (6) is used to fit a power relationship between these values. As a result of damage accumulated from repeatable loads, the asphalt binder lacks structural integrity [48]. The relationship between $C(t)$ and $D(t)$ is characterized by the following equation [43]:

$$C(t) = C_0 - C_1 (D)^{C_2}$$

(6)
where \( C_0 \) is assumed to be equal to one, and \( C_1 \) and \( C_2 \) are the regression coefficients.

**Chemical properties of EABs**

A Nicolet iS50 FTIR spectrometer was utilized to analyze molecules’ vibrations in EABs. By placing EABs on a diamond crystal, an attenuated total reflection mode was utilized. The experimental setup was carried out using OMNIC 9 software, with 32 scans at a resolution of 4 and wave numbers ranging from 4000 to 400 \( \text{cm}^{-1} \). A quantitative FTIR analysis was performed by evaluating the carboxyl index \( (I_{\text{CO}}) \), sulfoxide index \( (I_{\text{SO}}) \), aromatic index \( (I_{\text{CC}}) \), and aliphatic index \( (I_{\text{CH}}) \). At 1700 \( \text{cm}^{-1} \), the \( I_{\text{CO}} \) reveals aging owing to carboxyl (C=O), as indicated in Eq. (7). At 1030 \( \text{cm}^{-1} \), the \( I_{\text{SO}} \) represents aging due to sulfoxide (S=O); notice Eq. (8) [49–51]. The band’s area for methylene \( (\text{CH}_2) \) at 1460 \( \text{cm}^{-1} \) and methyl \( (\text{CH}_3) \) at 1375 \( \text{cm}^{-1} \) reflects the C–H bending vibrations; aging has no significant effect on these areas [50, 52]. Equations (9) and (10) are used to compute the C=C stretching in the \( I_{\text{CC}} \) and the C–H bending in the \( I_{\text{CH}} \), respectively [53, 54]. The increase in the \( I_{\text{CC}} \) and the decrease in the \( I_{\text{CH}} \) mirror the increase in the aging processes of asphalt binders because low-molecular-weight aliphatics are transformed into high-molecular-weight aromatics [53]. Between a baseline with low-molecular-weight aliphatics are transformed into high-molecular-weight aromatics [53]. When assessing the FTIR indices, the boundaries and the FTIR curved line, the band’s area was determined [50, 52, 55]. When assessing the FTIR indices, the boundaries of the baseline, presented in Table 2, should be the same for all binders [50].

The following equation represents the \( I_{\text{CO}} \):

\[
I_{\text{CO}} = \frac{\text{Area at } 1700 \text{ cm}^{-1} \text{ band}}{\text{Area at } 1460 \text{ cm}^{-1} \text{ band} + \text{Area at } 1375 \text{ cm}^{-1} \text{ band}}
\]

(7)

The \( I_{\text{SO}} \) is characterized by the following equation:

\[
I_{\text{SO}} = \frac{\text{Area at } 1030 \text{ cm}^{-1} \text{ band}}{\text{Area at } 1460 \text{ cm}^{-1} \text{ band} + \text{Area at } 1375 \text{ cm}^{-1} \text{ band}}
\]

(8)

The \( I_{\text{CC}} \) is illustrated by the subsequent equation:

\[
I_{\text{CC}} = \frac{\text{Area at } 1600 \text{ cm}^{-1} \text{ band}}{\sum \text{Area at } 1460, 1375, 1030, 1700, \text{ and } 1600 \text{ cm}^{-1} \text{ bands}}
\]

(9)

The \( I_{\text{CH}} \) is expressed by the next equation:

\[
I_{\text{CH}} = \frac{\text{Area at } 1460 \text{ cm}^{-1} \text{ band} + \text{Area at } 1376 \text{ cm}^{-1} \text{ band}}{\sum \text{Area at } 1460, 1375, 1030, 1700, \text{ and } 1600 \text{ cm}^{-1} \text{ bands}}
\]

(10)

**Thermal properties of EABs**

A TGA was performed on the EABs to characterize their thermal analysis. The thermal characteristics of EABs were evaluated using a Discovery TGA 550 model and according to ASTM E1131-20 [56]. Thermal characteristics included TG parameters [17–19]—\( T_{\text{onset}}, \) endset temperature (\( T_{\text{endset}} \)), and \%R—and DTG parameters [e.g., the temperature at the DTG curve’s first peak (\( T_1 \)) and the temperature at the DTG curve’s second peak (\( T_2 \))]. EABs weighing 15–25 mg were heated to 750 °C from room temperature using a maximum heating rate of 50 °C/min, TA® Instruments’ patented high-resolution dynamic method [57, 58], and a nitrogen flow rate of 60 ml/min. The heating rate is dynamically and continually changed during the sample’s decomposition in the high-resolution dynamic method to optimize resolution [57, 58]. As the rate of weight loss accelerates, the heating rate slows down. As a consequence, both resolution and productivity are improved, which are typically quicker than constant heating rate tests [58].

**Rheological properties of EABs**

**Results and analysis**

**Chemical properties of EABs**

**Thermal properties of EABs**

**Rheological properties of EABs**

**Table 2** Baseline boundaries for FTIR bands [50, 52, 55]

| FTIR band at wave number in cm\(^{-1}\) | Baseline boundaries in cm\(^{-1}\) |
|----------------------------------------|----------------------------------|
| Carboxyl at 1700 cm\(^{-1}\)           | 1660–1753 cm\(^{-1}\)            |
| Sulfoxide at 1030 cm\(^{-1}\)          | 995–1047 cm\(^{-1}\)            |
| Methylene at 1460 cm\(^{-1}\)         | 1400–1525 cm\(^{-1}\)           |
| Methyl at 1375 cm\(^{-1}\)            | 1350–1390 cm\(^{-1}\)           |
| Aromatics at 1600 cm\(^{-1}\)         | 1535–1670 cm\(^{-1}\)           |

*FTIR: Fourier transform infrared*
higher repeatability for the $|G^*| \sin \delta$ than for the $N_f$. The coefficient of variation (COV) values for the $N_f$ ranged between 0 and 25%, but the COV values for the $|G^*| \sin \delta$ were between 0 and 11%. The following equation reflects the calculation of the intermediate PG temperature for VABs:

$$\text{Intermediate PG temperature} = \frac{(\text{High} + \text{Low})}{2} + 4 \quad (11)$$

where, High is the high PG temperature, and Low is the low PG temperature.

The $N_f$ values at 22 °C for EABs measured at 2.5% and 5% strain levels are shown in Fig. 3a, b), respectively. At 22 °C, the EABs' $|G^*| \sin \delta$ values are illustrated in Fig. 3c. The highest $N_f$ values and the lowest $|G^*| \sin \delta$ values were discovered for the MO 6 EABs, revealing the highest resistance to fatigue cracking. The MO 6 mix included the highest ABR by RAP (30%); however, it contained VAB with the lowest intermediate PG temperature (19 °C), and it was the youngest mix during the coring process. Despite the stiff RAS's air-blown asphalt binder, EABs from the MO 52-1 mix with 34% ABR by RAS had the second-highest $N_f$ value at 2.5% strain level (Fig. 3a) and the third-lowest $|G^*| \sin \delta$ value (Fig. 3c). By comparing the US 50 and MO 52 EABs, the MO 52 EABs had higher $N_f$ and lower $|G^*| \sin \delta$ values, reflecting higher resistance to fatigue cracking. Both US 50 and MO 52 mixes contained VABs with a 25 °C intermediate PG temperature. However, the MO 52 mix was older and included a higher total ABR% than the US 50 mix. The same findings were concluded when comparing EABs from the MO 52 and MO 151 mixes: The MO 52 EABs had lower $N_f$ and higher $|G^*| \sin \delta$ values than the MO 151 mix. Furthermore, the intermediate PG temperatures of the VABs in both mixes were 25 °C. These findings reflect the potential of RAS binders to boost EABs' resistance to fatigue cracking.

The US 50 EABs had lower $N_f$ and higher $|G^*| \sin \delta$ values than the US 54-2 EABs. The US 54-2 mix had twice the
age of the US 50 mix during the coring process, and the intermediate PG temperature of the VAB in the US 54-2 mix was higher than that of the VAB in the US 50 mix. Nonetheless, the US 50 mix included higher ABR% by RAP than the US 54-2 mix. Additionally, the US 54-2 VAB was modified by SBS, which enhanced the EABs’ resistance to fatigue cracking due to the effect of the cross-linked elastomer network in SBS [61, 62]. The same findings were deduced by comparing the US 54-2 and US 54-3 EABs: The US 54-3 EABs showed lower $N_f$ and higher $|G^*|\sin\delta$ values than the US 54-2 EABs. SBS-modified VABs with intermediate PG temperatures of 28 °C were used in the US 54-2 and US 54-3 mixes, and the US 54-3 mix was one year younger than the US 54-2 mix. However, the US 54-3 mix had a higher ABR% by RAP than the US 54-2 mix. As a result, when RAP percentages in asphalt mixes were increased, the EABs’ resistance to fatigue cracking worsened.

The MO 151, US 54-3, and US 63 EABs had the lowest $N_f$ values, and the maximum $|G^*|\sin\delta$ values were determined for the MO 151 and US 54-3 EABs, signifying the worst resistance to fatigue cracking. For mixes including RAS and/or RAP, the US 54-3 was the second-oldest mix after the US 54-2 mix. However, the US 54-3 mix included higher ABR% by RAP than the US 54-2 mix. Therefore, incorporating RAS and RAP into asphalt mixes reduced the resistance of EABs to fatigue cracking. By analyzing the values of $|G^*|\sin\delta$ and $N_f$ at 5% strain level, the US 54-1 EABs had the second-highest resistance to fatigue cracking after the MO 6 EABs. Even though the US 54-1 mix was 13 years old at the time of coring, it was free of RAP or RAS. Consequently, using RAP and/or RAS in asphaltic mixes reduced EABs’ resistance to fatigue cracking when compared to EABs from mixes without RAS or RAP.

The C-D curves for EABs are depicted in Fig. 4, which indicates the relationship between damage intensity ($D$) and the integrity parameter ($C$). A higher $D$ value for the same $C$ value indicates superior resistance to fatigue cracking [63]. Thus, the highest resistance to fatigue cracking was for the MO 6 and US 54-1 EABs, which agrees with the $|G^*|\sin\delta$. The lowest resistance to fatigue cracking results were for the MO 151 EABs, which agrees with the $|G^*|\sin\delta$ results.

Figure 5 depicts the relationship between $N_f$ and $|G^*|\sin\delta$ at 22 °C for EABs from asphalt mixtures. Figure 5a shows the $N_f$ values at a 2.5% strain level, while Fig. 5b represents the $N_f$ values at a 5% strain level. Because the correlation coefficient ($|R|$) values were between 0.6 and 0.8 [64, 65], moderately strong power relationships were observed between the $N_f$ and $|G^*|\sin\delta$ values. In both figures, the trendlines indicate an inverse correlation between $N_f$ and $|G^*|\sin\delta$. EABs with the highest $N_f$ values had the lowest $|G^*|\sin\delta$ reflecting the highest resistance to fatigue cracking (e.g., MO 6 EAB).

The degradation of mechanical characteristics caused by the formation of microcracks or flaws in a material is commonly referred to as damage accumulation. The nucleation and development of material cracks often begin the damage accumulation process. These cracks accumulate to the point when the material fails completely, known as damage accumulation at failure ($D_f$) [66, 67]. The relationship between the $D_f$ and $N_f$ at 22 °C and 2.5% strain is deemed in Fig. 6a, whereas Fig. 6b shows the same relationship at 5% strain. Outliers were removed from figures. Because the $|R|$ value is between 0.8 and 1 [64, 65], the relationship is very strong. A direct polynomial relationship was observed between $D_f$ and $N_f$: The EAB with the highest $D_f$ had the highest $N_f$ (MO 6 EAB), indicating the strongest resistance to fatigue cracking.

![Fig. 4](image-url)  
**Fig. 4**  
*C–D* curves for EABs
Chemical properties of EABs

The FTIR qualitative analysis shows FTIR spectra for EABs from asphalt mixes for wave numbers greater than 1000 cm\(^{-1}\) (Fig. 7) and wave numbers less than 1000 cm\(^{-1}\) (Fig. 8). Because the asphalt binder is a hydrocarbon material, the majority of its molecular vibration involves carbon and/or hydrogen atoms [49]. Based on previous studies [14, 50, 68–70], and by analyzing EABs’ FTIR spectra for wave numbers greater than 1000 cm\(^{-1}\), Fig. 7, the EABs showed an FTIR band of O–H stretching at 3300 cm\(^{-1}\) wave number. A C–H stretching for aromatic (sp\(_2\) hybrids) was discovered at 3050 cm\(^{-1}\) wave number. From 3000 cm\(^{-1}\) to 2850 cm\(^{-1}\) wave numbers, C–H stretching for aliphatic (sp\(_3\) hybrids) was located. C=O stretching in carboxylic acid, C=C stretching for aromatic, and S=O stretching in sulfoxide bands were found at 1700 cm\(^{-1}\), 1600 cm\(^{-1}\), and 1030 cm\(^{-1}\) wave numbers, respectively.
By analyzing FTIR spectra for wave numbers less than 1000 cm$^{-1}$, as represented in Fig. 8, FTIR bands for C–H out-of-plane bending were found at 870 cm$^{-1}$, 815 cm$^{-1}$, and 748 cm$^{-1}$ wave numbers. A \((\text{CH}_2)_n\) rock vibration band was observed at 720 cm$^{-1}$ wave number. For the US 54-2 and US 54-3 EABs, two SBS bands were located at 699 cm$^{-1}$ and 966 cm$^{-1}$ wave numbers. The out-of-plane bending of the C–H group in the monosubstituted aromatic ring in polystyrene was linked to the band at 699 cm$^{-1}$ wave number [71, 72]. The FTIR band at 966 cm$^{-1}$ wave number was associated with trans-alkene C–H bending in polybutadiene [71]. Both the VABs of the US 54-2 and US 54-3 mixes were modified by SBS, and thus, their EABs showed SBS components.

In Fig. 9a, the FTIR quantitative analysis was assessed for each EAB by estimating the FTIR indices: $I_{\text{CO}}, I_{\text{SO}}, I_{\text{CC}}$. 

\[\text{Fig. 7} \text{ EABs’ FTIR spectra, wave numbers greater than 1000 cm}^{-1}\]

\[\text{Fig. 8} \text{ EABs’ FTIR spectra, wave numbers less than 1000 cm}^{-1}\]
The FTIR indices’ values were averaged for EABs from the same mix. The $I_{CO}$ showed the highest COV values (5.5–91%), and the $I_{CH}$ had the lowest COV values (1–4.9%). The COV values were between 0.7 and 13.6% for the $I_{SO}$ and between 0.1% and 22.7% for the $I_{CC}$. The $I_{CO}$ and $I_{SO}$ are used to assess the aging condition of the binders. Increasing the $I_{CO}$ and/or $I_{SO}$ reflects more aging processes that occurred in the binders. Additionally, the $I_{CH}$ and $I_{CC}$ indices are considered good indicators for binder aging because aliphatic compounds with lower molecular weights evolve into aromatic compounds with greater molecular weights during aging processes [14, 17, 53]. As a result, increasing the $I_{CO}$, $I_{SO}$, $I_{CC}$ and reducing the $I_{CH}$ represent an increase in the aging processes of asphalt binders. EABs from mixes without RAP or RAS, e.g., MO 94 and US 54-1, had the lowest $I_{CO}$ values; however, these mixes were the oldest.

The highest $I_{CO}$ values were noted for the US 54-3 and MO 151 EABs, which agrees with the rheological test results: These binders had the lowest resistance to fatigue cracking. The lowest $I_{CC}$ value was for EABs from the youngest mix (MO 6); however, the highest $I_{CC}$ values were for EABs from the MO 94 mix (the oldest one) and the US 54-3 mix. The lowest $I_{CH}$ values were for EABs from the US 54-3 mix, and the highest $I_{CH}$ values were for the MO 6, MO 151, and US 61 EABs. Interestingly, it was found that the US 54-3 EABs with the highest $I_{CC}$ values also had the lowest $I_{CH}$ values. Moreover, the MO 6 EABs with the lowest $I_{CC}$ values had the highest $I_{CH}$ values, which took place because the aliphatic molecules transform into aromatic molecules with aging [14, 17, 53]. Hence, increasing the $I_{CC}$ and decreasing the $I_{CH}$ reflect more aging processes in binders. $I_{SO}$ deteriorated in older asphalt mixes, including RAP and/or RAS.
because sulfoxide decomposed under high temperatures and long-term aging conditions [17, 73–75]. Thus, the lowest $I_{SO}$ was for EABs from mixes that included RAS (MO 52), followed by the MO 151 and US 54-3 EABs. Nevertheless, the highest $I_{SO}$ values were recorded for EABs from the MO 94 mix without RAP or RAS and then for EABs from the youngest mix (MO 6).

By analyzing the $I_{CO}$ plus $I_{CC}$ and $I_{SO}$ plus $I_{CH}$ in Fig. 9b, the US 54-1 had the lowest $I_{CO}$ plus $I_{CC}$ and the highest $I_{SO}$ plus $I_{CH}$ values, followed by the MO 6 EABs. The US 54-1 mix did not contain RAP or RAS, and the MO 6 was the youngest mix. These results revealed that both MO 6 and US 54-1 had the lowest aging FTIR indices, and thus, they showed the highest resistance to fatigue cracking. The highest $I_{CO}$ plus $I_{CC}$ value (0.33) and the lowest $I_{SO}$ plus $I_{CH}$ value (0.73) were for the US 54-3 and MO 151 EABs, which reflected the highest aging FTIR indices. As a result, the MO 151 and US 54-3 EABs had the lowest resistance to fatigue cracking.

### Thermal properties of EABs

Thermal characteristics of asphalt binders are analyzed by TGA by monitoring changes in TG parameters and DTG shapes [17–19, 32]. TG reflects the relationship between temperature and mass loss, whereas DTG explicates the relationship between temperature and the first derivative of weight with respect to temperature (decomposition rate) [49, 76, 77]. Figure 10 shows the TGA results of EABs from the US 61 2nd core, MO 6 5th core, and MO 151 5th core. These results included the TG parameters, DTG parameters, and DTG shapes. The estimated TG and DTG parameters of the US 61 2nd core EAB are shown in Fig. 10a: The $T_{onset}$ was 332.13 °C, $T_{endset}$ was 401.99 °C, %R was 16.80%, $T_1$ was 298.13 °C, and $T_2$ was 379.08 °C. Besides the TG and DTG parameters, the aging state of asphalt binders is manifested in the form of the DTG curve during thermal decomposition [17]. The DTGs of asphalt binders typically display three main zones, as represented in Fig. 10a. No mass loss occurs in the first zone, pyrolysis starts in the second zone, and the quickest cracking of molecules happens in the third zone [78]. Deef-Allah and Abdelrahman [17] discovered that

![Fig. 10 TG and DTG of EABs from a US 61 2nd core, b MO 6 5th core, and c MO 151 5th core](image)

| EAB Code | $T_{onset}$ (°C) | $T_{endset}$ (°C) | %R at 750 °C | $T_1$ (°C) | $T_2$ (°C) |
|----------|-----------------|------------------|-------------|------------|------------|
| US 54-1  | 341.37          | 402.71           | 15.61       | –          | 377.71     |
| MO 94    | 343.23          | 401.26           | 16.61       | –          | 379.10     |
| MO 52    | 342.39          | 406.10           | 18.92       | –          | 382.72     |
| US 63    | 339.11          | 407.47           | 19.22       | –          | 379.47     |
| MO 151   | 343.40          | 404.47           | 20.28       | –          | 378.02     |
| US 54-2  | 336.55          | 405.20           | 18.79       | –          | 380.58     |
| US 54-3  | 340.51          | 404.33           | 19.57       | –          | 375.89     |
| US 36    | 332.74          | 406.20           | 18.21       | –          | 381.28     |
| US 50    | 336.78          | 406.94           | 19.22       | –          | 381.31     |
| MO 6     | 320.04          | 412.32           | 19.44       | 294.17     | 386.95     |

$a$TG: thermograph

$b$DTG: derivative of thermograph

c$T_{onset}$: onset temperature
d$T_{endset}$: endset temperature
e%R: percentage of residue

$T_1$: temperature at the first peak of the DTG curve

$T_2$: temperature at the second peak of the DTG curve
for EABs from long-term aged field mixes, the second zone vanished, note Fig. 10c for the MO 151 5th core EAB. The MO 6 5th core EAB revealed the three DTG zones, as shown in Fig. 10b. The DTG of the US 61 2nd core EAB, shown in Fig. 10a, had three zones; however, the second zone began to disappear. The US 61 mix was older than the MO 6 mix by two years and had a stiffer VAB. Maltene shows two peaks in the DTG, whereas asphaltene has only one [32]. As a result, the disappearance of the second DTG zone implies a reduction in the EABs’ maltene component [17].

As presented in Table 3, the TG and DTG parameters for EABs from cores representing the same field mix were estimated and averaged. The MO 6 and US 61 EABs’ DTGs showed two peaks. However, the other EABs’ DTGs showed only one peak. The first peak corresponds to the second zone of the DTG, while the second peak belongs to the third zone of the DTG. This agrees with the results discussed in Fig. 10. From Table 3, the MO 151 EABs had the highest $T_{\text{onset}}$ and %R, reflecting the highest stiffnesses for these binders. The second-highest %R was for the US 54-3 EABs. Both US 54-3 and MO 151 EABs had the highest aging condition, as detected by the FTIR indices, and they showed the lowest resistance to fatigue cracking. The high stiffness of these EABs resulted from the high asphaltene content, as represented by the %R. Previous studies [79, 80] examined the thermal stability of the asphalt binder fractions—saturates, aromatics, resins, and asphaltenes—and it was found that the thermal stability was the highest for asphaltene, as the heaviest fraction with the highest molecular weight. Nevertheless, the thermal stability was the lowest for saturates, as the lightest fraction with the lowest molecular weight. Thus, asphaltene has the highest $T_{\text{onset}}$ and %R. The molecular chains of naphthene structures in saturates are easily broken at high temperatures. Thus, light volatiles and a little amount of coke—char or carbonaceous—are the decomposition components of saturates [79, 81]. The aromatics are composed of aromatic rings and side chains that are easily split from the aromatic rings. Therefore, coke is easily formed when aromatics are decomposed [79, 81]. Resins and asphaltene have a greater number of aromatic rings, which are not opened during the pyrolysis process. Additionally, asphaltenes are polynuclear molecules.
aromatic compounds with heteroatoms linked to oxygen-containing functional groups, and they are regarded as the primary cause of coke [79, 81, 82]. The lowest %R was noted for EABs from mixes without RAP or RAS (e.g., MO 94 and US 54-1); however, these mixes were the oldest. The US 54-1 mix was younger than the MO 94 mix by 1 year, so the US 54-1 EAB had a higher resistance to fatigue cracking than the MO 94 EAB, and the US 54-1 EAB had lower %R and T_onset values than the MO 94 EAB. The lowest T_onset value was recorded for the MO 6 EABs; these EABs had the highest resistance to fatigue cracking.

**Relationship between T_onset and resistance to fatigue cracking**

Figure 11a shows the relationship between T_onset and |G*|.sinδ, measured at 22 °C, for EABs. Outliers were not included in this figure. Because the |R| value is between 0.8 and 1, the relationship is very strong [64, 65]. T_onset and |G*|.sinδ have a direct polynomial relationship: EABs with the lowest T_onset had the lowest |G*|.sinδ values, indicating the highest resistance to fatigue cracking. The MO 6 EABs had the lowest T_onset and |G*|.sinδ values, demonstrating the best resistance to fatigue cracking.

**Relationship between %R and resistance to fatigue cracking**

Figure 12a shows the relationship between %R at 750 °C and |G*|.sinδ at 22 °C for EABs. Outliers were excluded from the figure. Because the |R| value is between 0.8 and 1 [64, 65], the relationship is very strong. A direct polynomial relationship was observed between |G*|.sinδ and %R: EABs

\[
|G*|.sin\delta = 624.8(\%R)^2 - 20787(\%R) + 178829
\]

\[R^2 = 0.65\]

\[N_f = 795.14(\%R)^2 - 31971(\%R) + 323904
\]

\[R^2 = 0.65\]

\[N_f = 2.1153(\%R)^2 - 138.37(\%R) + 1971.5
\]

\[R^2 = 0.75\]
with the highest \%R (e.g., MO 151 EAB) showed the highest \(|G^*| \sin \delta\) parameter, reflecting the poorest resistance to fatigue cracking. An increase in the \%R is interpreted as an increase in the asphaltene content and a decrease in the maltene content. Therefore, the stiffness of EABs increased when compared to the stiffness of EABs from mixes without RAP or RAS. The resistance of EABs to fatigue cracking decreased as the stiffness of EABs increased. Figure 12b depicts the relationship between the \%R and \(N_f\), measured under test conditions of 22 °C and 2.5% strain, for EABs. Figure 12c demonstrates the relationship between the \%R and \(N_f\), measured under test conditions of 22 °C and 5% strain, for EABs. Outliers were excluded from these figures. The relationships are very strong because the \(|R|\) value is between 0.8 and 1 [64, 65]. Inverse polynomial relationships were found between the \%R and \(N_f\) values. According to Fig. 12c, the EABs with the highest \%R had the lowest \(N_f\) values, reflecting the least resistance to fatigue cracking (e.g., MO 151 EAB). In the LAS test, the MO 151 EABs from the 2nd and 5th cores failed by showing zero \(N_f\) values during the coring phase, and it included 31% ABR by the FTIR indices in Fig. 9.

The relationship between \%R and \(T_{\text{onset}}\) for EABs is deemed in Fig. 13. Outliers were excluded from the figure. A moderately strong relationship is observed from this figure because the \(|R|\) value is between 0.6 and 0.8 [64, 65]. A direct polynomial relationship between the \%R and \(T_{\text{onset}}\) for EABs was noted: EABs with the highest \%R showed the highest \(T_{\text{onset}}\) values (e.g., MO 151), which is related to the highest asphaltene content. The MO 151 mix was 5 years old during the coring phase, and it included 31% ABR by RAP and RAS. EABs with the lowest \%R had the lowest \(T_{\text{onset}}\) values (e.g., US 61 and US 36). The MO 151 mix was younger than the US 61 and US 36 mixes. However, the MO 151 mix had a higher ABR% by RAP and RAS. As a result of the increase in asphaltene content caused by increasing the ABR% by RAP and RAS, the \%R and \(T_{\text{onset}}\) increased, reducing the EAB’s resistance to fatigue cracking.

**Relationships between FTIR Indices and resistance to fatigue cracking**

Figure 14 demonstrates the relationships between \(|G^*| \sin \delta\) values, determined under test conditions of 22 °C, and FTIR indices for EABs. Outliers were removed from the figures. There were inverse power relationships between \(|G^*| \sin \delta\) values and the \(I_{SO}\) or \(I_{CH}\), and there were direct power relationships between \(|G^*| \sin \delta\) values and the \(I_{CO}\) or \(I_{CC}\). Very strong relationships are observed from this figure because the \(|R|\) values are between 0.8 and 1 [64, 65]. As shown in Fig. 14a, the EABs with the highest \(I_{CO}\) values, such as US 54–3 and MO 151 EABs, had the lowest resistance to fatigue cracking by having the highest \(|G^*| \sin \delta\) values. These EABs, however, had the lowest \(I_{SO}\) values, while EABs from MO 6 mix, the youngest, had the highest \(I_{SO}\) value (Fig. 14b). These findings were related to the degradation of sulfoxide in older asphalt mixes containing RAP and/or RAS: sulfoxide degraded under high temperatures and long-term aging conditions [17, 73–75].

With aging, the aliphatic molecules transform into aromatic molecules [14, 17, 53], so the MO 6 and US 54–1 had the lowest \(I_{CC}\) (Fig. 14c), the highest \(I_{CH}\) (Fig. 14d), and the lowest \(|G^*| \sin \delta\) values. Conversely, the US 54–3 EABs had the highest \(I_{CC}\), the lowest \(I_{CH}\), and the highest \(|G^*| \sin \delta\) values.

Figure 15 emphasizes the relationships between FTIR indices and \(N_f\) values, measured under test conditions of 22 °C and 2.5% strain, for EABs. Figure 16 depicts the relationships between FTIR indices and \(N_f\) values, determined under test conditions of 22 °C and 5% strain, for EABs. Outliers were removed from these figures. Very strong relationships are detected in Figs. 15 and 16 because the \(|R|\) values are between 0.8 and 1 [64, 65]. However, in Fig. 16a, the relationship between \(N_f\) and \(I_{CO}\) is moderately strong because the \(|R|\) value is between 0.6 and 0.8 [64, 65]. From Fig. 5, the power relationship between \(|G^*| \sin \delta\) and \(N_f\) was shown to be inverse: The lowest \(|G^*| \sin \delta\) values and the highest \(N_f\) values were found in EABs with the best fatigue fracture resistance. Additionally, by analyzing the results in Fig. 14, direct power relationships were found between \(I_{CO}\) or \(I_{CC}\) and \(|G^*| \sin \delta\), and inverse power relationships were observed between \(|G^*| \sin \delta\) and \(I_{SO}\) or \(I_{CH}\). As a result, \(N_f\) values were shown to have direct power relationships with the \(I_{SO}\) or \(I_{CH}\), as well as inverse power relationships with the \(I_{CO}\) or \(I_{CC}\). The MO 6 EABs had the highest \(I_{SO}\) and \(I_{CH}\) values, and these EABs had the lowest \(I_{CO}\) and \(I_{CC}\) values. Therefore, the MO 6 EABs had the highest \(N_f\) values, reflecting the highest resistance.
to fatigue cracking. Certain aging circumstances, such as high temperatures and lengthy aging durations, as well as the presence of RAP and/or RAS in asphalt mixes, cause sulfoxide to degrade [17, 73–75], thus the newest mix, MO 6, had the highest \( I_{SO} \) values. The MO 6 had the lowest \( I_{CC} \) and the highest \( I_{CH} \) values—followed by the US 54-1 EAB—because aliphatic molecules change into aromatic molecules with aging [17, 53]. On the other hand, the US 54-3 and MO 151 EABs had the lowest \( N_f, I_{SO}, \) and \( I_{CH} \) values. Furthermore, the \( I_{CO} \) values of the US 54-3 and MO 151 EABs were the highest, while the \( I_{CC} \) value of the US 54-3 EAB was the highest.

### Relationships between FTIR Indices and %R

Figure 17 depicts the relationships between \( |G^*| \sin\delta \), tested at 22 °C, and FTIR indices \( a I_{CO}, b I_{SO}, c I_{CC}, \) and \( d I_{CH} \) for EABs. Outliers were excluded from the figure. Very strong relationships are detected because the \( |R| \) values are between 0.8 and 1 [64, 65]. Figure 12a depicts a direct polynomial relationship between \( |G^*| \sin\delta \) and \( \%R \) for EABs. Thus, there were direct polynomial relationships between the \( \%R \) for EABs and the \( I_{CO} \) or \( I_{CC} \), as deemed in Fig. 17a, c. On the contrary, there were inverse polynomial relationships between the \( \%R \) for EABs and the \( I_{SO} \) or \( I_{CH} \) (note Fig. 17b, d). The MO 94 and US 54–1 mixes did not include RAP or RAS, and thus, their EABs had the lowest \( \%R \) detected by TGA, and increased the EABs’ asphaltene content, \( %R \).
ageing components by increasing the $I_{CO}$ and $I_{CC}$, decreasing the $I_{CH}$, and causing a degradation in the $I_{SO}$.

**Relationships between FTIR Indices and $T_{onset}$**

In Fig. 18, the relationships between FTIR indices and $T_{onset}$ values for EABs are deemed. Outliers were excluded from the figure. Very strong relationships are observed in Fig. 18a, b because the $|R|$ values are between 0.8 and 1 [64, 65], and moderately strong relationships are recorded in Fig. 18c, d because the $|R|$ values are between 0.6 and 0.8 [64, 65]. There was a direct polynomial relationship between the $%R$ and $T_{onset}$ values for EABs, as discussed in Fig. 13. Additionally, from Fig. 17, there were direct polynomial relationships between $%R$ and $I_{CO}$ or $I_{CC}$ and inverse polynomial relationships between $%R$ and $I_{SO}$ or $I_{CH}$ were recorded. Therefore, direct polynomial relationships were deduced between $T_{onset}$ and $I_{CO}$ or $I_{CC}$, and inverse polynomial relationships between $%R$ and $I_{SO}$ or $I_{CH}$ were observed. The highest $T_{onset}$ value was for the MO 151 EAB. This EAB showed the highest $I_{CO}$ (Fig. 18a), the second-lowest $I_{SO}$ value in Fig. 18b, the lowest $I_{CH}$ value in Fig. 18d, and the highest $%R$ value in Fig. 17. The MO 151 mix contained the highest ABR% by RAP and RAS, which increased the $%R$ and $T_{onset}$ to the highest values due to the increase in the asphaltene content. The ageing components detected by FTIR

\[
y = 352.44(I_{CO})^{-1.09} \\
R^2 = 0.72
\]

\[
N_f = 7E+07(I_{SO})^{3.1163} \\
R^2 = 0.72
\]

\[
N_f = 0.4341(I_{CC})^{-4.785} \\
R^2 = 0.71
\]

\[
N_f = 145819(I_{CH})^{11.433} \\
R^2 = 0.72
\]
indices increased because of the increase in the asphaltene content, and thus, the MO 151 EABs’ resistance to fatigue cracking was the worst.

**Conclusions**

The resistance to fatigue cracking of EABs from field asphalt mixes, including RAP, RAS, both, or neither, was investigated using rheological tests in this study. Chemical and thermal analyses of EABs were explored using FTIR and TGA, respectively. The relationships between the rheological, thermal, and chemical results of EABs were established. Based on this study, the following conclusions were reached:

- When compared to EABs from mixtures without RAP or RAS, employing RAP or RAS in asphaltic mixes lowered EABs’ resistance to fatigue cracking. This was caused by the RAP’s aged asphalt binder and the RAS’s oxidized air-blown asphalt.
- The ages of the asphalt mixes, ABR percentages by RAP and/or RAS, and intermediate PG temperatures

Fig. 16 Relationships between $N_f$, tested at 22 °C and 5% strain, and FTIR indices a $I_{CO}$, b $I_{SO}$, c $I_{CC}$, and d $I_{CH}$ for EABs
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1 of VAB controlled the resistance of EABs to fatigue cracking.

- The resistance of EABs to fatigue cracking was diminished when the ABR% was increased using RAP.
- EABs from mixes containing RAS had higher fatigue resistance than EABs from mixes containing lower ABR% by RAP.
- The EABs with the highest $I_{CO}$ plus $I_{CC}$ value and the lowest $I_{SO}$ plus $I_{CH}$ value had the weakest resistance to fatigue cracking.
- The $IG$*$l$.$sin\delta$ and $N_f$ were found to have inverse relationships. EABs with the lowest $IG$*$l$.$sin\delta$ had the highest $N_f$, reflecting the strongest resistance to fatigue cracking.

- $D_f$ and $N_f$ were shown to have a direct relationship. EABs with the highest $D_f$ had the highest $N_f$, implying the strongest resistance to fatigue cracking.
- A direct relationship was recorded between $%R$ and $T_{onset}$. The EABs with the highest $%R$ showed the highest $T_{onset}$.
- Direct relationships were found between $|G*|$.sin$\delta$ and $T_{onset}$ or $%R$; however, inverse relationships were observed between $N_f$ and $T_{onset}$ or $%R$. The EABs with the highest $T_{onset}$ and $%R$ had the weakest resistance to fatigue cracking.
- Inverse relationships were detected between $|G*|$.sin$\delta$, $%R$, or $T_{onset}$ and $I_{SO}$ or $I_{CH}$. Direct relationships were noted between $|G*|$.sin$\delta$, $%R$, or $T_{onset}$ and $I_{CO}$ or $I_{CC}$.

Fig. 17 Relationships between $%R$ at 750 °C and FTIR indices a $I_{CO}$, b $I_{SO}$, c $I_{CC}$, and d $I_{CH}$ for EABs
Direct relationships were discovered between $N_f$ and $I_{SO}$ or $I_{CC}$. Inverse relationships were established between $N_f$ and $I_{CO}$ or $I_{CC}$.

**Recommendations**

Based on the limitations of this study, it is recommended to

- Extend the scope of the investigation by using various grades of VABs in mixes for the same ABR% using RAP and/or RAS.
- Contrast the fatigue cracking resistance of VABs with that of EABs.
- Employ different ABR percentages by RAS to confirm the effect of RAS on the fatigue cracking resistance of EABs.
- Utilize rejuvenators in mixtures, including both RAP and RAS, to explore the effect of incorporating those rejuvenators on improving the fatigue cracking resistance of EABs.

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**Declarations**

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