Evaluating the Low-temperature Properties of Asphalt Binders Extracted from Mixtures Containing Recycled Materials

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Abstract
The use of recycled materials – such as reclaimed asphalt pavement (RAP) and recycled asphalt shingles (RAS) – in asphalt mixtures reduces natural resources demands and decreases materials dumped in landfills. The aged binders included in the recycled materials alter binders’ low-temperature properties included in asphalt mixtures. Therefore, asphalt binders were extracted from asphalt mixtures collected from the field as cores. Due to the limited amount of extracted asphalt binders (EABs), a dynamic shear rheometer was used to examine the low-temperature properties [e.g., true temperature (\(T_t\)), continuous temperature (\(T_c\)), and delta continuous temperature (\(\Delta T_c\))]. Using recycled materials in asphalt mixtures increased EABs’ low temperatures, \(T_t\) and \(T_c\), and decreased EABs’ \(\Delta T_c\) values when compared to EABs from mixtures without recycled materials. Using RAS in asphalt mixtures degraded the low-temperature properties of EABs, \(T_t\) and \(T_c\) increased and \(\Delta T_c\) decreased, when compared to EABs from mixtures containing RAP. Increasing the asphalt binder replacement (ABR) percentages by recycled materials increased \(T_c\) and decreased \(\Delta T_c\). The flow activation energy (\(E_a\)) was related to the \(T_c\) and \(\Delta T_c\) values, and very strong relationships were observed between \(E_a\) and \(T_c\) and \(E_a\) and \(\Delta T_c\). The researchers modelled two low-temperature prediction models to predict \(T_c\) and \(\Delta T_c\) depending on the grade of the virgin asphalt binder, ABR types and percentages, and asphalt mixtures ages.

Keywords
recycled materials, low temperature, compliance, flow activation energy, 4-mm plates, delta \(T_c\)

1 Introduction
Using recycled materials – such as reclaimed asphalt pavement (RAP) and recycled asphalt shingles (RAS) – in the pavement industry is increasing in the U.S. due to the valuable constituents that make them more appropriate to be used with asphalt mixtures [1–3]. The main issue generated by using RAS in asphalt mixtures is the high stiffness of the asphalt component [4–6]. This asphalt was an oxidized air-blown type, which was stiffer than the asphalt binder included in the RAP [5]. Alavi et al. [2] evaluated the low-temperature performance grades (PGs) of three RAP sources from three plants in California, and it was found to be –4 °C. Bahia and Swiertz [6] found that blending RAS binder with a fresh binder, PG 58–28, changed the low temperature with 0.4 °C per one percentage of asphalt binder replacement (ABR).

Delta \(T_c\) (\(\Delta T_c\)) parameter, proposed by Anderson et al. [7], was identified as the difference between the temperature at which the stiffness reached the critical temperature and the temperature at which the relaxation (m-value) reached critical temperature [8]. Good to fair correlations were found between the \(\Delta T_c\) parameter and mixture cracking testing (e.g., double-edged notch test, Texas overlay tester, and thermal stress restrained specimen test) [8, 9]. The AASHTO PP 78 suggested a threshold minimum value for the \(\Delta T_c\) as −5 °C because a significant loss in the resistance to low-temperature cracking occurred below this threshold [8, 10]. More negative \(\Delta T_c\) parameter indicated increase cracking susceptibility due to the loss of relaxation properties [8, 11]. McDaniel and Shah [8] found \(\Delta T_c\) values for the two RAP binders, after 20 h long-term aging, were −4 °C and −5.5 °C. The researchers did not evaluate the \(\Delta T_c\) for the RAS binder because it was too stiff to be poured into the bending beam rheometer (BBR) molds [8]. The addition of 2–8% RAS binder to PG 64–22 virgin asphalt binder (VAB) enhanced the VAB’s ability to relax thermal stresses by increasing the \(\Delta T_c\) parameter [8]. The researchers related
these findings to the complex interactions between the VAB and RAS binder. There were difficulties in blending the RAS binder and the VAB in the lab [8].

In the transition-state-theory context, the flow activation energy ($E_a$) is the amount of thermal energy to overcome an energy barrier of asphalt binder's molecules and atoms to move to an adjacent vacant place [12, 13]. Lower $E_a$ indicated that less energy was required to overcome the energy barrier and to cause flow [14]. It was found that the $E_a$ depended on the composition of the asphalt binder because asphalt binders with the same PG had different $E_a$ values [15]. Moreover, the short- and long-term aging processes increased the $E_a$ values [14–16]. During these aging processes, the oxidation increased the number of polar aromatics, and hydrocarbon molecules (asphaltenes) that increased the intermolecular forces caused stronger interactions and more resistance to flow [14, 15].

The primary objective of this study was to explore the low-temperature properties of extracted asphalt binders (EABs) from mixtures containing different ABR percentages by recycled materials (RAP, RAS, or both) and different asphalt binders' PGs, and various ages. The EABs' low-temperature properties were related to $E_a$ values. Two prediction models were developed for EABs with PG 64−22 VABs and different recycled materials' ABR percentages.

### 2 Materials and methods

#### 2.1 Materials

Thirty-one field cores were collected from nine routes in Missouri, U.S.A. These routes were constructed before 2016, and the cores were gathered in 2016 (samples No. 1 to No. 12) and 2019 (samples No. 13 to No. 31). Therefore, EABs were treated as long-term aged binders. The field cores represented nine asphalt mixtures. The asphalt mixtures included different ABR percentages by recycled materials (RAP, RAS, or both). Furthermore, two mixtures contained neither RAP nor RAS (e.g., US 54-7 and MO 94). Details about these cores are presented in Table 1.

#### 2.2 Methods

##### 2.2.1 Extraction and recovery of asphalt binders

Asphalt binders were extracted from the field cores using the centrifuge extraction process according to ASTM D2172/D2172M-17e1 [17]. Trichloroethylene (TCE) solvent was used in the extraction process. The mineral matter, dust finer than #200 sieve, was removed from the extracted effluent – asphalt binder dissolved in TCE plus mineral matter – using a filterless centrifuge. Asphalt binders were recovered from the asphalt binder-solvent solutions, after mineral matter removal, using a rotavap. The procedures for implementing this experiment were illustrated in ASTM D5404 / D5404M-21 [18].

##### 2.2.2 Low-temperature properties of EABs using a dynamic shear rheometer

There were difficulties in evaluating the low-temperature properties of EABs using the BBR due to the limited amount

### Table 1 Details of field cores

| No. | Sample Code | Route/Dir | Virgin Asphalt PG | AC (%) | ABR by RAP-RAS (%) | Year |
|-----|-------------|-----------|-------------------|--------|-------------------|------|
| 1   | US 63-2-F1  | US 63 SB  | 64−22             | 5.6    | 20-10             | 2008 |
| 2   | US 63-2-F2  |           |                   |        |                   |      |
| 3   | US 63-2-F3  |           |                   |        |                   |      |
| 4   | MO 52-1-F1  | MO 52     | 64−22             | 4.8    | 0-34              | 2010 |
| 5   | MO 52-1-F2  |           |                   |        |                   |      |
| 6   | MO 52-1-F3  |           |                   |        |                   |      |
| 7   | US 54-7-F1  | US 54 WB  | 64−22             | 6.2    | 0-0               | 2003 |
| 8   | US 54-7-F2  |           |                   |        |                   |      |
| 9   | US 54-7-F3  |           |                   |        |                   |      |
| 10  | US 54-8-F1  | US 54     | 70−22             | 5.6    | 9-0               | 2006 |
| 11  | US 54-8-F2  |           |                   |        |                   |      |
| 12  | US 54-8-F3  |           |                   |        |                   |      |
| 13  | MO 151-F1   | MO 151    | 64−22             | 4.7    | 16-15             | 2014 |
| 14  | MO 151-F2   |           |                   |        |                   |      |
| 15  | MO 151-F3   |           |                   |        |                   |      |
| 16  | MO 151-F4   |           |                   |        |                   |      |
| 17  | MO 151-F5   |           |                   |        |                   |      |
| 18  | US 54-F1    | US 54 E   | 70−22             | 5.7    | 12-0              | 2010 |
| 19  | US 54-F2    |           |                   |        |                   |      |
| 20  | US 54-F3    |           |                   |        |                   |      |
| 21  | MO 6-F1     | MO 6 W    | 58−28             | 5.9    | 30-0              | 2015 |
| 22  | MO 6-F2     |           |                   |        |                   |      |
| 23  | MO 6-F3     |           |                   |        |                   |      |
| 24  | MO 6-F4     |           |                   |        |                   |      |
| 25  | MO 6-F5     |           |                   |        |                   |      |
| 26  | MO 94-F1    | MO 94     | 64−22             | 5.6    | 0-0               | 2005 |
| 27  | MO 94-F2    |           |                   |        |                   |      |
| 28  | MO 94-F3    |           |                   |        |                   |      |
| 29  | US 36-F1    | US 36 E   | 64−22             | 5.1    | 25-0              | 2011 |
| 30  | US 36-F2    |           |                   |        |                   |      |
| 31  | US 36-F3    |           |                   |        |                   |      |

- a Virgin asphalt performance grade as indicated in the Job Mix Formula (JMF).
- b Total asphalt content (AC) after the extraction process as represented in the JMF by the contractor.
- c Construction year.
of EABs. Therefore, a dynamic shear rheometer (DSR) was utilized for this purpose. To evaluate the low-temperature properties of EABs by the BBR at three temperatures, at least 33 grams of EAB were required. However, an EAB sample of 0.02265 gram was used in the DSR to characterize its low-temperature properties at various temperatures. To obtain the stiffness $S(t)$ and $m$-value, the DSR shear results in a frequency domain were converted to BBR flexural results in a time domain.

**Measuring the compliance of the DSR**

The DSR’s compliance was measured by freezing the upper and lower 4-mm plates together using distilled water at −40 °C. An oscillation amplitude sweep test was conducted using torque values from 100 to 3000 μN.m at a frequency of 1 Hz (6.28 rad/s) [19]. The slope of the linear relationship between torque in N.m and displacement in m.rad was calculated as the DSR’s compliance in m.rad/N.m (Fig. 1). The DSR compliance, 24.068 m.rad/N.m, was used to correct EABs’ measurements by inserting this value in the software of DSR.

**Frequency sweep test**

The EABs were tested using 4-mm diameter and 1.75-mm gap samples through frequency sweep testing. Oscillation frequency sweep tests were utilized at different temperatures (−24, −18, −12, −6, 0, 6, and 12 °C). For each temperature, 50.00, 39.81, 25.12, 15.85, 10.00, 6.31, 3.98, 2.51, 1.58, 1.00, 0.63, 0.39, 0.25, 0.15, and 0.10 rad/s angular frequency values were used [19]. The strain value was 0.001% to ensure it was obtaining data within the linear viscoelastic (LVE) region. The normal force was kept within 1 ± 0.1 N through testing to overcome EAB samples' contractions and adhesion losses between the sample and upper plate.

**Converting DSR shear results into BBR flexural results**

The master curves were developed from the frequency sweep testing results at the expected low PG temperatures plus ten degrees Celsius. A sigmoidal function in the mechanistic-empirical pavement design guide discussed the rate dependency of the dynamic modulus master curve for asphalt mixtures [20, 21]. However, the sigmoidal function was used to evaluate the behaviors of the asphalt binders’ master curves [19, 22]. This function is presented in Eq. (1), and it was utilized to predict the elastic ($G'$) and viscous ($G''$) moduli at different reduced frequencies ($\omega_r$) [19]. The elastic modulus ($G'$) is characterized by the following equation:

$$\log G' = \delta + \frac{\alpha}{1 + e^{(\beta + \gamma) \log(\omega_r)}}, \tag{1}$$

where $G'$ is the elastic modulus, $\omega_r$ is the reduced angular frequency, and $\delta$, $\alpha$, $\beta$, and $\gamma$ are the fitting parameters ($\delta$ is the lower asymptote, $\alpha$ is the difference between the lower and upper asymptotes' values, and $\beta$ and $\gamma$ define the shape between the asymptotes and the location of the inflection point ($10^{\beta/\gamma}$) [23]).

The shear stress relaxation modulus [$G(t)$] was obtained from Eq. (2) [24, 25]. The stiffness [$S(t)$] was calculated using Eq. (3) [26]. The stiffness and $m$-value for each EAB at the low PG temperature plus ten degrees Celsius were considered at 60 seconds [19]. The following equation characterized the $G(t)$:

$$G(t) = G'(\omega_r) - 0.4G''(0.4\omega_r) + 0.014G''(10\omega_r). \tag{2}$$

The stiffness value is calculated by the following equation:

$$S(t) = \frac{1}{D(t)} = \frac{2(1 + \nu)}{J(t)}, \tag{3}$$

where $D(t)$ is the tension/compression creep compliance, $J(t)$ is the shear creep compliance [the inverse of $G(t)$], and $\nu$ is the Poisson’s ratio (0.35).

**2.2.3 Flow activation energy**

The flow activation energy ($E_a$) was calculated for each EAB using the viscosity-based Arrhenius model (Eq. (4)) [27] and the shift factors-based Arrhenius model (Eq. (5)) [28, 29]. Frequency sweep test was conducted for each EAB, using 25-mm diameter and 1-mm thickness plates, at 58 to 82 °C with an increment of 6 °C. For each temperature, 100 to 0.01 rad/s angular frequencies were utilized. The strain value was selected, based on the strain amplitude sweep test results, to ensure the frequency sweep test was conducted at the LVE region. The viscosity-based Arrhenius model is characterized by the following equation:
\[ \eta^* = Ae^{E_a/RT}, \]  

where \( \eta^* \) is the complex shear viscosity at zero or low shear rate, 0.01 rad/s [27], in Pa.s, \( A \) is a pre-exponential parameter, \( E_a \) is the flow activation energy in kJ mol\(^{-1}\), \( R \) is the universal gas constant (0.008314 kJ mol\(^{-1}\) K\(^{-1}\)), and \( T \) is the temperature in °K.

The shift factors-based Arrhenius model is represented by the following equation:

\[ \ln a_T = \left( \frac{E_a}{R} \right) \left( \frac{1}{T} - \frac{1}{T_0} \right), \]  

where \( a_T \) is the temperature shift factor, \( T \) is the temperature in °K, and \( T_0 \) is the reference temperature in °K.

3 Results and analysis

3.1 Frequency sweep test results

The frequency sweep test results for the MO 6-F2 EAB are shown in Fig. 2(a). This figure illustrates the \( G' \) and \( G'' \) measured at 50 to 0.1 rad/s angular frequencies (\( \omega \)) and −24 to 12 °C temperatures. At the lowest temperatures, −24 °C, the difference between the \( G' \) and \( G'' \) values was the highest. Increasing the temperature and decreasing the frequency resulted in a decrease in the difference between the \( G' \) and \( G'' \) values. The frequency sweep test results were utilized to create the master curve at specific temperatures. Fig. 2(b) depicts the master curve results, \( G' \) and \( G'' \) versus \( \omega \) in log scale, at −12 °C (−22 °C low PG temperature).

3.2 Calculation of EABs' stiffnesses and \( m \)-values

The EABs' stiffness values were calculated at 60 seconds using Eq. (3). The \( m \)-value was the slope of the tangent line at 60 seconds of the fitted relationship between the log time and log \( S(t) \). Fig. 3 illustrates the log time versus log \( S(t) \) for the MO 6-F2 EAB measured at −12 °C. The \( S(t) \) and \( m \)-value were 167.88 MPa and 0.314, respectively. This depicted that the MO 6-F2 EAB passed −12 °C, −22 °C low PG temperature, because the \( S(t) \) was less than 300 MPa and the \( m \)-value was greater than 0.3. The same procedures were followed for the MO 6-F2 EAB at −18 °C, −28 °C low PG temperature, and the EAB failed at this temperature because the \( S(t) \) was greater than 300 MPa (310.03 MPa) and the \( m \)-value was less than 0.3 (0.264). Thus, the low PG temperature of the MO 6-F2 EAB was −22 °C.

3.3 True and continuous low temperatures of EABs

The true (\( T_t \)) and continuous (\( T_c \)) low temperatures were calculated and presented in Table 2 for EABs. The \( T_t \) was estimated as the maximum of the \( T_c, \text{stiffness} (T_{c, s}) \) and \( T_c, \text{m-value} (T_{c, m}) \). The \( T_{c, s} \) and \( T_{c, m} \) values were estimated using Eq. (6) and Eq. (7), respectively. The \( T_{c, s} \) is represented by the following equation:

\[ T_{c, s} = T_t + \frac{(T_t - T_c) (\log 300 - \log S)}{\log S - \log S_t} - 10. \]  

The \( T_{c, m} \) is characterized by the following equation:

\[ T_{c, m} = T_t + \frac{(T_t - T_c) (0.3 - m)}{m_1 - m_2} - 10, \]  

Fig. 3 Stiffness and \( m \)-value of the MO 6-F2 EAB at −12 °C
where $T_1$ is the temperature at which $S(t)$ and $m$-value passed, $T_2$ is the temperature at which $S(t)$ and $m$-value failed, $S_1$ is the $S(t)$ value at $T_1$, $S_2$ is the $S(t)$ value at $T_2$, $m_1$ is the $m$-value at $T_1$, and $m_2$ is the $m$-value at $T_2$.

Fig. 4 demonstrates the average $T_c$ values for EABs from the same asphalt mixtures. The lowest $T_t$ and $T_c$ values were recorded for the MO 54-7 EABs followed by MO 6, US 54, and then US 63 EABs. The US 54-7 mixture was 10 years old, and it included VAB with a PG of 70–22; nevertheless, it contained 9% ABR percentage by RAP. The highest $T_t$ and $T_c$ values were noted for the MO 151 EABs followed by MO 52-1, US 54, and US 63-2 EABs. The MO 151 mixture was 5 years old, and it included 31% ABR percentage by RAP and RAS. The MO 52-1 mixture was the youngest after the MO 6 mixture; however, it contained 34% ABR percentage by RAS. This proved that using RAS deteriorated the low-temperature properties of the EABs when compared to EABs from mixtures containing RAP. The US 54 mixture was 9 years old, and it contained VAB with a PG of 70–22; however, it included 12% ABR percentage by RAP. The US 63-2 mixture was 8 years old and contained 30% ABR percentage by RAP and RAS. These findings reflected that the grade of the VAB, the ABR percentage by recycled materials, and the mixture's age controlled the low temperature of the EABs.

### 3.4 Relationship between $T_c$ and ABR percentage

The relationship between EABs' $T_t$ and ABR percentage are depicted in Fig. 5. A very strong polynomial relationship was detected between $T_c$ and ABR percentage because

![Fig. 4 $T_c$ values of EABs](image-url)

![Fig. 5 Relationship between $T_c$ and ABR percentage](image-url)

#### Table 2 True and continuous low temperatures of EABs

| EAB Code | Mixture Code | $T_t$ (°C) | $T_c$, $S$ (°C) | $T_c$, $m$ (°C) | $T_c$ (°C) |
|----------|--------------|-----------|----------------|----------------|----------|
| MO 6-F1  | MO 6         | −16       | −27.13         | −21.41         | −21.41   |
| MO 6-F2  | −22          | −27.68    | −23.68         | −23.68         | −23.68   |
| MO 6-F3  | −22          | −29.50    | −24.68         | −24.68         | −24.68   |
| MO 6-F4  | −16          | −27.00    | −21.01         | −21.01         | −21.01   |
| MO 6-F5  | −16          | −26.41    | −20.26         | −20.26         | −20.26   |
| MO 94-F1 | MO 94        | −10       | −15.81         | −16.25         | −15.81   |
| MO 94-F2 | −10          | −15.81    | −16.25         | −15.81         | −15.81   |
| MO 94-F3 | −10          | −18.26    | −17.91         | −17.91         | −17.91   |
| MO 151-F1| MO 151       | 2         | −7.63          | −4.27          | −4.27    |
| MO 151-F2| −4           | −14.96    | −7.37          | −7.37          | −7.37    |
| MO 151-F3| 2            | −10.85    | −4.27          | −4.27          | −4.27    |
| MO 151-F4| −4           | −14.24    | −4.64          | −4.64          | −4.64    |
| MO 151-F5| 2            | −6.99     | −1.13          | −1.13          | −1.13    |
| US 54-F1 | US 54        | −4        | −9.05          | −7.20          | −7.20    |
| US 54-F2 | −4           | −12.75    | −10.90         | −10.90         | −10.90   |
| US 54-F3 | −10          | −14.45    | −13.06         | −13.06         | −13.06   |
| US 54-7-F1| US 54-7      | −22       | −22.46         | −23.62         | −23.62   |
| US 54-7-F2| −22          | −25.00    | −25.42         | −25.00         | −25.00   |
| US 54-7-F3| −16          | −22.53    | −23.17         | −22.53         | −22.53   |
| US 54-8-F1| US 54-8      | −16       | −20.65         | −17.22         | −17.22   |
| US 54-8-F2| −16          | −21.25    | −20.70         | −20.70         | −20.70   |
| US 54-8-F3| −16          | −19.95    | −17.08         | −17.08         | −17.08   |
| US 63-2-F1| US 63-2      | −4        | −13.36         | −10.47         | −10.47   |
| US 63-2-F2| −10          | −19.15    | −13.39         | −13.39         | −13.39   |
| US 63-2-F3| −10          | −16.61    | −11.91         | −11.91         | −11.91   |
| MO 52-1-F1| MO 52-1      | −4        | −20.04         | −4.61          | −4.61    |
| MO 52-1-F2| −4           | −20.57    | −7.24          | −7.24          | −7.24    |
| MO 52-1-F3| −4           | −18.74    | −6.57          | −6.57          | −6.57    |
| US 36-F1 | US 36        | −10       | −19.58         | −14.58         | −14.58   |
| US 36-F2 | −16          | −20.71    | −16.88         | −16.88         | −16.88   |
| US 36-F3 | −10          | −20.24    | −15.18         | −15.18         | −15.18   |
the absolute value of the correlation coefficient (|R|) was greater than 0.8 [30]. The lowest $T_c$ values were observed for EABs from mixtures without recycled materials followed by EABs from mixture containing 9% ABR percentage by RAP. The highest $T_c$ values were noted for EABs from the mixture containing 31% ABR percentage by RAP and RAS followed by EAB from the mixture containing 34% ABR percentage by RAS.

### 3.5 Relationship between $\Delta T_c$ and ABR percentage

In this section, the relationship between EABs’ $\Delta T_c$ and ABR percentage was investigated. The $\Delta T_c$ was calculated and averaged for EABs from the same mixture using Eq. (8):

$$\Delta T_c = T_{c,5} - T_{c,9}. \quad \text{(8)}$$

A very strong exponential relationship was deemed in Fig. 6 with |R| value equal to 0.95. The highest $\Delta T_c$ values, greater than 0.4 °C, were observed for the EABs from mixtures without RAP or RAS (MO 94 and US 54-7); however, these mixtures were the oldest. The lowest $T_c$ value, −13.65 °C, was noted for the MO 52-1 EAB with 34% ABR percentage by RAS and followed by EABs from mixtures containing RAP and RAS. For EABs from mixtures containing RAP and RAS, increasing the ABR percentages by RAS decreased the $\Delta T_c$ values. The EABs from mixtures containing RAP and RAS, increasing the ABR percentages by RAS decreased the $\Delta T_c$ values when compared to EABs from mixtures without recycled materials. Additionally, the RAS had the worst effect on the $T_c$ values when compared to the effect of RAP. EABs from mixtures containing RAS had the lowest $\Delta T_c$ values followed by mixtures containing RAP and RAS.

From Fig. 6, three types of EABs had $\Delta T_c$ values below the minimum threshold (−5 °C). These binders included the highest ABR percentages by RAP, RAS, or RAP and RAS. The EABs with positive $\Delta T_c$ values, MO 94 and US 54-7 EABs, were S-controlled binders. The S-controlled binders failed the stiffness limit, 300 MPa, at a temperature warmer than the temperature of the $m$-value [31]. However, the remaining binders with negative $\Delta T_c$ values were m-controlled binders. The m-controlled binders failed the $m$-value threshold of 0.3 at a temperature warmer than the stiffness temperature [31]. It was found that the m-controlled binders exhibited lower thermal stress resistance [32, 33].

### 3.6 Relationships between $E_a$ and low-temperature properties

The $E_a$ values for each EAB using the viscosity-based and shift factor-based Arrhenius model are illustrated in Table 3. The lowest $E_a$ values were recorded for EABs from mixtures without recycled materials and followed by EABs from mixtures containing RAP. The highest $E_a$ values were noted for EABs from mixtures containing RAP and RAS and were followed by EABs from a mixture including RAS. Relationships between $T_c$ and $E_a$ and between $\Delta T_c$ and $E_a$ were established and analyzed in Fig. 7 and Fig. 8, respectively. Very strong exponential relationships were observed in both figures with |R| values greater than or equal to 0.8. The relationship between $\Delta T_c$ and $E_a$ (Fig. 8) was stronger than the relationship between $T_c$ and $E_a$ (Fig. 7).

### 3.7 Fitting models to characterize the low-temperature properties

Based on this study, the low-temperature properties, $T_c$ and $\Delta T_c$, mainly depended on the mixtures’ ages, the VABs’ grades, recycled material types, and ABR percentages by recycled materials. Two models were fitted in this section; the first one characterized the $T_c$ and the second one described the $\Delta T_c$. The fitted models were based on 20 EABs from 6 mixtures with PG 64–22 VABs. The mixtures included RAP, RAS, both, or none.

#### 3.7.1 $T_c$ prediction model

The $T_c$ values of EABs were predicted using Eq. (9) by knowing the mixtures’ ages, recycled material types, and ABR percentages by recycled materials. Fig. 9 demonstrates a very strong relationship between the actual and the predicted $T_c$ values. The following equation characterized the $T_c$ values for EABs:

$$T_c = -0.943049 - 0.003012\exp(0.244624 \times \text{ABR}^\prime) \quad \text{R}^2 = 0.909$$

![Fig. 6 Relationship between $\Delta T_c$ and ABR percentage](image_url)
\[ T_c = -60.66583243 + 7.0071334803 \times Age + (ABR - 21.1) \times \mu, \quad (9) \]

where \( T_c \) is the continuous low temperature of EAB, \( Age \) is the age of mixture, \( ABR \) is the percentage of asphalt binder replacement by recycled materials. It should be greater than or equal to 25%, and \( \mu \) is a factor that depends on the type of \( ABR \) by recycled materials (2.5800289056 for zero \( ABR \), -2.81899816 for \( ABR \) by RAP, -0.727390718 for \( ABR \) by RAP and RAS, and 0.9663599725 for \( ABR \) by RAS).

### Table 3: Flow activation energy values for EABs

| EAB Code | Mixture Code | \( E_a \) (kJ/mol) Based on the zero-shear viscosity | \( E_a \) (kJ/mol) Based on the shift factors |
|----------|--------------|-----------------------------------------------|-----------------------------------------------|
| MO 6-F1  | MO 6         | 159.63                                        | 158.47                                        |
| MO 6-F2  | MO 6         | 156.63                                        | 161.28                                        |
| MO 6-F3  | MO 6         | 151.52                                        | 154.18                                        |
| MO 6-F4  | MO 6         | 161.19                                        | 161.53                                        |
| MO 6-F5  | MO 6         | 162.26                                        | 162.78                                        |
| MO 94-F1 | MO 94        | 145.22                                        | 147.33                                        |
| MO 94-F2 | MO 94        | 149.66                                        | 154.10                                        |
| MO 94-F3 | MO 94        | 149.54                                        | 151.36                                        |
| MO 151-F1| MO 151       | 175.22                                        | 179.79                                        |
| MO 151-F2| MO 151       | 173.41                                        | 169.82                                        |
| MO 151-F3| MO 151       | 166.95                                        | 172.47                                        |
| MO 151-F4| MO 151       | 168.80                                        | 172.20                                        |
| MO 151-F5| MO 151       | 180.89                                        | 185.71                                        |
| US 54-F1 | US 54        | 165.90                                        | 167.09                                        |
| US 54-F2 | US 54        | 159.48                                        | 159.18                                        |
| US 54-F3 | US 54        | 149.27                                        | 153.55                                        |
| US 54-7-F1| US 54-7     | 152.26                                        | 154.35                                        |
| US 54-7-F2| US 54-7     | 147.23                                        | 154.39                                        |
| US 54-7-F3| US 54-7     | 151.49                                        | 157.48                                        |
| US 54-8-F1| US 54-8     | 153.07                                        | 155.21                                        |
| US 54-8-F2| US 54-8     | 148.85                                        | 151.90                                        |
| US 54-8-F3| US 54-8     | 153.85                                        | 152.71                                        |
| US 63-2-F1| US 63-2     | 168.54                                        | 165.28                                        |
| US 63-2-F2| US 63-2     | 168.18                                        | 168.68                                        |
| US 63-2-F3| US 63-2     | 168.54                                        | 165.28                                        |
| MO 52-1-F1| MO 52-1     | 165.46                                        | 171.02                                        |
| MO 52-1-F2| MO 52-1     | 164.88                                        | 166.69                                        |
| MO 52-1-F3| MO 52-1     | 162.30                                        | 171.96                                        |
| US 36-F1  | US 36        | 165.75                                        | 169.35                                        |
| US 36-F2  | US 36        | 164.82                                        | 164.57                                        |
| US 36-F3  | US 36        | 165.88                                        | 162.16                                        |

#### 3.7.2 Delta \( T_c \) prediction model

The \( \Delta T_c \) values of EABs were predicted using Eq. (10). Fig. 10 depicts a very strong relationship between the actual and the predicted \( \Delta T_c \) values. The highest \( \Delta T_c \) values were observed for EABs from mixtures without recycled materials; however, the EABs from mixtures containing RAS had the lowest \( \Delta T_c \) values. The following equation characterized the \( \Delta T_c \) values for EABs:

\[ E_a = 149.52808 + 34.07392\text{Esec}(0.0869483 \times T_c) \\
R^2 = 0.640 \]

\[ E_a = 146.19819 + 6.26969\text{Eexp}(-0.218342 \times \Delta T_c) \\
R^2 = 0.765 \]

\[ E_a = 146.19819 + 6.26969\text{Eexp}(-0.218342 \times \Delta T_c) \\
R^2 = 0.765 \]
\[ \Delta T_c = 2.8357241101 - 1.430810768 \times \text{Age} \]
\[ + (\text{ABR} - 21.1) \times \mu, \]  

(10)

where \( \Delta T_c \) is the delta continuous low temperature of EAB, \( \text{Age} \) is the age of mixture, \( \text{ABR} \) is the percentage of asphalt binder replacement by recycled materials. It should be greater than or equal to 25%, and \( \mu \) is a factor that depends on the type of \( \text{ABR} \) by recycled materials (\(-0.809202214\) for zero \( \text{ABR} \), \(1.0328823464\) for \( \text{ABR} \) by RAP, \(0.3876768713\) for \( \text{ABR} \) by RAP and RAS, and \(-0.611357004\) for \( \text{ABR} \) by RAS).

4 Conclusions

This study focused on exploring the low-temperature properties of extracted asphalt binders (EABs) from 31 field cores, representing 9 asphaltic mixtures, containing different virgin asphalt binders (VABs), including different types and percentages of asphalt binder replacement (ABR) by recycled materials, and being different ages. Asphalt mixtures contained different percentages of \( \text{ABR} \) by reclaimed asphalt pavement (RAP), recycled asphalt shingles (RAS), both, or none. The low-temperature properties of EABs were investigated using a dynamic shear rheometer by measuring true low temperatures (\(T_t\)), continuous low temperatures (\(T_c\)), and delta \(T_c\) (\(\Delta T_c\)). The different relationships between \(\text{ABR}\) percentages and \(T_t\) values, \(\text{ABR}\) percentages and \(\Delta T_c\), flow activation energy \(E_a\) and \(T_c\), and between \(E_a\) and \(\Delta T_c\) were explored. Finally, two models were proposed to predict the \(T_c\) and \(\Delta T_c\) values of EABs from mixtures containing PG 64−22 VABs, including different \(\text{ABR}\) types and percentages, and being different ages. This study dictated the following conclusions:

- The use of recycled materials in asphalt mixtures undermined the low-temperature properties — increased the \(T_t\) and \(T_c\) values and decreased the \(\Delta T_c\) — of EABs when compared to EABs from mixtures without recycled materials.
- The use of RAS degraded the low-temperature properties of EABs when compared to EABs from mixtures containing RAP.
- A very strong polynomial relationship was revealed between the \(T_c\) values of EABs and \(\text{ABR}\) percentages. Increasing \(\text{ABR}\) percentages by recycled materials increased the \(T_c\) values.
- A very strong exponential relationship was observed between the \(\Delta T_c\) values of EABs and \(\text{ABR}\) percentages. Increasing the percentages of \(\text{ABR}\) with recycled materials decreased the \(\Delta T_c\) values.
- Very strong exponential relationships were found between the \(E_a\) and \(T_c\) or \(\Delta T_c\) values of EABs.
- The researchers constructed two prediction models to characterize \(T_c\) and \(\Delta T_c\) for EABs. These models were based on the grade of VABs, types and percentages of \(\text{ABR}\) by recycled materials, and ages of the mixtures.

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