Nondestructive Low-Temperature Cracking Characterization of Asphalt Materials

Behzad Behnia1; William G. Buttlar2; and Henrique Reis3

Abstract: An acoustic-emission approach to evaluate the low-temperature cracking performance of asphalt binders is presented. The acoustic activity of a thin film of asphalt binder bonded to a granite substrate is monitored while the layer is exposed to decreasing temperatures from around 20°C to approximately −50°C. Results of eight different asphalt binders at three different aging levels, i.e., unaged (TANK), short-term aged (RTFO), and long-term aged (PAV), are presented. The acoustic emission (AE) embrittlement temperatures are found to be sensitive to binder type as well as binder aging level. Results show that for most binders, their AE-based embrittlement temperature is a few degrees lower than their bending beam rheometer (BBR) critical cracking temperatures. DOI: 10.1061/(ASCE)MT.1943-5533.0001826. © 2016 American Society of Civil Engineers.

Author keywords: Low-temperature cracking; Acoustic emissions; Embrittlement temperature; Bending beam rheometer (BBR); Critical cracking temperature.

Introduction

The United States has more than 6.5 million km (4 million miles) of paved public roads. Asphalt concrete is a widely used pavement material, covering the surface of approximately 94.6% of all highway pavements, making this material a prominent factor in the performance of U.S. transportation infrastructure. Americans spend 5.5 billion hours in traffic each year with an associated cost of more than $120 billion in extra fuel and lost time (U.S. National Economic Council 2014). The same report also emphasizes the current insufficient funding available to maintain and repair the existing surface transportation system with a shortfall of approximately $36 billion per year. A substantial amount of these maintenance needs arise from premature cracking of pavements.

Low-temperature cracking, also known as thermal cracking, is the most common type of deterioration in asphalt pavements located in cold regions. Thermal tensile stresses develop within asphalt pavements due to the tendency of restrained pavement layers to contract as the temperature decreases. The distribution of thermally induced tensile stresses throughout the pavement thickness is nonuniform with the greatest thermal stress at the pavement surface, where changes in the temperature are the highest. Thermal stresses gradually reduce from the surface to the bottom of the pavement. As the pavement cools down, when the thermal stress exceeds the tensile strength of the asphalt pavement, top-down thermal cracks occur in the top material layer. Fig. 1 schematically illustrates typical thermal cracking pattern in asphalt pavements along with the thermal cracking formation mechanism in asphalt pavements due to thermally induced stresses through the pavement thickness (Kim 2008).

Thermal cracks in asphalt pavements are expensive and difficult to properly treat. They form as a result of low pavement temperatures and/or high cooling rates (Kim 2008). If left untreated, thermal cracks will continue to deteriorate (spall), and will continue to widen with time (which can also occur even when treated), allowing moisture to readily infiltrate the pavement system. Low-temperature cracking manifests itself as transversely oriented surface-initiated cracks of various lengths and widths. Thermal cracks severely reduce the life of roadway and adversely impact rideability. They lead to significant declines in pavement serviceability and a resulting exponential increase in maintenance costs to restore pavements to their original condition. In the United States every year, millions of dollars are being spent in repair and rehabilitation of thermal cracks in pavements. In a recent study conducted by Islam and Buttlar, the presence of cracks in pavement was found to add an additional user cost of over $300 per vehicle per 19,000 km (12,000 mi) driven (Islam and Buttlar 2012).

Detrimental effects of low-temperature cracking have motivated a number of studies in an effort to experimentally design and control asphalt properties related to the low-temperature performance of asphalt pavements. However, accurate predictions of thermal cracking and associated failure mechanisms still remain a challenge (Apeagyei et al. 2009; Buttlar et al. 2011; Behnia et al. 2016). The Superpave binder tests developed under the Strategic Highway Research Program (SHRP) have certainly improved the performance tests (Anderson and Kennedy 1993) with which those in the asphalt industry can specify and purchase asphalt binders [AASHTO MP1 (Anderson et al. 2001)], by providing fundamental material tests over a broad range of production and service temperatures. However, these tests were not developed for highly modified binders, and were not developed for the design and control of reclaimed asphalt pavement (RAP) and warm-mix materials. Although the bending beam rheometer (BBR)-based results have correlated well to thermal cracking in the field for straight-run binders, it is more appropriate to employ the direct tension test (DTT) in conjunction with the BBR as an option to the AASHTO MP1 specification to enable a broader range of binders to be evaluated. However, the DTT device suffers from poor repeatability, is relatively...
expensive, and requires significant operator training and care. In addition, the combination of the BBR and DTT carries a significant equipment cost [AASHTO MP1a (AASHTO 1998) and AASHTO T313 (AASHTO 1999)].

The present study focuses on developing an acoustic-emission-based (AE-based) testing method to address the current shortage of a rapid and practical test to evaluate the embrittlement temperature of asphalt binders. Acoustic emissions have been used extensively to characterize the microscopic fracture processes and to evaluate damage growth in materials. The use of acoustic-emission testing for evaluating asphalt materials dates back several decades (Hellier 2001). Khosla and Goetz used AE techniques to detect crack initiation and propagation in indirect tensile (IDT) specimens at \(-23^\circ\text{C}\) (Khosla and Goetz 1979). The study found that failure by fracture is indicated by a sharp increase in total AE counts and that significant AE counts occur at about 80% of the peak load. Valkering and Jongeneel used the AE technique to monitor temperature cycling tests with restrained asphalt concrete specimens at low temperatures (10 to \(-40^\circ\text{C}\)) (Valkering and Jongeneel 1991). They observed that the repeatability of AE measurements is good, the AE activity (number of events) correlates with thermal fracture temperatures, and the AE activity in restrained specimens at low temperatures is caused by distress initiation in the binder. Hesp et al. (2000) used AE measurements to detect crack initiation and propagation in restrained specimens at low temperatures (\(-32\) to \(-20^\circ\text{C}\)). They concluded that the Styrene-Butadiene-Styrene (SBS)-modified mixes produced less AE activity than unmodified mixes. Li et al. (2006) used AE techniques to characterize fractures in semicircular-bend asphalt specimens at low temperatures (\(-20^\circ\text{C}\)) (Li and Marasteau 2006). They also concluded that (1) large amounts of accumulated AE events occur at 70% of material strength, (2) the maximum intensity of AE peaks correlates with the development of macrocracks, and (3) the location of AE events suggests that a several-centimeter-sized process zone forms before peak load. Nesvijski and Marasteau (2006, 2007) used an AE spectral analysis approach to characterize fracture in semicircular-bend asphalt specimens at low temperatures and concluded that an AE approach could be used for evaluation of asphalt pavements. All of these previous studies involved the need for mechanical tests, which are relatively expensive and time-consuming to perform as compared to the techniques developed and presented here.

Materials and Experimental Procedure

In the present work, a total of 24 different binders (eight different types of binders, each at three different aging levels) were utilized. Following is the list of eight different types of asphalt materials from the Strategic Highway Research Program (SHRP) core binders used in this study: AAA-1 (PG 58-28), AAB-1 (PG 58-22), AAC-1 (PG 58-16), AAD-1 (PG 58-28), AAF-1 (PG 64-10), AAG-1 (PG 58-10), AAK-1 (PG 64-22), AAM-1 (PG 64-16). Each type of binder was tested at three different aging levels, i.e., unaged (TANK), short-term aged (RTFO), and long-term aged (PAV). The RTFO and PAV aging of binders were performed in accordance with ASTM D2872-04 (ASTM 2004) and ASTM D6521-08 (ASTM 2008), respectively.

AE Binder Sample Preparation

AE binder sample consists of thin film of asphalt bonded to granite substrate. AE asphalt samples were prepared using aluminum molds identical to those used in a standard bending beam rheometer (BBR) test. Teflon polytetrafluorethylene tape was utilized as a debonding aid during molding. A 10-mm-thick granite slab was used as the substrate. To ensure proper bonding and restraint between the asphalt binder samples and the substrates, the granite substrates were preheated to approximately 135°C. Asphalt binder at a temperature of 135°C was poured into the aluminum mold wrapped in Teflon polytetrafluorethylene tape placed on the heated slab. Prepared binder samples were allowed to cool down to room temperature for 2 h before conducting AE tests. The AE binder sample preparation (Buttlar et al. 2011) procedure is illustrated in Fig. 2.

AE Testing Procedure

To perform AE test, a prepared binder sample is placed inside the Shuttle ULT-25 portable freezer (Athens, Ohio) and cooled down from 20 to \(-50^\circ\text{C}\). The average coefficient of thermal contraction of asphalt binders \((a_{\text{Asphalt}} = 300 \times 10^{-6}/\text{°C})\) is about 38 times

![Diagram](https://example.com/diagram.png)

Fig. 1. Typical thermal cracking pattern in asphalt pavement and thermal cracking formation mechanism in asphalt pavement due to thermally induced stresses through the pavement thickness.

greater than that of granite material \( (\alpha_{\text{Granite}} = 8 \times 10^{-6} \text{1/\(^\circ\text{C}\)}) \) (Marasteanu et al. 2007). Due to the difference between the thermal contraction coefficients of asphalt and granite materials, as the AE sample cools down the asphalt layer is restrained from contracting (as a stress-free layer) due to the granite substrate, causing increasing thermally induced stresses in the sample. Fig. 3(a) illustrates the thermally induced tensile as well as shear stresses developed within asphalt sample when subjected to decreasing temperatures. The progressively higher thermal stresses in the binder eventually results in formation of thermal cracks, which are
accompanied by the release of elastic strain energy in the form of transient mechanical waves. Fig. 3(b) shows the change in the thermal stress and tensile strength of asphalt materials due to decrease in the temperature. Transversely oriented thermal cracks occur when the thermally induced tensile stresses equal the tensile strength of the material. In other words, in Fig. 3(b) the cracking temperature of asphalt binder is the temperature corresponding to the intersection point of stress and strength curves [Fig. 3(b)] (Hills and Brien 1966).

In the present study, the critical cracking temperatures of the asphalt binders were determined by processing and analyzing the emitted elastic waves captured during the tests using the AE technique. Fig. 4 schematically illustrates an AE testing sample of asphalt binder bonded to a granite substrate. Typical time-domain as well as frequency-domain representations of AE signal associated with an AE event are presented in Fig. 5. The AE testing setup used in this study is schematically shown in Fig. 6. AE testing procedures were established: AE stress waves are detected with piezoelectric sensors, amplified, filtered, and then recorded. The temperature of the sample is recorded using a K-type thermocouple connected to four-channel temperature data logger (Omega temperature data logger, Norwalk, Connecticut). Wideband AE sensors (Digital Wave, Model B1025, Digital Wave Corporation, Centennial, Colorado) with a nominal frequency range of 20–1.5 MHz were utilized to monitor and record acoustic activities of the sample during the test. High-vacuum grease was used to couple the AE sensors to the test sample. AE signals were preamplified 20 dB using broadband preamplifiers to reduce extraneous noise. The signals were then further amplified 21 dB (for a total of 41 dB) and filtered using a 20 kHz high-pass double-pole filter using the Fracture Wave Detector (FWD) signal condition unit. The signals were then digitized using a 16-bit analog to digital converter (ICS 645B-8, Digital Wave Corporation, Centennial, Colorado) using a sampling frequency of 2 MHz and a length of 2,048 points per channel per acquisition trigger. The outputs were stored for later processing using Wave Explorer software (Hill et al. 2013, 2016).

Evaluation of AE activity of asphalt samples is performed on recorded AE signals and associated test temperatures. An AE event is an individual waveform having a threshold voltage of 0.1 V and energy equal to or greater than $4 V^2-\mu s$. The emitted energy associated with each event is one of the characteristics of an AE signal and can be computed using the following equation,

$$E_{AE} = \int_0^t V^2(t) dt$$  \hspace{1cm} (1)

To minimize the amount of extraneous data including electronic noise, the piezoelectric AE sensors were conditioned in the cooling chamber prior to starting of test. In addition, all events with energy lower than $4 V^2-\mu s$ were filtered out. All results presented in this paper are based on these described filtering procedures.

In addition to AE test, the BBR test was conducted in accordance with ASTM D6648-01 (ASTM 2001) and AASHTO T313-02 (AASHTO 2011) to determine the propensity of asphalt binders to thermal cracking. Two parameters, the flexural creep stiffness ($S$) and slope of log stiffness-time curve ($m$-value), were determined by measuring the midpoint deflection of simply supported beam-shaped asphalt samples subjected to a constant creep load applied to the midpoint of the beam. The flexural creep stiffness of asphalt binder and the slope of the log creep stiffness versus
log loading time curve at $t = 60$ s are considered as the creep stiffness and the $m$-value of asphalt material, respectively (AASHTO 1999).

**Determining the Proper Location to Measure Temperature of AE Asphalt Sample**

One important aspect of the AE-based test is to monitor and record the temperature of the asphalt sample throughout the test. It is however very important to measure the temperature that accurately represents the temperature of the whole sample. To determine the proper location to measure the temperature, three thermocouples, designated A, B, and C and positioned at three different locations, were employed. Thermocouple A was positioned next to the asphalt sample at the interface of the binder and granite. Thermocouples B and C were embedded inside the binder sample, 3 and 6 mm deep inside the sample, respectively [Fig. 7(a)]. Plots of temperature versus time of AE asphalt sample measured by those three thermocouples is shown in Fig. 7(b). It is observed that initially at the beginning of the test, there is a thermal lag of $6^\circ C$ between outside and inside of the sample. This thermal lag gradually decreases as the sample cools down until it becomes almost zero when temperature approaches $-10^\circ C$. At temperatures below $-10^\circ C$, the temperature measured by all three thermocouples are almost the same. Considering the fact that the embrittlement temperature of almost all asphalt binders is below $-10^\circ C$, Location A which is the interface of asphalt binder and granite, appears to be a proper place to position thermocouples to measure the temperature of asphalt sample during AE test. All temperature reported in this study were measured using thermocouples position adjacent to asphalt sample at the interface of asphalt and granite.

**Results and Discussion**

A typical plot of AE test results is shown schematically in Fig. 8. Four distinct regions were found to exist in the cumulative AE event counts versus temperature plot, namely: precracking, transition, stable cracking, and fully cracked regions. In the precracking region, differential thermal contraction between the asphalt binder and granite substrate caused thermal stresses to accumulate in the binder specimen, eventually leading to material fracture. In the Precracking region, no AE events are detected. Progressively higher thermal stresses in the specimen result in the formation of thermal microcracks in the material, which is accompanied by the release of mechanical elastic waves. This manifest itself as a cluster of high-amplitude waves during the test. The temperature corresponding to the AE event with the first peak energy level has been termed the embrittlement temperature, which is considered as the starting point of the transition region. The embrittlement temperature shows the onset of damage in asphalt material. It is hypothesized that the embrittlement temperature represents a fundamental material state that is independent of sample size and sample shape, as long as a statistically representative volume or larger is used (Dave et al. 2011; Behnia et al. 2011; Behnia 2013).

The transition region can be considered as the region where material behavior gradually changes from a quasi-brittle to a brittle state where resistance to fracture is generally very low, allowing cracks to propagate readily. The stable cracking region usually initiates at a very low temperature when the material is brittle and generates a significant amount of AE activity. The AE event counts versus temperature plot in this region usually has a steep slope that remains relatively constant. The starting point of the stable cracking region is the temperature at which the concavity of AE events counts curve changes from convex to linear. Based upon examination of AE data, this region is thought to be below the glass transition region of the binder.

The fully cracked region starts after the stable cracking region when the rate of AE activity of asphalt sample begin to reduce until it reaches zero at the end of this region. The starting point of the fully cracked region is the temperature at which the shape of AE

![Fig. 7.](image-url) (a) Position of Thermocouples A, B, and C in the AE asphalt sample; (b) typical plots of temperature versus time for AE asphalt sample obtained from Thermocouples A, B, and C

![Fig. 8.](image-url) Typical plot of cumulative AE event counts versus temperature with four distinctive regions, namely precracking, transition, stable cracking, and fully cracked (Behnia 2013)
events; only a small portion of AE events are high energy. The energy content of an AE event is related to the size of the microdamage generating that event. The higher-energy events are resulted from formation of larger microcracks, some of which may probably be visible by naked eye, whereas the lower-energy-level events are produced by hairline microcracks within the sample such as formation of spiral cracking (Dave et al. 2011; Behnia et al. 2011).

The embrittlement temperature ($T_{EMB}$) of asphalt binders evaluated through AE testing is compared with the critical cracking temperature ($T_{CR}$) obtained from the BBR Superpave asphalt binder test. The critical cracking temperature for the asphalt binders were determined using the test results described by Marasteanu et al. and using the procedure described in national cooperative highway research program (NCHRP) Report 452 (McDaniel and Anderson 2001). The equations used for determining critical temperature ($T_{CR-BBR}$) using Superpave tests are shown below for the cases of creep stiffness ($T_{CR-s}$) and m-value ($T_{CR-m}$) from BBR test.

Here, $S_1$ and $S_2$ are the BBR creep stiffnesses and $m_1$ and $m_2$ are the rate of change of binder stiffness $[S(i)]$ with respect to time at test temperatures of $T_1$ and $T_2$, respectively:

\[
T_{CR-S} = T_1 + \frac{\log(300) - \log(S_1)}{\log(S_2) - \log(S_1)} (T_2 - T_1) - 10 \tag{2}
\]

\[
T_{CR-m} = T_1 + \frac{\log(0.300) - \log(m_1)}{\log(m_2) - \log(m_1)} (T_2 - T_1) - 10 \tag{3}
\]

\[
T_{CR-BBR} = \max(T_{CR-S}, T_{CR-m}) \tag{4}
\]

### Table 1. AE-Based Embrittlement Temperatures along with BBR Cracking Temperatures of AAF1, AAG1, AAK1, and AAD1 Asphalt Binders

<table>
<thead>
<tr>
<th>Asphalt binder</th>
<th>$T_{EMB}$ (°C)</th>
<th>COV (%)</th>
<th>$T_{BBR}$ (°C)</th>
<th>COV (%)</th>
<th>$T_{BBR} - T_{EMB}$ (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TANK AAB1 (PG58-28)</td>
<td>-35.78</td>
<td>2.98</td>
<td>-34.69</td>
<td>7.54</td>
<td>2.89</td>
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<tr>
<td>RTFO AAB1 (PG58-28)</td>
<td>-35.78</td>
<td>3.68</td>
<td>-32.83</td>
<td>5.34</td>
<td>2.95</td>
</tr>
<tr>
<td>PAV AAB1 (PG58-28)</td>
<td>-32.09</td>
<td>3.74</td>
<td>-30.89</td>
<td>8.07</td>
<td>1.20</td>
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<tr>
<td>TANK AAB1 (PG58-22)</td>
<td>-30.46</td>
<td>3.56</td>
<td>-27.81</td>
<td>14.34</td>
<td>2.65</td>
</tr>
<tr>
<td>RTFO AAB1 (PG58-22)</td>
<td>-29.45</td>
<td>2.21</td>
<td>-26.32</td>
<td>3.27</td>
<td>3.13</td>
</tr>
<tr>
<td>PAV AAB1 (PG58-22)</td>
<td>-24.33</td>
<td>3.25</td>
<td>-23.13</td>
<td>7.92</td>
<td>1.20</td>
</tr>
<tr>
<td>TANK AAC1 (PG58-16)</td>
<td>-29.36</td>
<td>3.77</td>
<td>-24.90</td>
<td>8.99</td>
<td>4.46</td>
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<tr>
<td>RTFO AAC1 (PG58-16)</td>
<td>-27.77</td>
<td>1.26</td>
<td>-21.37</td>
<td>11.86</td>
<td>6.40</td>
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<tr>
<td>PAV AAC1 (PG58-16)</td>
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<td>-35.19</td>
<td>2.79</td>
<td>-27.03</td>
<td>3.35</td>
<td>8.16</td>
</tr>
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### Table 2. AE-Based Embrittlement Temperatures along with BBR Cracking Temperatures of AAF1, AAG1, AAK1, and AAM1 Asphalt Binders

<table>
<thead>
<tr>
<th>Asphalt binder</th>
<th>$T_{EMB}$ (°C)</th>
<th>COV (%)</th>
<th>$T_{BBR}$ (°C)</th>
<th>COV (%)</th>
<th>$T_{BBR} - T_{EMB}$ (°C)</th>
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<tbody>
<tr>
<td>TANK AAF1 (PG64-10)</td>
<td>-24.47</td>
<td>4.74</td>
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<td>7.99</td>
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<tr>
<td>TANK AAG1 (PG58-10)</td>
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<td>TANK AAK1 (PG64-22)</td>
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<td>TANK AAM1 (PG64-16)</td>
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<td>-21.01</td>
<td>7.32</td>
<td>5.52</td>
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</table>

The AE embrittlement temperatures along with the corresponding BBR-based critical cracking temperatures for the various asphalt binders tested at different age conditioning levels are provided in Tables 1 and 2. In all cases, a minimum of four replicates were used to produce the average values and statistical measures presented in this section, shown in Fig. 10. The coefficient of variation (COV\%) of both AE and BBR results are also presented. The COV statistic is temperature-scale dependent (different results would be obtained for results expressed in Kelvin versus degrees Celsius, for instance), and would produce infinite values for means approaching zero. For the present application, where embrittlement temperatures are in a relatively narrow range and sufficiently below zero, the COV statistic was deemed to be a useful statistical parameter to describe the repeatability of the measurements obtained.

Results show that both AE embrittlement temperature and BBR critical cracking temperature of asphalt binders are sensitive to ageing levels, where $T_{\text{cracking}}(\text{TANK}) < T_{\text{cracking}}(\text{RTFO}) < T_{\text{cracking}}(\text{PAV})$. Comparison of AE and BBR results are presented in Fig. 11. It is observed that AE embrittlement temperatures correlated well with BBR-based cracking temperatures with $R^2 = 0.85$. Results also indicate that in almost all cases, the AE embrittlement temperature of asphalt material is lower than its corresponding BBR-based critical cracking temperature. This can be attributed to the fact that the BBR stiffness and $m$-value critical cracking thresholds (upper limit of $S = 300$ MPa and lower limit of $m$-value = 0.300) are only practical values selected based on the performance of asphalt materials in the field. In fact, BBR thresholds were established with an inherent factor of safety to avoid low-temperature cracking. In other words, for an asphalt binder when the values of the stiffness or the $m$-value exceeds those critical thresholds it does not mean that thermal cracks begin to develop within the binder sample. In contrast, in the AE test, thermal micro-cracks begin to develop within the sample as soon as the temperature reaches the embrittlement temperature of the material. The fact that the BBR-based critical temperature of most binders are warmer than embrittlement temperature of that material indicates that BBR cracking thresholds are somehow conservative, and in most cases low-temperature performance of asphalt binders is better than what their performance grade (PG) low temperatures suggest. It was also observed that the repeatability of the AE testing technique was found to be better than the BBR testing method as the COV\% of AE-based results were consistently lower than those of BBR-based results.

The developed AE-based approach would yield significant pay-off to practice for both upstream and downstream suppliers and producers. Upstream suppliers of asphalt could use the proposed technology to rapidly assess the low-temperature characteristics of trial formulations. Pavement owners could use the technology for quality assurance of binders and mixtures, for periodic assessment of pavement condition, and for the scheduling of preventive
maintenance and rehabilitation, where cracking is of concern. In addition, the testing approach can provide a convenient method to screen asphalt binders prone to the effects of low-temperature physical hardening and increased embrittlement with long-term aging. Physical hardening has been shown to increase stiffness and decrease fracture resistance in asphalt binders held at low temperatures (Bahia and Anderson 1993).

Conclusions

An acoustic-emission-based testing approach to evaluate the low-temperature cracking performance of asphalt binders has been developed. Results corresponding to eight different types of asphalt binders at three different aging levels (unaged, short-term aged, and long-term aged) are presented. A thin layer of asphalt binder (6 mm thick) bonded to a granite substrate was used as the AE sample and cooled down from 20 to −50°C. As the sample temperature decreased, thermally induced tensile stresses developed within the sample due to differential thermal contraction between granite substrate and asphalt binder. When thermal stresses exceed the tensile strength of the binder, transversely oriented thermal cracks are formed, which are accompanied by the release of elastic strain energy in the form of transient mechanical waves, i.e., AE activity. The critical cracking temperature of the asphalt binder was determined by processing and analyzing recorded AE signals and associated test temperatures. AE test results were compared against thermal cracking temperatures obtained from BBR tests. The following conclusions can be drawn based upon the AE-based and BBR-based testing results of the asphalt binders:

- The temperature corresponding to the first major acoustic-emissions event is defined as the embrittlement temperature \(T_{\text{EMB}}\). The embrittlement temperature corresponds to the onset of thermal microcracks within the sample. It is hypothesized that the embrittlement temperature represents a fundamental material state that is independent of material constraint, sample size, and sample shape, as long as a statistically representative volume or larger is used;
- The AE embrittlement temperature of an asphalt binder is sensitive to binder type as well as to its aging level. The higher the aging level, the warmer its embrittlement temperature;
- Comparison of the AE-based embrittlement temperatures with the corresponding BBR-based critical cracking temperature of asphalt binders showed that, for most binders, the embrittlement temperature is slightly (generally a few degrees) lower than the BBR-based critical cracking temperature;
- The repeatability of the AE testing technique was found to be as good as or superior to other low-temperature binder tests currently in use such as the BBR-based method;
- The overall trends of \(T_{\text{EMB}}\) of several different binders were consistent with the BBR cracking temperatures. This provides more confidence in the use of the \(T_{\text{EMB}}\) quantity as a screening tool to quickly assess the cracking resistance of asphalt materials;
- The AE-based embrittlement measurement differs significantly from existing standard mechanical tests [BBR, DTT, IDT, DC (T), and TSRST] and likewise differs from more-recently proposed tests, such as the ABCD fracture test (Jung and Vinson 1994; Kim 2005, 2007). None of the existing or proposed tests has all of the features of the AE embrittlement test, namely being small, portable, and suitable for sensing a material and could be especially advantageous when a direct tension (DT) test is required; and
- Evaluation of thermal conductivities and coefficients of thermal contraction of granite and asphalt materials is recommended for finite-element modeling of AE test or for performing numerical simulation of heat transfer within AE sample during the test. While the results of this investigation appear promising, more field validation trials and test optimization efforts are still needed to move the test forward to implementation in the industry.

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