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# Application of Acoustic Emissions Technique in Assessment of Cracking Performance of Asphalt Pavement Materials

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## Abstract

This chapter focuses on various applications of acoustic emissions (AE) technique in evaluation of cracking in asphalt pavements including (1) assessment of low-temperature cracking of asphalt binders and mixtures and (2) quantitative characterization of rejuvenators' efficiency in restoring aged asphalt pavements to their crack-resistant state. The AE-based embrittlement temperature results of 24 different asphalt materials consisting of eight different binders, each at three oxidative aging levels are presented. Results show that embrittlement temperatures correlated well with corresponding bending beam rheometer (BBR-based) critical cracking temperatures with  $R^2 = 0.85$ . This chapter also presents application of AE for evaluation of rejuvenators' efficiency on asphalt materials at various oxidative aging levels. The Geiger's iterative source location method was employed to accurately determine embrittlement temperatures throughout the thickness of rejuvenator-treated asphalt samples. Results showed that the low temperature cracking properties of oxidative aged materials after 2 weeks of dwell time of rejuvenator have been recuperated. Moreover, it was observed that cracking characteristics of aged asphalt 6–8 weeks after applying rejuvenator far exceeded that of the virgin materials. The promising results suggest that the AE technique can be considered as a viable approach for the assessment of low temperature behavior of asphalt pavements.

**Keywords:** acoustic emission, thermal cracking, asphalt pavements, bending beam rheometer, source location, rejuvenator, oxidative aging

## 1. Introduction

As an important component of the transportation infrastructure, asphalt pavement is composed of multi-layer complex system of different materials subjected to various combinations of traffic as well as environmental loadings. During their lifetime asphalt pavements experience various forms of distresses as they undergo oxidative aging, freeze-thaw cycles, and traffic repetitions. One of the most widespread type of deterioration in asphalt roads which shortens the pavement life and results in premature failure of the pavement structure is cracking. An accurate and realistic assessment of cracking performance of asphalt pavements has remained as a challenging task for civil engineers.

The AE technique has become very popular in recent decades due to its unique ability in detecting and locating microstructural failures in different types of materials. This method has been successfully used for damage detection of various materials such as steel, concrete, wood, and rock. However, for the case of asphalt roads, there has been only a limited application of this technology in damage assessment of asphalt pavements. In one of the studies Khosla and Goetz [1] used the acoustic emission approach at low temperatures to locate crack initiation and propagation in indirect tensile (IDT) asphalt concrete specimens. They found that the material failure due to fracture was accompanied by a sudden increase in total AE counts where a big portion of AE counts occurred at about 80% of the peak load. In another study conducted by Valkering and Jongeneel [2], AE technique was implemented to carefully monitor the thermally-induced cracking in asphalt concrete materials subjected to low temperature cooling cycles ( $-10^{\circ}\text{C}$  to  $-40^{\circ}\text{C}$ ). Results showed that the AE activity of the material such as number of events were strongly correlated with the extent of thermal fracture in the specimens. Results also demonstrated that at low temperatures the source of AE activities in restrained specimens were crack initiation originated from defects exists in the material. In the research study performed by Hesp et al. [3] the AE method was employed for restrained asphalt concrete specimens at low temperatures ( $-32^{\circ}\text{C}$  to  $-20^{\circ}\text{C}$ ) to measure and to detect crack initiation and propagation in the restrained samples. They compared the total amount of AE activities in different mixtures and found that the styrene-butadiene-styrene (SBS)-modified asphalt concrete materials exhibited less AE activities as compared to that of for the unmodified asphalt concrete mixes. The AE approach was implemented by Li et al. [4–8] to evaluate and to quantify fracture in semi-circular bending (SCB) asphalt specimens at  $-20^{\circ}\text{C}$ . They concluded that most of the AE activities in the material happens at about 70% of the material strength. Their results also showed that the maximum intensity of AE amplitudes correlated well with the extent of macrocracking damage in the specimen. They also found that the location of AE events is the good indicator of approximate size of the fracture process zone (FPZ). Nesvijski and Marasteanu [9, 10] in another research study, used the AE spectral analysis approach at low temperatures in order to investigate and assess fracture in semi-circular bending (SCB) asphalt samples. They were able to successfully demonstrate that the AE approach could be applied for accurate characterization of cracking in asphalt concrete materials.

This chapter will focus on various applications of the acoustic emission technique in asphalt pavements including: (1) assessing the low-temperature cracking performance of asphalt binders and asphalt pavement materials (2) use of acoustic emission technique for quantitative evaluation of restoring aged asphalt pavements with rejuvenators.

## **2. Implementation of AE approach for low-temperature cracking assessment of asphalt binders and asphalt concrete materials**

Low temperature cracking, a.k.a. thermal cracking, is a very common type of damage occurring in asphalt pavements located either in regions with cold climates or in milder climate regions with large daily temperature fluctuations. In asphalt pavements built in cold climates with severe winters, thermal cracking usually happens as a result of fast cooling rates (single-event thermal cracking). On the other hand, in asphalt roads located in regions with milder climate, thermal cracks develop at a slower rate, and it usually takes several cooling cycles for cracks to initiate and propagate through the pavement thickness (thermal fatigue cracking) [11]. When the temperature drops, surface of the pavement has the lowest temperature,

and the temperature changes are highest there. Thermal tensile stresses develop in the restrained pavement layer due to the change in pavement temperature. The thermally-induced stresses are greatest in the longitudinal direction of the road which will lead to formation of transversely-oriented surface-initiated thermal cracks of various lengths and widths along the road.

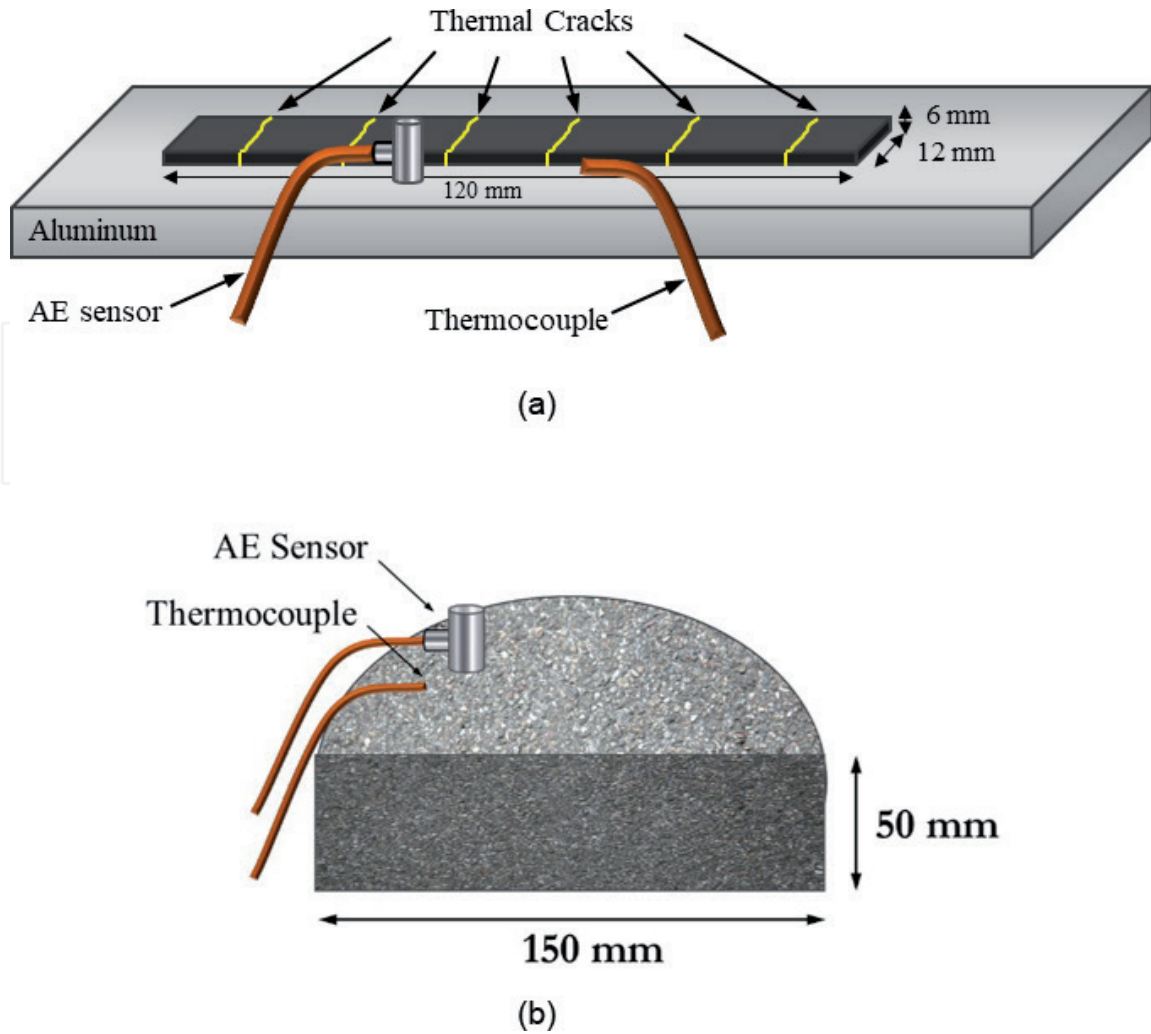
Numerous research studies have demonstrated that the low temperature characteristics of asphalt pavements are closely related to that of the asphalt binder used in pavement construction. The AE method is implemented to evaluate the thermal cracking in asphalt binders. The AE binder sample consists of a 6 mm thick layer of asphalt binder bonded to an aluminum plate. To conduct the test, prepared specimens are placed inside the freezer and exposed to decreasing temperatures, ranging from 20°C to -40°C, or even to -50°C, if necessary for some polymer modified binders. To continuously monitor and record the sample temperature, a K-type thermocouple is placed on the specimens' surface. Due to the relatively small size of the AE sample, there is a thermal lag at the beginning of the test, which becomes negligible at temperature lower than -10°C. Differential thermal contraction between aluminum and asphalt binder induces progressively higher thermal stresses in the binder leading to formation of thermal cracks in the material. Thermal cracks formation in the sample is accompanied by a release of elastic energy in the form of transient waves which could be picked up using the AE piezoelectric sensor(s) mounted on aluminum plate. The critical cracking temperature, a.k.a. the embrittlement temperature, of the asphalt binders tested are determined by processing and analyzing the emitted elastic waves captured during the tests using the AE technique. **Figure 1a** schematically illustrates an AE testing sample of asphalt binder with an aluminum substrate [12–21].

To conduct the AE test for asphalt concrete materials, a semicircular-shaped asphalt concrete sample with a 50°mm thickness and a 150°mm diameter is used as the testing specimen, see **Figure 1b**. The testing sample for asphalt concrete can be fabricated from either field cores or from gyratory compacted samples. To conduct the AE test, similar to the binder test, the prepared AE sample is subjected to decreasing temperatures ranging from 20°C to -40°C and the acoustic activities and temperature of asphalt material test sample is continuously monitored and recorded using piezoelectric AE sensors and a K-type thermocouple, respectively. The source of acoustic emission activities in asphalt concrete materials is formation of thermally-induced microdamages within the asphalt mastic. As a heterogeneous viscoelastic material, the thermally induced stresses develop in asphalt concrete due to the thermal contraction mismatch between aggregates and surrounding asphalt mastic [12–26].

The acoustic emission testing set up used for assessing asphalt materials consists of several wideband piezoelectric AE sensors along with pre-amplifiers and data acquisition system with processing and analysis software. The Digital Wave-Model B1025 wideband AE sensors with nominal frequency range of 20 kHz to 1.5 MHz used in this study in order to record and continuously monitor AE activities of the material while conducting the experiment. To reduce extraneous noise, the AE signals picked up by AE sensors are first pre-amplified 20 dB using broad-band pre-amplifiers. Then AE signals are amplified again 21 dB for a total of 41 dB. At the end signals are filtered using a 20 kHz high-pass double-pole filter through using the signal conditioning unit. A 16-bit analog to digital converter (ICS 645B-8) with 2 MHz sampling frequency and a length of 2048 points per channel per acquisition trigger are used to digitize the signals and outputs are stored for the post-processing.

In general there are two methods normally used to analyze AE signals: (1) the “classic” or “parameter-based” method; (2) the “quantitative” or “signal-based” approach. In the first approach, the AE signals are not recorded, instead only some





**Figure 1.**  
AE testing samples used for (a) asphalt binders (b) asphalt concrete materials.

AE parameters are recorded and analyzed. Whereas in the signal-based approach, the actual AE signals are recorded and used to analyze the materials microstructure. The failure and microdamage occurring in the material could generate significant number of AE signals within a very short time generating big amount of AE data. In the parameter-based method only some rudimentary analysis can be performed on AE data however it is faster than the quantitative method. On the other hand, while the signal-based approach is slower, it is capable of more sophisticated analysis of performance of the material.

For evaluation of thermal cracking in asphalt materials, both parameter-based and signal-based techniques were implemented on recorded AE signals and associated test temperature. AE event is an individual waveform with the threshold of 0.1 V and the energy level equal to or greater than  $4 \text{ V}^2 \mu\text{s}$ . The emitted energy associated with each event is one of the important characteristics of an AE signal and can be calculated using Eq. (1), where  $E_{AE}$  is the AE energy of an event ( $\text{V}^2 \mu\text{sec}$ ) with duration of time  $t$  ( $\mu\text{sec}$ ) and recorded voltage of  $V(t)$  [1].

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

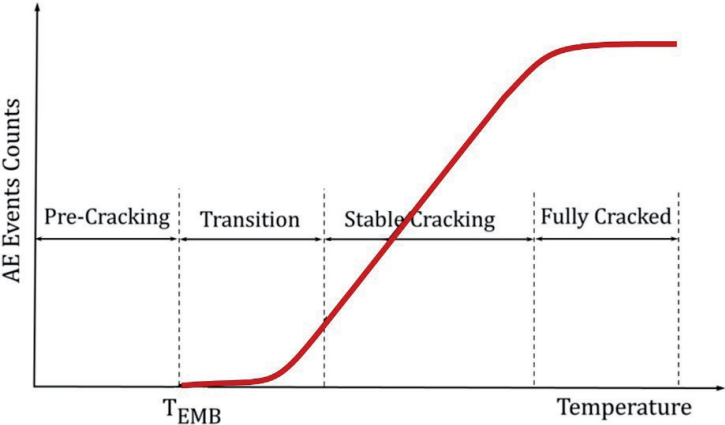
**Figure 2** shows a typical plot of AE events counts versus temperature for typical asphalt binder and asphalt concrete AE tests which consists of four distinct

regions, namely: (1) pre-cracking, (2) transition, (3) stable cracking, and (4) fully cracked regions. In the “pre-cracking region”, thermally-induced stresses in the sample are building up and they are still below the strength of the material. As a result no damage and consequently no AE events are observed within this region. In the “transition” region, as soon as the thermal stresses reach the strength of the material, microdamages form in the material which manifests itself as a cluster of high amplitude AE events. The temperature corresponding to the AE event with the first peak energy within the transition region has been termed the “embrittlement temperature,” as shown in **Figure 3**. The embrittlement temperature is the onset of damage in asphalt material. Results has demonstrated that the embrittlement temperature is a fundamental material state which is independent of material constraint, sample size (as long as a statistically representative volume or larger is used), and sample shape [15]. In the “transition region”, material behavior gradually changes from a quasi-brittle to a brittle state where resistance to fracture is generally very low, allowing microdamages to propagate readily.

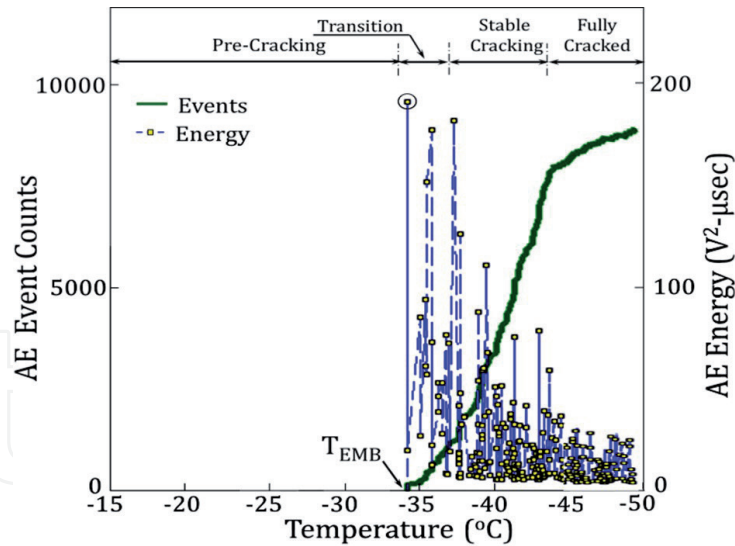
The third region is the “stable cracking region” which normally initiates at a very low temperatures when the material is brittle. Significant amount of AE activities are observed during this region. The last region, is the “fully cracked region” where the rate of AE activities of the sample begins to reduce until it reaches almost zero at the end of this region. The AE activities originate from formation of new micro-damage inside the sample. Thus reduction in the rate of AE activity can be linked to the presence of plenty of microdamage in the sample. This region is usually observed when the sample is cooled down to very cold temperatures allowing all microdamage to develop within the sample [15].

**Figure 4** illustrates the typical envelope locus of AE event energies of asphalt samples and demonstrates the intensity of the released energies of AE events. In the pre-cracking region, the envelope locus is zero and suddenly at the beginning of the transition region it jumps to its maximum magnitude. The magnitude of AE event energies gradually tapers off in stable cracking region until it reaches almost zero in the fully cracked region.

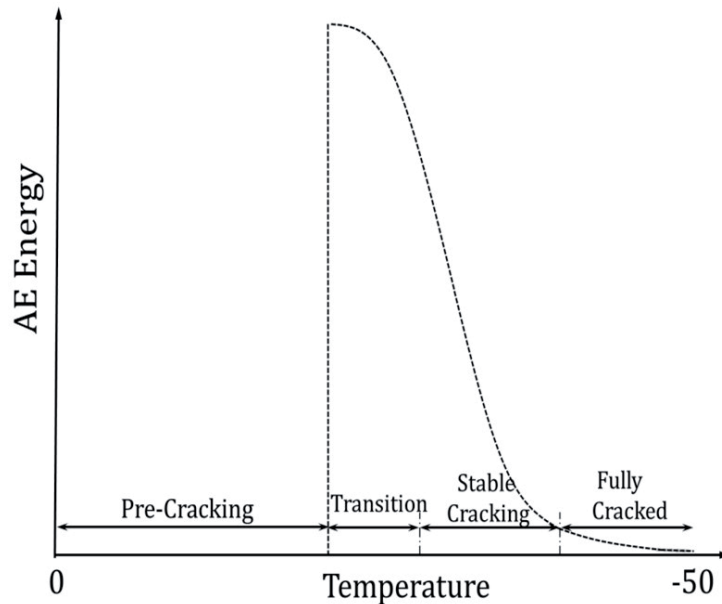
The histogram presented in **Figure 5** shows the graphical representation of the distribution of AE events energies for asphalt materials. Results suggest that only a small portion of AE events are high energy events while the rest of the events are in fact low energy. Generally, the energy content of an event is proportional with the size of the microdamage causing that event. The high energy events result from the formation of large microcracks while the low energy AE events could be linked to formation of hairline microcracks in the material.



**Figure 2.**  
*Typical AE event counts vs. temperature plot regions.*



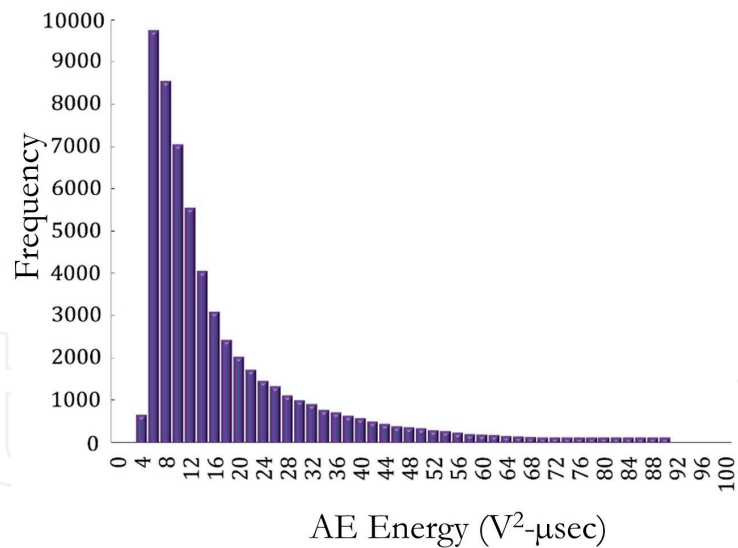
**Figure 3.**  
*Typical plot of event count and AE energy vs. temperature [15].*



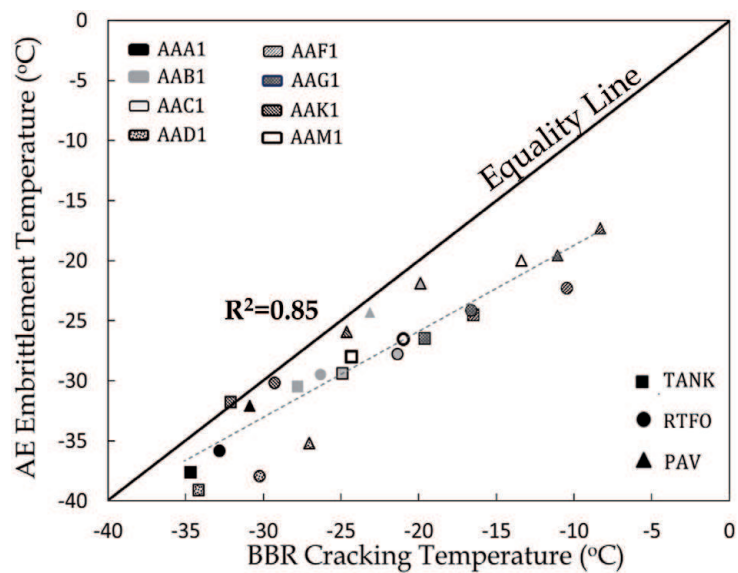
**Figure 4.**  
*Typical envelope locus of AE events energy during thermal cooling [15].*

The AE test results for 24 different types of asphalt materials (eight different binders, each at three aging levels) including: 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) are presented in **Figure 6**. In this experiment each binder was tested at three aging levels: (1) unaged (TANK) (2) short-term aged (RTFO), and (3) long-term aged (PAV). The ASTM D2872-04 (ASTM 2004) and ASTM D6521-05 (ASTM 2008) were used to perform the oxidative aging process of RTFO and PAV binders, respectively. It should be mentioned that in PG XX-YY used for expressing the Performance Grade of asphalt materials, XX corresponds to the expected average high temperature of asphalt pavement over a 7 days, and YY is the lowest expected temperature of the pavement.

Results show that the AE embrittlement temperatures correlated well with the bending beam rheometer (BBR-based) critical cracking temperatures with  $R^2 = 0.85$ . Results suggest that AE-based embrittlement temperatures are lower than the corresponding BBR-based critical cracking temperatures. This could be



**Figure 5.**  
Typical histogram of AE events energies for asphalt binder material [15].



**Figure 6.**  
Correlation between AE embrittlement temperature and BBR-based cracking temperature illustrating the conservative nature of the BBR-based cracking temperatures [21].

attributed to the fact that the AE-based embrittlement temperatures are directly related to the cracking performance of the material while the BBR- base critical temperatures are based upon the binder’s rheological material properties and include an inherent factor of safety to avoid low-temperature pavement cracking. In addition, numerous studies have demonstrated that AE approach is sensitive to aging level of the material and could successfully evaluate asphalt materials at different oxidative aging levels. Finding of different studies show that the embrittlement temperature of asphalt materials is sensitive to aging levels, where  $T_{EMB-TANK} < T_{EMB-FTFO} < T_{EMB-PAV}$ .

### 3. Use of acoustic emission technique for quantitative evaluation of restoring aged asphalt pavements with rejuvenators

Oxidative aging is a common problem in asphalt pavements which leads to an increase in stiffness and loss of ductility and cohesion of binders. It negatively



affects the fracture resistance of pavements. Certain chemical properties of the asphalt binders such as asphaltenes to maltenes ratio changes in the oxidation process. The oxidation rate of asphalt materials is accelerated at high temperatures and/or high exposure to ultraviolet light and air [21–26]. Different methods such as pavement surface milling and the application of rejuvenators are employed to restore asphalt pavements to their crack-resistant state. Application of rejuvenators is one of the popular techniques to restore the physical and chemical properties of aged asphalt materials. Rejuvenators change the asphaltenes to maltenes ratio to its original state leading to softening the aged asphalt materials [21–26]. Rejuvenators are generally sprayed on the surface of aged pavements. It is very important that rejuvenator could penetrate the surface via capillary action and gravity and diffuse through the aged asphalt.

Currently there is no standardized method to assess the performance of rejuvenators when applied in the field. The efficiency of rejuvenators is evaluated by the following three methods which are cumbersome and time consuming and they are not often used.: (1) estimating the penetration of rejuvenator in the pavement by comparing the penetration value of the binder at 25°C in the asphalt binder extracted from untreated and treated sample; (2) comparing the asphalt binders' viscosity at 60°C obtained from untreated and treated cores; and (3) comparing the amount of loss in aggregates in the abrasion test in untreated vs. treated samples [26].

The AE source location approach has recently been employed to assess the efficiency of rejuvenators in restoring aged asphalt materials to their original crack resistant condition. The Geiger's iterative source location method was used to accurately detect the source of AE activities in the material [26, 27]. This iterative technique is based on the Gauss-Newton algorithm. To build the arrival time function of the  $i^{\text{th}}$  sensor, see Eq. (2), data from at least four sensors is required for the Geiger's method:

$$f_i(x, y, z, t) = T_s + \frac{1}{v} \sqrt{(x_i - X_s)^2 + (y_i - Y_s)^2 + (z_i - Z_s)^2} \quad (2)$$

where  $(X_s, Y_s, Z_s)$  represent the spatial coordinates of the AE source,  $(x_i, y_i, z_i)$  is the coordinates of the  $i^{\text{th}}$  sensor,  $v$  is the velocity of wave in the material,  $t_i$  and  $T_s$  represent the known receiving time and unknown AE source event occurring time by the  $i^{\text{th}}$  sensor, respectively. Taylor series is used to expand Eq. (2) at a point  $(x_0, y_0, z_0)$ , close to the actual source leading to Eq. (3):

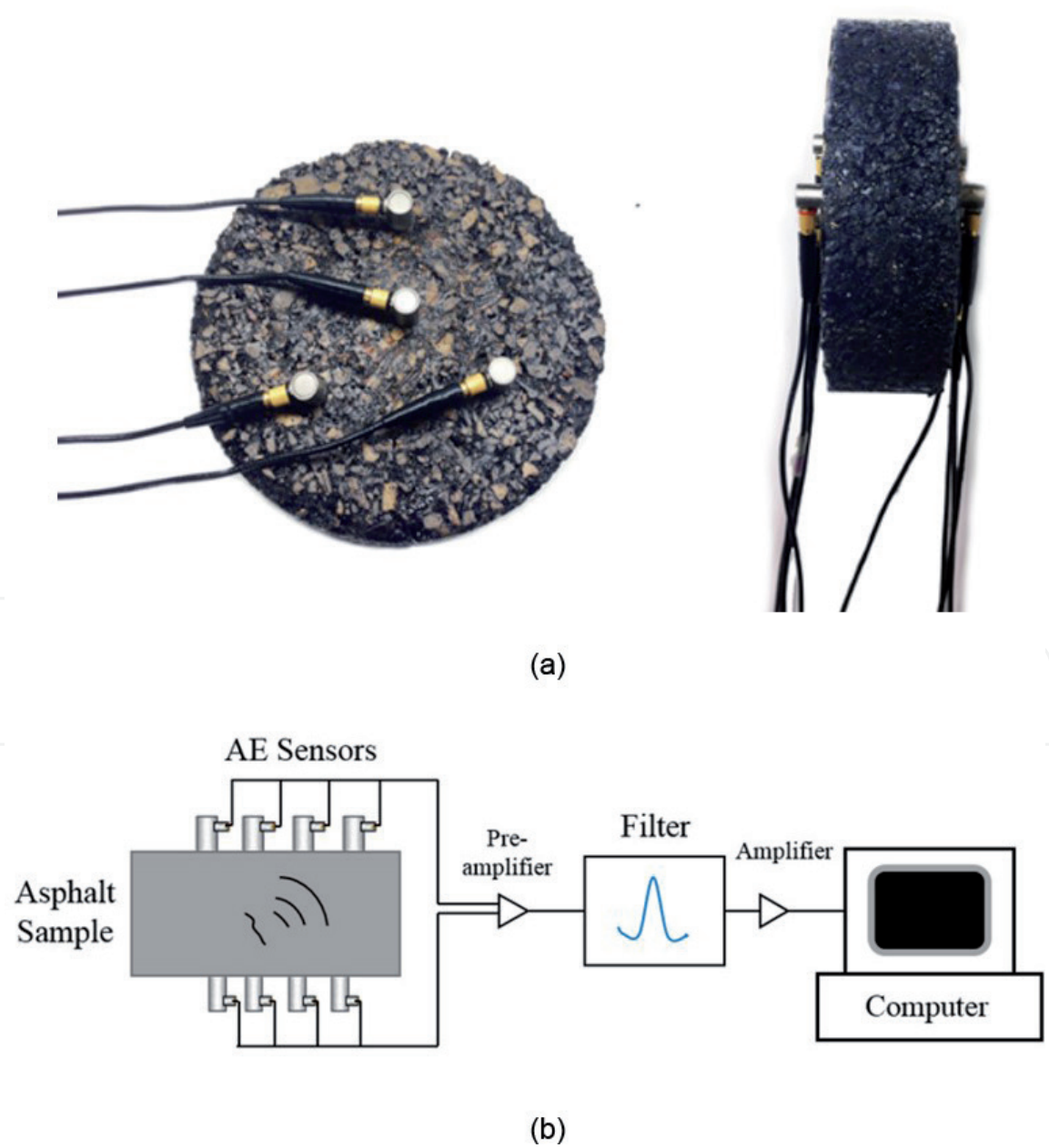
$$f_i(x, y, z, t) = f_i(x_0, y_0, z_0, t_0) + \epsilon_i \quad (3)$$

where  $\epsilon_i$  is the residual term, a.k.a. the correction vector, which is the difference between the calculated arrival time and the observed arrival time with respect to the  $i^{\text{th}}$  sensor. The correction vector can be determined using the first order derivatives of the arrival time function. The Geiger's method tries to minimize the correction vector by going through several iterations of Eq. (4).

$$\epsilon_i = \frac{\partial f_i}{\partial x} \delta x + \frac{\partial f_i}{\partial y} \delta y + \frac{\partial f_i}{\partial z} \delta z + \frac{\partial f_i}{\partial t} \delta t \quad (4)$$

In this chapter results from one of the studies on evaluation of rejuvenators on aged asphalt materials are presented where PG64-22 was used as the based binder. The asphalt content of the mixture was 5.6% by weight and the gyratory compacted specimens were made using a maximum aggregate size of 19 mm. Some specimens were aged in the oven for 2 h at 155°C to simulate the aging level during plant production. Part of the specimens were aged in the oven for 36 h at 155°C (in addition to the short term aging) to mimic the long term aged asphalt pavement materials. The oxidative aging process was done on loose mixtures in order to obtain uniformly-aged compacted samples. **Figure 7** shows one of specimens with eight AE sensors mounted on the top and bottom surfaces of the specimen, four sensors on each side. To avoid numerical instability, AE sensors pattern at the bottom of the specimen has a 45° offset angle with respect to the pattern of sensors coupled on the top surface.

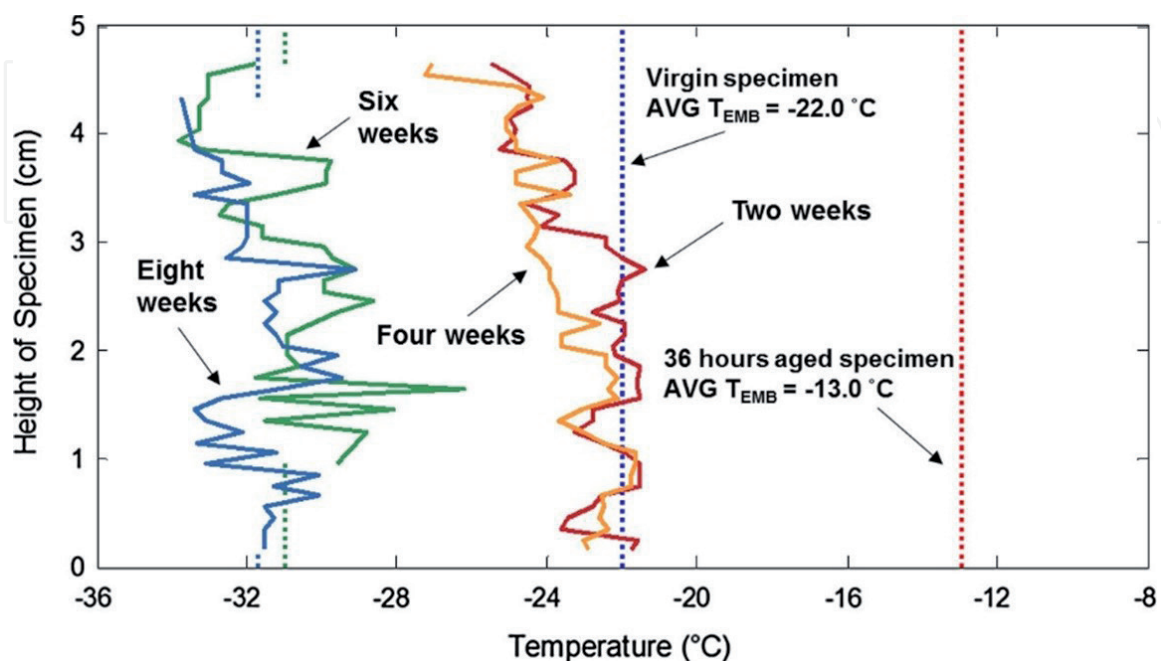
Some aged specimens were treated by spraying a thin layer of rejuvenator on the top surface of the sample. The amount of rejuvenator used was 10% by weight



**Figure 7.**  
(a) Oxidative aged AE testing sample with eight piezoelectric sensors, four sensors on each side. (b) AE testing setup used for source location [21].

of the asphalt binder. The rejuvenator-treated specimens were then stored for a prescribed dwell time of 2, 4, 6, and 8 weeks before performing the AE tests. After each dwell time, specimens were tested using the same AE source location procedure used to test the 36 h and 2 h aged specimens, allowing the estimation of the embrittlement temperatures throughout the sample thickness.

To characterize the efficiency of rejuvenator on the aged asphalt materials, the embrittlement temperatures of the material were determined throughout the thickness of asphalt concrete samples by implementing the AE source location method. **Figure 8** illustrates the embrittlement temperatures results vs. sample thickness for different aged asphalt concrete materials. The effect of oxidative aging on the embrittlement temperature is clearly noticeable as the embrittlement temperature of the short-term aged sample ( $-22^{\circ}\text{C}$ ) is lower than that of the 36 h aged samples ( $-13^{\circ}\text{C}$ ). It is also observed that for all specimens the embrittlement temperatures of oxidative aged materials after 2 weeks of dwell time of rejuvenator have been recuperated. The test results obtained from samples after 6 and 8 weeks of dwell time were quite surprising as the embrittlement temperatures of the aforementioned samples far exceeded the embrittlement temperatures of the virgin materials. Moreover, the method was also able to successfully capture the embrittlement temperature gradation throughout the sample thickness for the dwell times of 2 and 4 weeks. This could be attributed to the fact that the rejuvenator has had enough time to penetrate and act on the top material layers. Results suggest that the AE method can be employed to accurately evaluate the graded embrittlement temperature properties of oxidative aged asphalt pavements. One important outcome of this study is that the AE approach can be used to intelligently select the best maintenance strategies for oxidative aged asphalt roads through optimizing the amounts of rejuvenators required to restore pavement to the original crack-resistant condition, or by optimizing the relative amount of milling and surface replacement of asphalt roads. In addition, the AE results obtained from source location approach were found to be consistent with those of obtained from non-collinear ultrasonic wave mixing method [28–31].



**Figure 8.** Average measured embrittlement temperatures of rejuvenator-treated oven-aged asphalt concrete samples (for 36 h at  $135^{\circ}\text{C}$ ) after dwell times of 2, 4, 6 and 8 weeks [21, 25, 26].

#### 4. Concluding remarks


The acoustic emission approach has been successfully implemented to address the shortage for accurate and reliable techniques to evaluate cracking performance of asphalt pavements. In addition, the AE method has been applied for assessing the efficiency of rejuvenator-treated pavements and to evaluate and characterize virgin, short-term, and long-term asphalt binders and asphalt concrete materials. The AE technique has also been employed in different areas such as evaluating asphalt pavements containing recycled materials such as RAP or RAS, assessing the effect of cooling cycles upon the structural integrity of pavements, and characterizing the thermal cracking performance of graded, i.e., aged asphalt pavements. The promising results from aforementioned studies suggest that the AE technique can be considered as a viable approach for the assessment of asphalt pavements. Moreover, when used for preventive maintenance and rehabilitation, AE method can serve as a powerful tool in enhancing pavement sustainability. Both up-stream and down-stream suppliers and producers of asphalt concrete binders could benefit from AE technique. The up-stream supplies of polymer, chemical, and other additives (warm-mix additives, antistrip agents) could use AE for rapid assessment of low-temperature characteristics of trial formulations, and could quickly evaluate the compatibility of blended additive systems. Asphalt mixture designers could take advantage of the AE technology in order to verify binder grade selection and to optimize the amount of recycled materials used in the pavement. Finally, the pavement owners could implement AE for quality assurance of asphalt binders and asphalt mixtures, for periodic pavement condition assessments, and for the scheduling of preventive maintenance and rehabilitation, where pavement cracking is of concern.

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