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NCHRP IDEA Program

Development and Implementation of the Asphalt Embrittlement Analyzer

Final Report for
NCHRP IDEA Project 170

Prepared by:
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DEVELOPMENT AND IMPLEMENTATION OF THE ASPHALT EMBRITTLEMENT ANALYZER

NCHRP-IDEA Project 170

FINAL REPORT

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NCHRP IDEA PROGRA

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EXECUTIVE SUMMARY

NCHRP IDEA Project 170 involved the development of an acoustic emission-based Asphalt Embrittlement Analyzer (AEA) device as an advanced diagnostic tool to assess the degree of aging, crack resistance, and resiliency of near-surface properties in asphalt pavements. A sophisticated computer code was developed to analyze acoustic emission (AE) signals, to identify microcrack presence and location, and to produce a diagnostic schematic illustrating embrittlement temperature versus location (depth from surface of pavement).

The AEA differs significantly from existing standard mechanical tests [BBR, DTT, IDT, DC(T), TSRST], and likewise differs from more recently proposed tests, such as the ABCD fracture test, the BBR test for asphalt mixtures, and the modified DENT binder test. None of the existing or proposed tests has all of the features of the AEA test, namely: simplicity and portability; ability to characterize the continuous and rapid change in surface properties as a function of depth from the surface; suitability for characterization of both binders and mixtures; relative insensitivity to sample size and fracture size effect; relative insensitivity to sample geometry; and suitability for determining the optimum timing and method(s) for preventive maintenance and rehabilitation. In addition, as a design tool, the AEA can be used to assess the effectiveness and proper use of rejuvenators in achieving the goal of restoring the pavement surface to a crack-resistant state.

The AEA can provide highway agencies and pavement evaluation/preservation/materials testing firms with a powerful tool to accurately assess and monitor pavement condition, and strategically select an appropriate maintenance strategy to restore crack resistance in a cost-effective manner. By avoiding damaging forms of pavement surface cracking, such as top-down fatigue, thermal, and block cracking, pavement structure can be retained (asset preservation), costly rehabilitation can be delayed, and user costs can be significantly decreased. In addition, by using this technology to maintain the pavement in a resilient (flexible, healable) and predominantly micro- and macrocrack-free state, the damaging effects of moisture damage and raveling may likewise be delayed or prevented. Furthermore, by applying thin maintenance treatments at the right time, significant sustainability benefits can be realized by avoiding or delaying the employment of thicker, hot-mixed overlay systems. This approach also helps in the design and evaluation of thinner treatment systems, and treatments which often involve the use of cold or warm applied asphalt binder systems and recycled materials, thereby reducing the use of new materials, reducing fuel usage, and lowering the carbon footprint of the pavement.

Finally, collaboration with Troxler Electronics has provided an initial framework for device simplification, cost reduction, and commercialization.

2 INTRODUCTION

Asphalt concrete is a widely used pavement material, covering the surface of approximately 95% of all highway pavements in the United States. The popularity of asphalt as a pavement surface material derives from the fact that it delivers a smooth, quiet surface, and can be rapidly constructed, particularly in the case of rehabilitation (resurfacing) operations. Immediately after construction, asphalt is a remarkably tough and resilient material, because it is comprised of a highly ductile and healable binding matrix (asphalt binder), combined with hard aggregate particles, which provide stiffness and strength to the system. When compared with portland cement concrete, asphalt concrete can possess 5, 10, or even 20 times more fracture energy owing to its ductile binder matrix and toughness-adding aggregate structure. Although traffic loads and thermal cycles tend to cause microdamage in the asphalt binder system under certain conditions, this damage can be healed if the binder has retained sufficient fluidity. Even as the pavement develops minor rutting and distributed microdamage, pavement serviceability and smoothness can remain at a very high level for many years of service.

However, with time, asphalt binder ages, particularly near the surface of the pavement, which causes the binder to lose its ductility and resiliency. Oxidative hardening leads to stiffening and embrittlement of the asphalt binder, which reduces healing capacity, and increases the rate of microcrack propagation. Furthermore, the pavement system is more prone to coalesced macrocrack formation, and may begin to develop various forms of surface cracking. For instance, the brittle pavement surface will be prone to temperature-induced channeling cracks, such as thermal and block cracks, or traffic-induced top-down fatigue cracks. In addition, brittle surface conditions make the pavement more prone to moisture damage and raveling. Major distress forms such as the aforementioned generally lead to an exponential decline in pavement serviceability and an exponential increase in maintenance costs to restore pavement condition. In a recent study conducted by Islam and Buttlar (*1*), a rough pavement network was found to add an additional user cost of over $300 per vehicle per 12,000 miles driven. The encouraging news from the study was that properly timed maintenance treatments, resulting in moderately smooth pavement over its life, yield an approximate 50-to-1 return on investment.

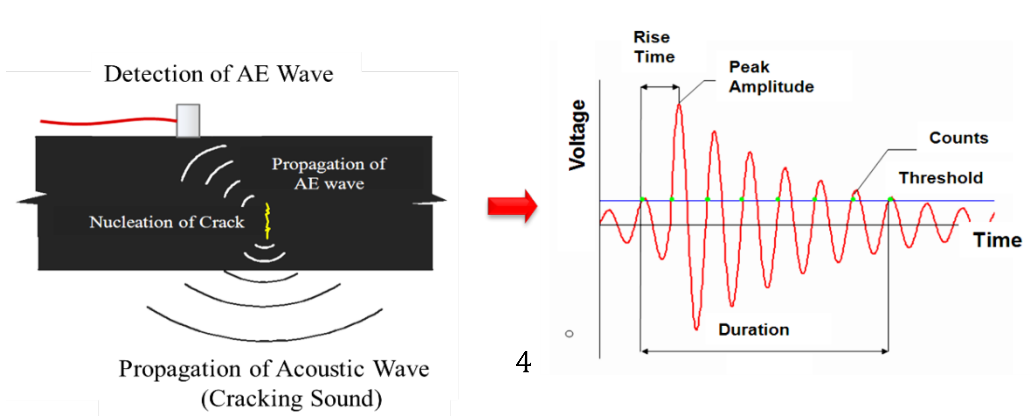
As a result, even for a given location and specified mixture type, changes in all of the above variables could lead to drastically different asphalt concrete surface characteristics from day one and throughout the life of the pavement. Thus, a blanket maintenance policy may either lead to improperly timed or nonoptimal maintenance strategies. This could in turn lead to unnecessary expense (if the pavement surface is rehabilitated before it reaches a dangerously brittle state and/or if an unnecessarily high amount of surface removal is specified) or, if maintenance occurs too late, advanced forms of cracking can develop, leading to much higher user costs and/or very expensive rehabilitation costs. For the practical low-temperature evaluation of binders, binder blends, and mixtures for the purpose of formulation, design, control, and forensics, there is still a need for a test which is: **rapid**; **simple**; **compact and portable**; **applicable to modern materials** (highly modified, recycled, warm-mix); **versatile**, able to test binders *and* mixtures and suitable for lab-produced *and* field materials; **extendable to in situ** pavement **evaluation**; **capable of testing thin** mixture **specimens**, **independent of size effect**; and **designed specifically to aid in the timing and selection of preventive maintenance and rehabilitation treatments.**

In a previous NCHRP IDEA project (144), an acoustic emission-based test method was developed at the University of Illinois as a result of a cross-disciplinary collaboration between the Civil and Environmental and Industrial Engineering departments, which shows great potential in accomplishing these needs. A review of the system developed under that project is provided in Section 1.2. Although the system showed great potential for the characterization of the embrittlement temperature of asphalt binders and mixtures, additional improvements were still needed to make the test more attractive to practitioners and more standardized. The needed improvements included: (1) development of a linear, closed-loop cooling system, and (2) ability to assess graded properties; that is, to obtain a continuous characterization of embrittlement temperature vs. depth when testing field-aged pavement cores.

The current NCHRP IDEA Project 170 involved the development and implementation of an Asphalt Embrittlement Analyzer (AEA) device as a rapid, reliable, and powerful tool to accurately characterize the steeply graded properties of an aged asphalt pavement surface. The overarching goal of this project was to provide a powerful tool for pavement designers and those responsible for preventive maintenance, allowing them to develop custom-design maintenance strategies such as optimizing the relative amount of milling and surface replacement needed to restore a pavement to its original crack-resistant state and assessing the effectiveness of rejuvenators in pavement surface restoration.

2.1 ACOUSTIC EMISSIONS

The Acoustic Emission (AE) technique is a widely used nondestructive testing (NDT) method. An AE event is defined as the sudden release of localized strain energy in the form of transient mechanical elastic waves in a stressed material. These emitted mechanical waves can be detected and recorded using sensitive piezoelectric sensors, i.e., acoustic emission sensors, mounted on a material surface (Figure 1).



(a) (b)

FIGURE 1 (a) Nucleation, propagation, and detection of AE waves; (b) Typical AE signal (*2, 3*).

A typical AE testing setup is schematically illustrated in Figure 2. AE stress waves are detected using piezoelectric sensors, amplified, filtered, and then recorded. The microcracking process, which is the source of AE events in this case, generates short-lived AE signals with rise times in the order of 10^{-6} to 10^{-4}; therefore, sensitive amplifier and filters are used to condition AE signals.

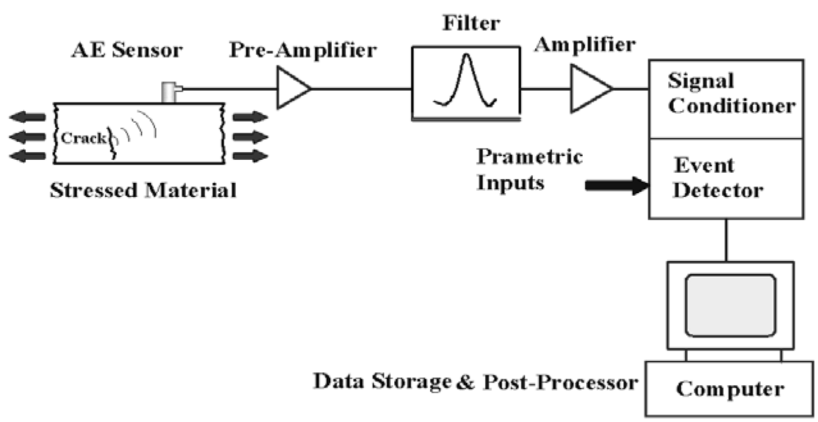


FIGURE 2 Schematic representation of Acoustic Emission testing setup (*2, 3*).

2.2 DEVELOPED ACOUSTIC EMISSION-BASED TESTING METHOD

The AE-based testing method is a simple and practical testing method that was originally developed under the recent NCHRP IDEA Project 144, conducted at the University of Illinois. The developed method can be used to accurately and rapidly evaluate the low temperature cracking behavior of asphalt materials and characterize the cracking temperature, or "Embrittlement Temperature," of asphalt binders and asphalt mixtures (*2*–*5*). In addition, this technique has been successfully implemented to characterize modern warm mix asphalt and mixtures with high amounts of RAP, to help ensure the durability of these environmentally-friendly materials (*6*).

Figure 3 illustrates typical asphalt binder and mixture samples and typical AE testing configurations. A typical AE binder sample, by design, is identical in dimensions to a Superpave bending beam rheometer specimen, consisting of a 6-mm thick rectangular shape layer of asphalt binder bonded to granite substrate. To conduct AE test, asphalt binder samples are cooled down from 20°C to −50°C. Differential thermal contraction between granite substrates and asphalt binders induces progressively higher thermal stresses in the binders resulting in thermal crack formation, which is accompanied by a release of elastic energy in the form of transient waves. Cracking temperature of asphalt binders was predicted by processing and analysis of emitted elastic waves (*4*).

AE asphalt concrete specimens are 50-mm thick semicircular samples which are sliced from field cores or laboratory compacted samples. Similar to asphalt binder samples, asphalt concrete samples are cooled down from room temperature to temperatures well below the glass transition temperature. Progressively higher thermal stresses in the specimen due to differential thermal expansion coefficients between asphalt mastic and aggregates result in the formation of thermal microcracks in the asphalt mastic, which is accompanied by the release of transient elastic waves. This manifests itself as a cluster of high amplitude transient waves during the test.

When conducting AE tests, specimen temperature is continuously recorded through using K-type thermocouple placed on the specimen surface. Wideband AE piezoelectric sensors (Digital Wave, Model B1025) with a nominal frequency range of 50 kHz to 1.5 MHz are utilized in order to monitor and record acoustic activities of the sample during the test. High-vacuum grease is used to couple the AE sensors to the specimen surface. Since by nature the acoustic signals are of low energy, the sensor data is immediately fed into a preamplifier to minimize noise interference and prevent signal loss. Signals from AE sensors are pre-amplified by 20 dB using broad-band pre-amplifiers. Then, the signal is further amplified by 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 are then digitized using a 16-bit analog-to-digital converter (ICS 645B-8) using a sampling frequency of 2 MHz and a length of 2048 points per channel per acquisition trigger. The outputs are stored for later processing using Digital Wave software (WaveExplorerTM V7.2.6) (*2, 4, 5*).

A number of parameters are extracted from the AE test. Analysis of thermally induced AE activity of asphalt mixture specimens is conducted on calculated AE energy, event counts and specimen temperature. The emitted energy associated with each event is calculated by using the following equation shown below, where E_{AE} is AE energy of an event (V^2- μsec) with duration of time t (μsec) and recorded voltage of $V(t)$ (*2, 4, 5*).

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

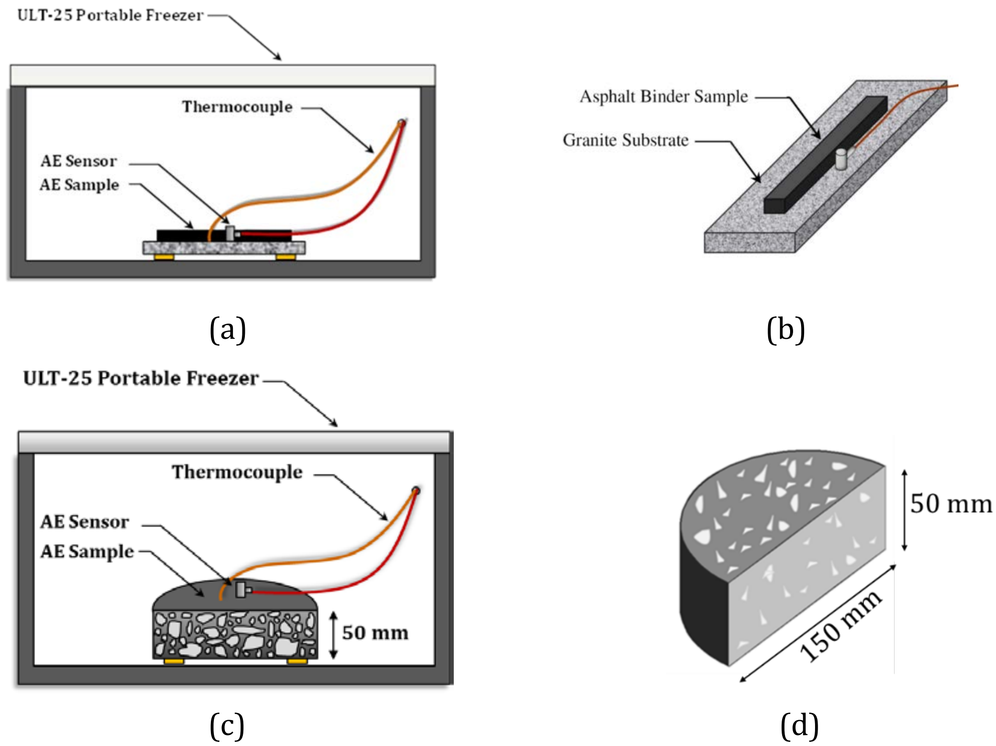


FIGURE 3 (a) AE testing setup for asphalt binders; (b) AE asphalt binder sample (thin film of asphalt binder bonded to granite substrate); (c) AE testing setup for asphalt mixtures; (d) AE asphalt mixture sample.

A typical plot of AE test results for asphalt binder is shown in Figure 4. For both asphalt binders and asphalt mixtures, there are three distinct regions in the plot: (1) pre-cracking; (2) transition; and (3) stable cracking regions. The first region is the "pre-cracking" region, during which the material does not undergo any microdamage, and as a result, does not exhibit any AE activity. This period occurs prior to the onset of material fracture. The second region, the 'transition region,' begins when thermal microcracking reveals itself via relatively high-energy AE events, which occur immediately after the pre-cracking period starts. Progressively higher thermal stresses in the specimen eventually cause thermal microcracks to develop in the asphalt mastic, as well as at the interface between asphalt mastic and aggregates. Microcracks result primarily from a combination of asphalt mastic brittleness (at lower temperatures) and from the action of thermally-induced tensile stresses within the material, perhaps enhanced by the stress concentrations at the interface between the mastic and the aggregates.

It should be noted that, although microcracks occur at low temperatures, the identification of the current embrittlement temperature of the binder or mixture is useful for assessing the current aged state of the material. Highly aged asphalt surfaces may be prone to a number of low and intermediate temperature distress types, as described earlier. Thus, the tool can be used to assess the current low temperature, in situ PG grade of the asphalt binder, which can in turn be used to time preventive maintenance and rehabilitation treatments before damaging distress forms occur. Arguably, virtually every asphalt pavement surface distress besides rutting/shoving, traditional (bottom-up fatigue), and polishing can be managed by monitoring and managing/maintaining a proper low-temperature grade. This in turn leads to the retention of a resilient, micro- and macro crack pavement surface.

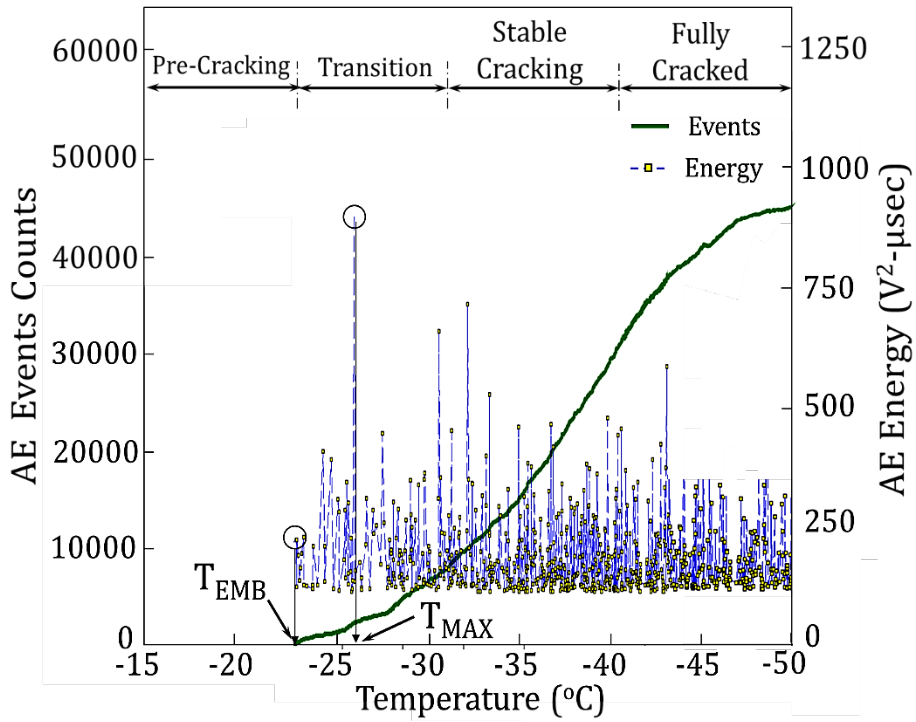


FIGURE 4 Typical AE test result for asphalt binder (*4*).

3 DEVELOPING THE ASPHALT EMBRITTLEMENT ANALYZER (AEA)

The previously developed acoustic emission (AE) based testing method has been proven to be highly effective as a tool to rapidly determine the low temperature cracking threshold (embrittlement temperature) of asphalt binders and mixtures. The test involves the use of an acoustic emission sensor to listen for microcrack development in binder or mixture samples as they are cooled to very low temperatures. This system has a number of important applications, such as providing an alternate tool for the characterization of the low temperature "grade" of an asphalt binder, and for evaluating trial asphalt mixture involving recycled materials, and low energy approaches (such as warm mix asphalt) (*5*–*7*). However, the single sensor system cannot provide a continuous material profile, such as an embrittlement temperature profile versus depth in a field cored sample. Having such a profile would provide a means for accurately assessing in situ pavement surface conditions and developing cost-effective strategies for pavement surface renewal.

The Asphalt Embrittlement Analyzer (AEA) involves the use of a multi-sensor, acoustic emission-based embrittlement temperature detection system to accurately characterize the material embrittlement threshold versus depth from surface using small-diameter field cores. By cooling a field core sample, acoustic emission sensors can listen for and identify the temperature at which the material reaches a brittle state (the state where macrocracks propagate rapidly). By employing multiple sensors, the location of microcracks (which emit the transient stress waves) can be determined using source location technique (similar to GPS triangulation). In this manner, a continuous material profile can be generated for the field core, leading to a color-coded plot of embrittlement temperature versus depth from surface. In the following, first the acoustic emission source location technique will be introduced, followed by the technical details regarding the proposed AEA system.

3.1 ACOUSTIC EMISSION SOURCE LOCATION TECHNIQUE

The use of nondestructive evaluation through the inspection of acoustic emissions has gained popularity and credibility in recent decades. Technology has advanced enough to allow faster acquisition speeds and processing of data, making the events at higher frequencies easier to monitor (*8*). The use of AE monitoring allows the sources of energy release in a structure to be determined. In structures, AE sources are from internal damage or developments such as fatigue crack growth, corrosion, and fretting. The use of ultrasonic sensors allows the energy released by the source to be tracked and monitored as it propagates through the structure (*9*). This allows the tester to determine where a structure has developed any damage and what area internally it is affecting. AE source location has the benefit of allowing the internal mechanism to be determined without having to invasively damage the material by testing to failure, or cutting through it to find where the damage occurred. There are several methods for determining the source location of an AE event, but they are all based off of the same principles. The acoustic sensors placed on the material are used to record the time of the first event they detect; this event is taken to be the arrival of the wave emitted by the AE source. The time at which the event is detected, known as the Time of Arrival (ToA), is used in conjunction with the known wave speed for the material to determine how far away the source of the AE event is from the sensor. The methods then use this distance measurement from several sensors in order to more accurately pinpoint the location of the AE source (*10*).

3.1.1 SOURCE LOCATION METHODS

As the use of acoustic emission detection has become more popular, the desire to find the most accurate and precise method for determining the location of AE events has increased. This has led to the development of several different methods for determining the source location. As noted before, the methods are all very similar in nature, using the time of arrival with the wave speed to determine the source location. The differences come from the equations used to find the locations as well as the required setups for the detection.

3.1.2 Time of Arrival

The ToA is based on the arrival times of the acoustic emission signal at each of the sensors. The arrival times are then used between two of the sensors to create a hyperboloid along which the source resides in relation to the two sensors. This is repeated for each sensor pair, the hyperboloids are superimposed, and the point of intersection is taken as the location of the acoustic emission source. Equation 1 is used to describe the hyperbola created with the arrival times.

$$R = \frac{1}{2}\frac{D^2 - \Delta t^2 {C_{AE}}^2}{2\Delta t C_{AE} - D cos\theta} \qquad (1)$$

Where D is the distance between the two AE sensors, Δt is the difference in arrival times between the two sensors, and C_{AE} is the wavespeed of the medium. Figure 5 shows the geometry used to create the hyperbola described by Equation 1. The source is known to lie along the hyperbola as shown (*11*).

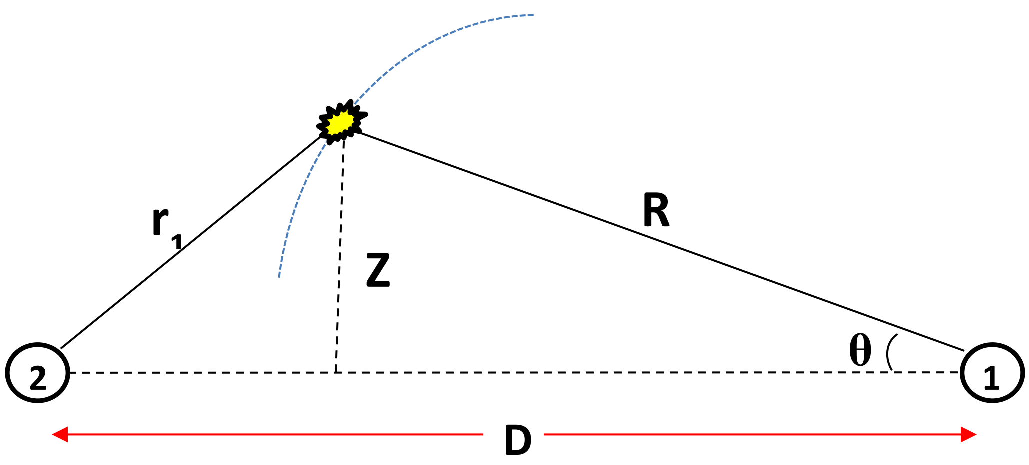


FIGURE 5 Time of arrival hyperbola between two sensors (*11*).

3.1.3 Delta *t* source location

The Delta *t* method of source location uses an array of AE sensors in order to acquire the arrival time of an acoustic event at their location. The difference in arrival times (Δt) between pairs of sensors is used to map contour lines of Δt for each sensor pair. This allows the contour lines to be used to triangulate the source of the AE data received from previous, current, and potential future events. The preferred method to construct this wave map is to use Hsu-Nielson (H-N) sources to generate an AE event. H-N sources are normally generated by using a mechanical pencil, and breaking the lead on the surface of the specimen. The Delta *t* information from these signals can be used to generate the wave map to determine source locations of future internal events. This method makes source location easier as well, since it requires no wavepath or wavespeed assumptions or any complex calculation. The general method for calculating the Delta *t* location uses the following equations:

$$x_1 + x_2 = d \qquad (2)$$

$$x_1 - x_2 = \Delta t * V \qquad (3)$$

Where x_1 is the distance between the AE source and the first sensor, x_2 is the distance between the source and the second sensor, and d is the distance between sensor 1 and sensor 2. Δt is the difference between the time of arrival at the sensors. V is the velocity of the wave. Using these two equations one can determine the distance from the source to either sensor. This allows the distance from both sensors to the location to be used to develop a contour map for the subsequent source location calculation.

Baxter (*11*) presents the Delta *t* source location method in a step-by-step fashion, indicating five main steps to the process:

1. **Determine the area of interest:** The Delta *t* method is not made to cover an entire part or structure as it would take a very large number of sensors and time. The preferred method is to determine an area of interest, usually an area where cracking is expected to occur from past results, or a part of the structure that is prone to failure or damage. The sensors should be arranged around this area in a manner that will make triangulation of the signals easier; that is, an equilateral triangle for three sensors, a square for four, etc.
2. **Construct a grid**: Once the area of interest is determined, a grid is constructed on the test area. The grid should be a relatively high resolution, as the higher the grid resolution the more accurate the source location. The grid should be arranged around the sensors to make reference between the grid and the sensor locations as easy as possible.
3. **Conduct H-N source events to obtain time of arrival data:** H-N source events should be applied at the nodes of the grid to provide AE arrival times at each sensor. Several events at each node should be captured in order to provide an average result and reduce error in the test. Baxter recommends at least five events per node. It is not necessary to do tests at every single node, just enough to construct a contour map.
4. **Calculate the Delta *t* map**: Using the H-N source event data recorded from before, the Delta *t*, difference in arrival times, will be calculated for each sensor pair. An average of times is calculated for each node and used to develop a map for each sensor pair. The map will show the contour lines of equal Delta *t* for each sensor pair.

5. **Compare actual data**: Actual source location testing can then be performed on data with an actual AE event. The specimen is instrumented with the sensors kept in the same arrangement. Now, the AE event received by the sensors can be used to find a Delta *t* for the sensor pairs. The map developed in step 4 for each sensor pair is then overlaid with the AE event results in order to find a convergence point, which represents the source location. The more sensors, the higher the confidence in the convergence point. Thus it is recommended to use at least three sensors for a plate specimen, or in the case of asphalt a cylindrical specimen, more sensors would likely be used. After providing these steps, Baxter goes through an example test set up for the Delta *t* source location. A composite air craft component, with thickness changes and a hole was used. A grid was constructed on its surface with four AE sensors placed on the four outer corners of the grid, as shown in Figure 6.

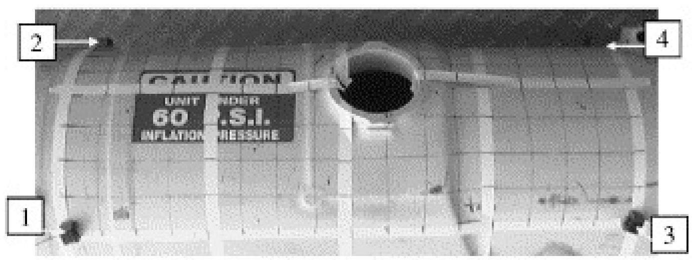


FIGURE 6 Delta *T* grid on aircraft component, from Baxter (*11*).

Several H-N source events were then applied at the nodes of this grid and recorded using the attached sensors. The test area was 400 mm x 800 mm, with a grid density of 50 mm used to create a total of 153 nodes. The contour maps were then generated from the H-N data. To test the accuracy of the maps, several H-N sources were applied within the grid to act as the AE events for this test. The maps were then used to determine the location of these events. The results were compared to testing doing the time of arrival method. The average error using the Delta *t* method was found to be about 1.7% as opposed to the TOA method which had an error of 4.8%. This shows that the Delta *t* method, while simpler mathematically, can be more accurate with a high enough resolution of a grid and enough events to make an accurate contour map (*4*).

3.1.4 BEST-MATCHED POINT SEARCH METHOD

The best-matched point search method of source location uses two stages in the process of finding the AE event's starting point: (1) point generation and (2) point matching. The point generation stage creates an array of points with vectors, r, that define the special location within the geometry of the specimen. The time it takes for an elastic wave to propagate from *r* to a sensor, *i*, is represented by:

$$t_i(r) = \frac{|r - s_i|}{v_{gr}(e)} \tag{4}$$

Where *r* is the location vector in space, t_i is the theoretical time it takes for the wave propagation, s_i is the location of sensor *i* in space, v_{gr} is the group velocity of the wave, and *e* is the unit vector that defines the direction of propagation between *r* and *si* as shown:

$$e = \frac{(r - s_i)}{|r - s_i|} \tag{5}$$

Like the previous methods the Delta *t* time is calculated between two sensors. This is done for the entire array of sensors, taking each pair to find the Delta *t* value between them. The point matching stage is then applied. Here the Delta *t* array is filtered to find the Delta *t* values that match the experimental values as closely as possible. The source's location is given by:

$$r = argminr[\sum i, j \left(\Delta t_{ij}^{exp} - \Delta t_{ij}(r)\right)^z] \tag{6}$$

Where Δt_{ij}^{exp} are the Delta *t* values recorded from experimental measurements. The summation is applied to every combination of the sensors. Once this is done for each unique pairing, the source location is determined by comparing the Delta *t* values for each sensor in the pair, and using the time difference to determine where the source location is in relation to each sensor based off of the known wave velocity. The number of combinations required is given by *N*, where *S* is the number of sensors:

$$N = \frac{(s^2 - S)}{2} \tag{7}$$

3.2 DEVELOPMENT OF ASPHALT EMBRITTLEMENT ANALYZER (AEA)

The asphalt embrittlement analyzer involves using an acoustic emission approach to detect the occurrence of microcracks in asphalt concrete core samples extracted from the field when exposed to thermal loading; that is, when cooled from room temperature to well below the glass transition temperature of the binder, for instance, down to -50^{o}C. A computational engine and graphical user interface for the asphalt embrittlement analyzer was developed. This software computes the location of thermally induced microcracks and displays the source locations as colored dots in a 3D model of the asphalt concrete test sample. The dots representing the source locations are color-coded to display the corresponding temperature at which the acoustic emission events (induced by the thermal cracks) occurred.

The AEA software continuously monitors the occurring cracks and the corresponding crack locations in the asphalt during the cooling process. The user needs only to input all the parameters of the testing sample geometry and transduced location. The software computes and displays the calculated locations of cracks in a three-dimensional (3D) model representing the sample. Furthermore, the software, using a color-coded scheme, also provides information of the temperature at which the cracks occur.

The AEA system provides the user with the following functions:

- A reliable and user-friendly computer software with an interactive graphical user interface (GUI).
- 3D color-coded plot of embrittlement temperature throughout the sample to visualize thermally induced microcracks within the specimen.
- Fast computing algorithm to calculate the positions of the developed cracks; that is, source location.
- Color coding of the cracks; that is, dots, with the corresponding temperatures at which the cracks occur.
- Simulating the asphalt sample with color-coded cracks in a 3D model.

3.2.1 BLOCK DIAGRAM OF THE COMPUTATIONAL ENGINE AND GUI:

Figure 7 shows the block diagram representation of the computational engine and the GUI. Below is a description of each block module.

3.2.1.1 *ACOUSTIC WAVEFORM ANALYZER MODULE*

The acoustic waveform analyzer filters the raw wave data imported from the analog-digital converter. This module analyzes the filtered wave data, calculates the position of cracks, and outputs the results to the 3D model module. Figure 8 is the flowchart design for this module.

Before analyzing the acoustic emission wave data, it is necessary to filter acoustic emission data to discard data not related to the cracks of the asphalt. The analyzer will take the input wave data from analog-digital (A/D) converter and filter noise and reflections at the specimen boundaries from AE waves from the data generated from the sensors.

There are three different types of filter algorithms used by the acoustic analyzer. The first filter is an amplitude filter, which can filter out data noise. This filter algorithm sets a threshold amplitude and eliminates the wave data below the threshold; for example, 0.1V. Figure 9 shows a schematic diagram of a typical acoustic emission waveform. This value is determined by the most common noise filter threshold for the acoustic emission. The second filter, known as Swansong filter (*10*), uses the ratio of the signal duration/amplitude to eliminate reflections of

AE waves at the specimen boundaries. Here, the limit of duration over amplitude is set to 500 us/v, which is determined by statistical analysis of reflection wave data. A third filter, similar to the second filter, is based on the rising time and the amplitude of wave. Here, the threshold of the ratio of the rise time over amplitude is set to 100 us/v. Figure 10 shows the threshold, duration and the rise time of a sample acoustic emission wave data.

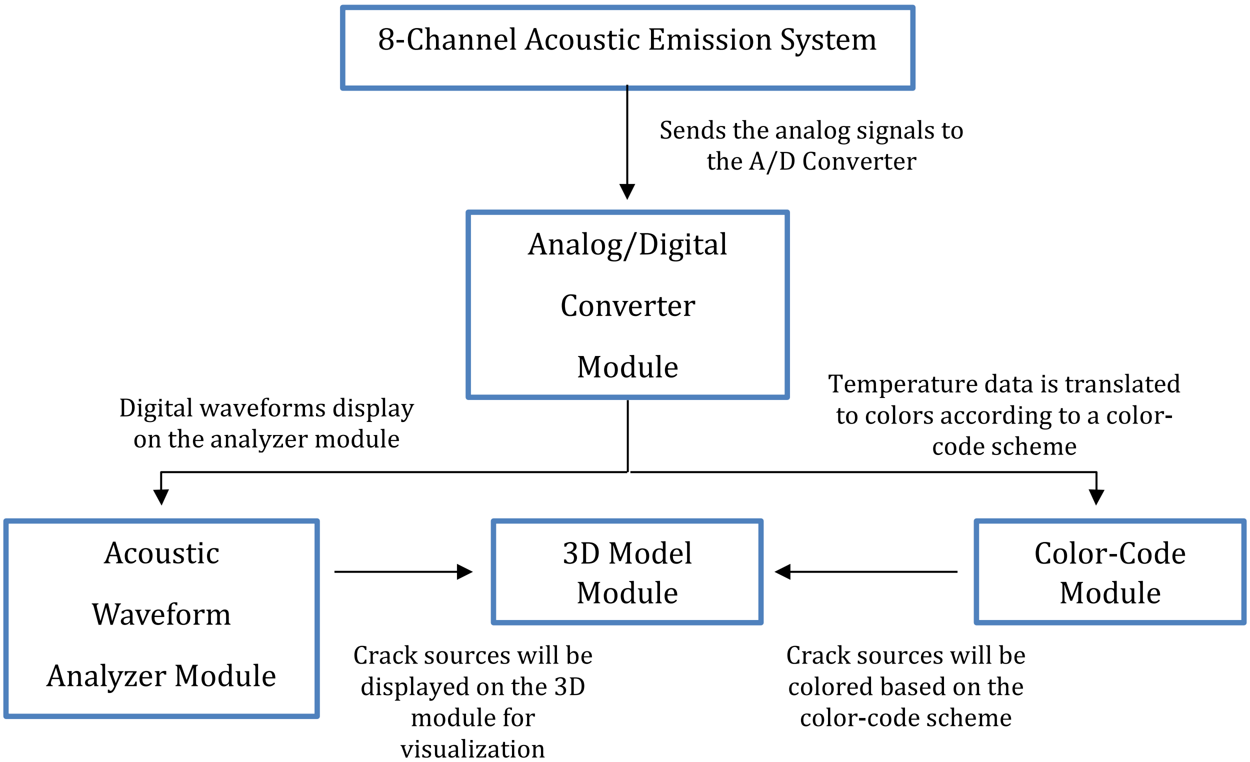


FIGURE 7 Block diagram of computational engine and graphical user interface for asphalt embrittlement analyzer.

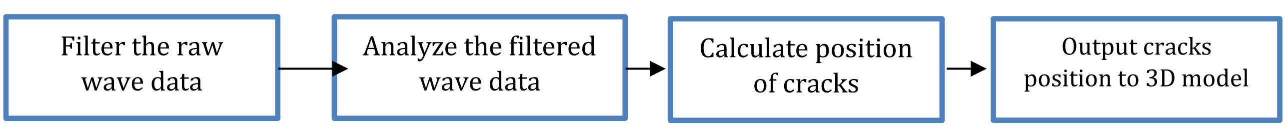


FIGURE 8 Acoustic waveform analyzer flow chart.

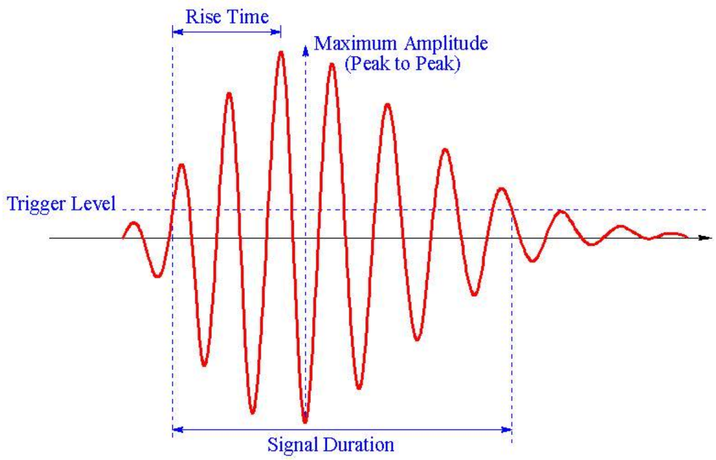


FIGURE 9 Schematic diagram showing a typical acoustic emission waveform (*4*).Using the filtered data, the analyzer collects the times when sensors receive the AE wave generated by the crack formation; that is, the times of arrival at each sensor. If there are more than four sensors detecting the generated AE wave, the analyzer compares the maximum amplitude of waves generated by each sensor and selects the four that have the highest maximum amplitudes. If there are fewer than four sensors detecting the AE wave, the analyzer ignores this event.

To calculate the position of crack (x, y, z) and the time t_0 at which cracking occurs, the analyzer uses positions of the four chosen sensors (x_1, y_1, z_1; x_2, y_2, z_2; x_3, y_3, z_3; x_4, y_4, z_4) and the corresponding detecting time (t_1, t_2, t_3, t_4) to obtain the values of x, y, z, t_0 by solving a system of equations (8), (9), (10), and (11) shown below. In this system of equations, v is the dilatational velocity of wave propagation in asphalt concrete, which is assumed to be 3,500m/s. Other velocities can be prescribed.

$$\sqrt[2]{(x-x_1)^2+(y-y_1)^2+(z-z_1)^2} = v \times (t_1 - t_0) \qquad (8)$$

$$\sqrt[2]{(x-x_2)^2+(y-y_2)^2+(z-z_2)^2} = v \times (t_2 - t_0) \qquad (9)$$

$$\sqrt[2]{(x-x_3)^2+(y-y_3)^2+(z-z_3)^2} = v \times (t_3 - t_0) \qquad (10)$$

$$\sqrt[2]{(x-x_4)^2+(y-y_4)^2+(z-z_4)^2} = v \times (t_4 - t_0) \qquad (11)$$

The four unknown variables can be solved by a system of four quadratic equations. There may be multiple solutions or no real solution. If there is no real solution, the analyzer ignores this event. If there are multiple solutions, the analyzer module checks whether the calculated source location is consistent with the calculated time at which the AE event occurred. The source location should be within the asphalt sample and the time at which the event occurred; that is, t_0 should be smaller than the receiving times; that is, the times of arrival t_1, t_2, t_3, and t_4. If there is still more than one solution, the solution associated with the larger value of t_0 is selected. All the valid positions of cracks are outputted to the 3D model builder module.

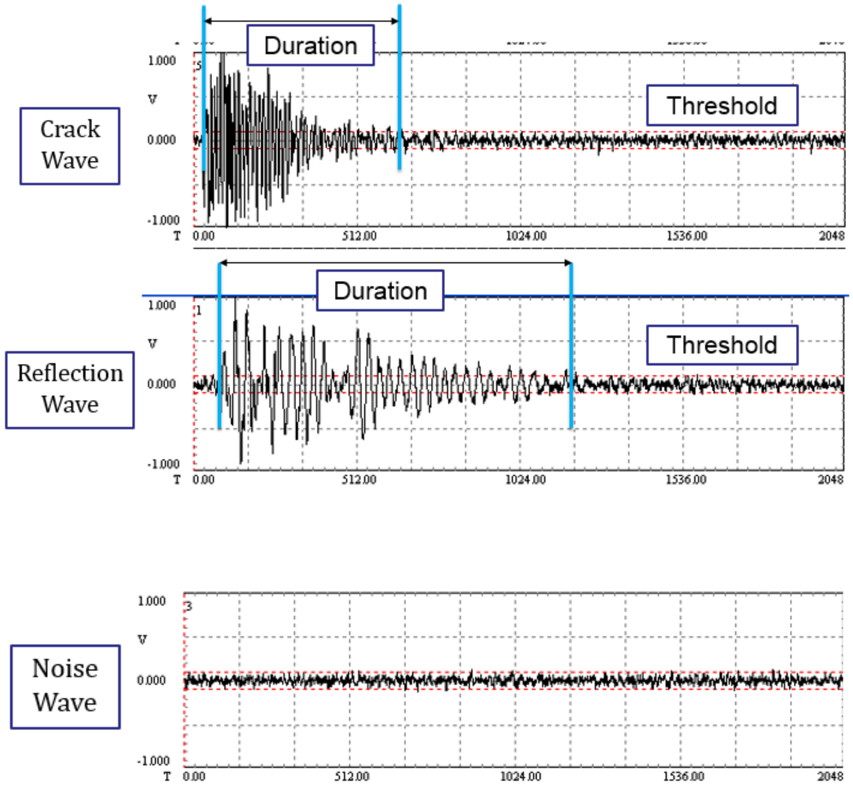


FIGURE 10 Comparison between acoustic emission events due to crack development, wave reflection at the specimen boundaries, and noise.

3.2.1.2 *Three-Dimensional Model Builder Module*

The three-dimensional model module simulates a 3D model of the asphalt sample based on its dimension and material properties. The locations of the cracks are also displayed using this model. The cracks are represented as colored dots based upon the temperature at which they occur with information provided by the color-code module.

The three-dimensional model module gives the user a visual representation of position of the cracks within the asphalt test sample. The locations of the cracks are displayed on this model. The cracks are labeled using colored dots based on the color-code module, and a selected color bar code. The module can help visualize test samples with both cylindrical and rectangular geometry.

The GUI with an example of the 3D model is shown in Figure 11, and it can address samples with both cylindrical and rectangular geometry. The GUI includes input boxes for sensor positions, sample size, raw wave data, temperature data and event vs. time data. A 3D asphalt model with many cracks detected is shown at the right side of the GUI in this example. This figure was selected to show the effect of not neglecting invalid solutions that provide source locations outside the volume of the test specimen. The '+'s signs on the surface of the cylinder show the position of sensors. The points with different colors, depending on the temperature of sample when the crack occurs, are the position of cracks. The 3D model can be rotated so that the user is able to check the position of cracks more conveniently.

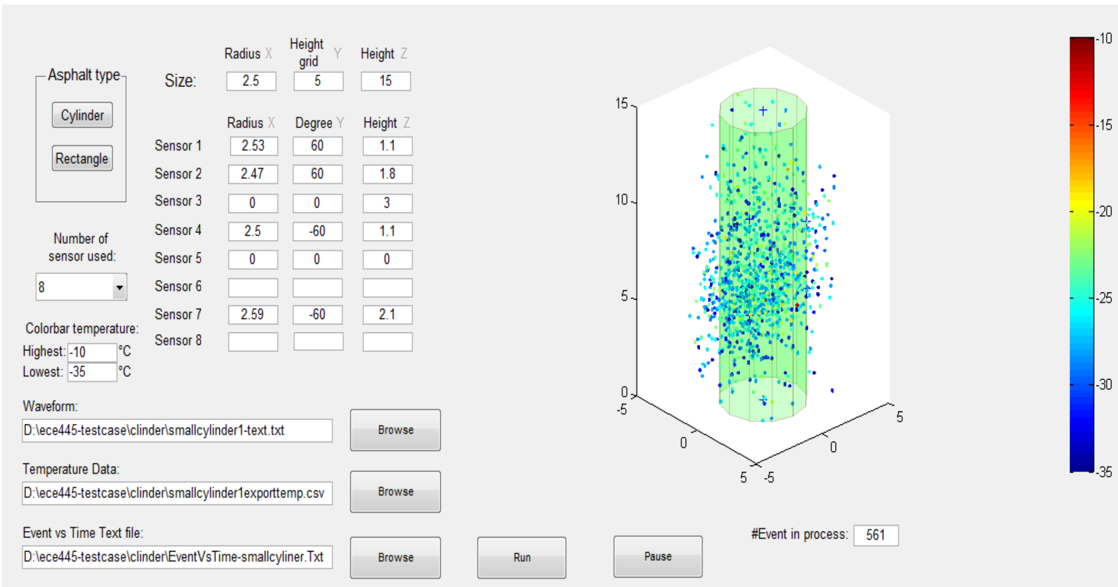


FIGURE 11 GUI showing a cylindrical AC specimen. Figure illustrates the need of using filters to assure that source location solutions are within the volume of the test specimen. In this case filtering was not performed, and the points outside the specimen are due to wave reflections at the specimen boundaries.

3.2.1.3 *Color-Code Module*

The color-code module read the temperature data corresponding to the cooling time from the thermocouple, and provides the cracking position in the 3D model using color-coded labels; that is, colored dots. Cracks occurring at different temperatures have corresponding different colors displayed. The chosen colors for the cracks are selected from a prescribed color bar, which is also displayed in the model. The color-code module helps user to visualize the temperature at which the cracks occur. This module reads the temperature of the asphalt sample and provides the source location in the 3D model with a color-coded label. Events, that is, cracks, happening at different temperatures are displayed using different colors. Events occurring at the warmest temperature are marked as dark-red dots. Events occurring at the lowest temperature are marked as dark-blue dots. The events occurring between the warmest and lowest temperatures are displayed with a corresponding color on a color-coded scale.

3.2.2 VALIDATION OF SOURCE LOCATION

Requirements for the filtering algorithms for the acoustic waveform analyzer were verified by comparing the unfiltered test result and filtered test result (Figure 12).

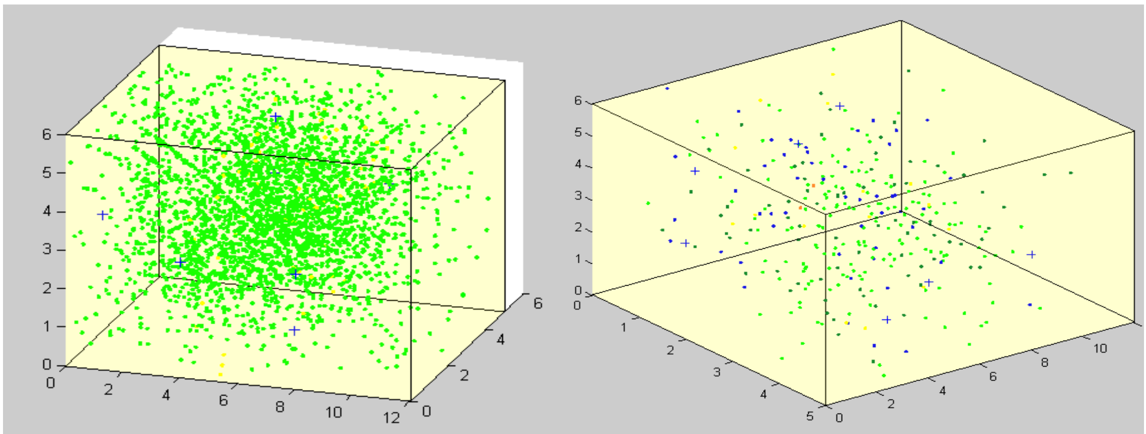


FIGURE 12 Comparison between unfiltered and filtered test results.

Because of AE wave reflections at the specimen boundaries, more events are estimated as compared to reality. To assess the error in source location, pencil lead breaks tests were performed at the surface of a rectangular asphalt sample to simulate the cracks at that location. Among five simulation tests, four calculated positions had less than 1 cm deviation from the actual crack position. The average deviation of the five calculated positions was 0.934 cm (< 0.4 in.). This deviation is mainly caused by the stochastic nature (i.e., size and distribution of aggregates) of the asphalt concrete. Although additional resolution in the future may be possible via custom-designed sensors and improved analysis techniques, for the purposes of pavement assessment and rehabilitation, the accuracy obtained under the current equipment and methods was deemed as acceptable.

TABLE 1
CALCULATED SOURCE LOCATION VERSUS ACTUAL SOURCE LOCATION

Test No.	Actual Location (X,Y,Z) in (cm)	Calculated Location/cm (X,Y,Z) in (cm)	Deviation from Location (cm)
1	(10,2,6)	(10.08,1.72,5.81)	0.08
2	(10,0,3)	(9.68,0.10,3.00)	0.31
3	(2,0,4)	(-0.33,-1.80,7.02)	2.76
4	(6,1,6)	(5.68,0.13,7.57)	0.93
5	(8,4,6)	(8.00,4.00,7.00)	0.59

3.3 LINEAR CLOSED-LOOP COOLING

The industry partner to this IDEA project, Troxler Electronics, Inc., was tasked with the upgrade of the Stirling-based cooling system. As reported in the previous NCHRP IDEA project (144), a very efficient and quiet (electrically and mechanically) cooling unit was identified for use with the AEA test. A Stirling engine-based cooling system, available from Global Cooling, has been successfully used to cool binder and mixture specimens for the purpose of embrittlement temperature determination. However, for test standardization purposes, it was decided to pursue linear cooling of specimens as a means to ensure more standard thermal loading from lab to lab, and specimen to specimen. In discussion with Global Cooling, the modification of the Stirling engine-based cooling system to permit closed-loop, linear cooling based on an external temperature probe was not a (theoretically) difficult task. However, Global Cooling was not interested in providing the engineering/modification for the purposes of feasibility testing. Troxler engineers were called upon to assist with this task, instead, and achieved closed-loop cooling with the modifications shown in Figure 13.

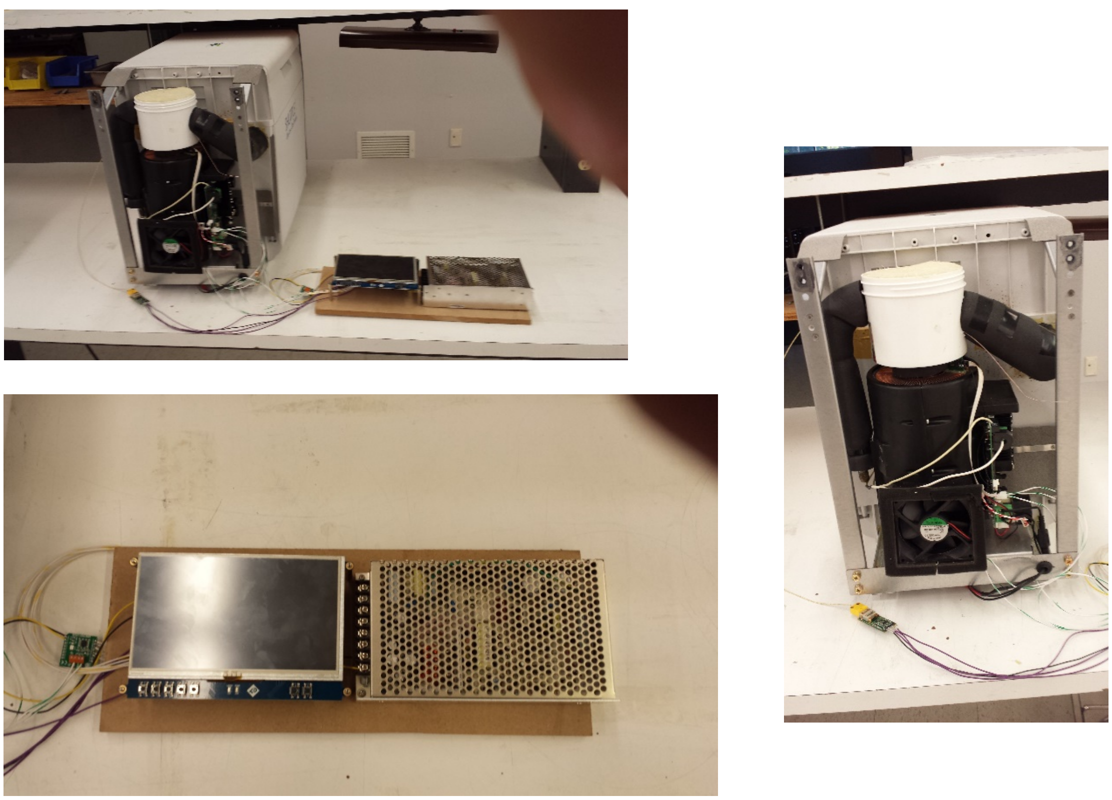


FIGURE 13 Closed-loop cooling system.

Modifications involved the addition of an external temperature probe, unwiring the Stirling engine from the standard, front-panel fixed temperature control of a standard Global cooling unit, and wiring the engine to a newly-provided, ultra-portable Beagle Bone PC and interface board. Once wiring and programming of the Beagle Bone computer was complete, precise linear, closed-loop temperature control was easily achieved.

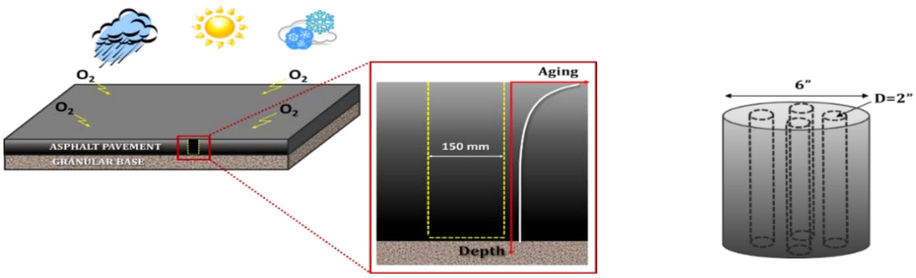
3.4 AEA Applications

The Asphalt Embrittlement Analyzer (AEA) can be used to accurately assess the steeply graded properties of an aged asphalt pavement surface, and to intelligently select the best maintenance strategy for that pavement. Highway agencies have recognized the importance of pavement preservation, and the determination of effective preservation strategies has gained considerable attention over the past two decades. However, it is difficult to know when to apply preventive surface maintenance to an asphalt pavement and what type of pre-treatment and treatment to apply due to:

1. Different asphalt sources and asphalt modifiers have widely varying aging rates.
2. Aging rate will depend upon mixture variables, such as binder volume, voids in the mineral aggregate, aggregate type and the amount and interconnectivity of air voids.
3. Initial binder properties will depend upon the amount of rounding of the Superpave binder grade (up to nearly 6 degrees Celsius of rounding can occur), and will also depend upon construction factors such as mix production temperature, mixing plant characteristics and operating circumstances (some plants, when run at lower production rates, lead to increased binder aging), silo storage time, etc.
4. Depending upon the above variables, the depth to which the asphalt surface has become brittle at a given point in time would be nearly impossible to predict.
5. Due to the exponential grading of binder properties from the surface down, it is difficult to apply existing binder and mixture tests to accurately assess this property gradient. For instance, binder tests require costly extraction and recovery techniques, which also alter the properties of the binder relative to its in situ state. Mixture tests require specimen dimensions that prohibit the ability to capture the steep property gradient present near the aged asphalt surface. For instance, the fracture process zone ahead of a crack tip generally encompasses around 40 mm, whereas the most severe aging on an asphalt pavement may occur in the top few millimeters of the surface.
6. For pavements with very shallow embrittlement depths, rejuvenators may provide a very economical approach to surface renewal. However, to date, a simple evaluation tool to assess the compatibility and effectiveness of rejuvenators has not been developed.

The developed AEA system addresses the current need for an efficient and reliable evaluation tool for preventive surface maintenance of pavements. Figure 13(a) schematically shows an aged asphalt pavement that has been exposed to the environment (snow, rain, hot and cold weather) and undergone significant oxidative aging. The aging profile of the pavement versus depth is depicted, showing highly aged materials at the surface and less aged materials towards the bottom of the pavement. A 150-mm (6-in.) diameter field core is taken and up to four 50-mm (2-in.) diameter cylindrical samples are prepared to be used for AEA, Figure 13(b).

During conducting AEA, as the temperature decreases, the thermally induced microcracks will first occur where more highly aged material is located; That is, at the surface of the pavement core, followed by thermal microcracks in less aged material; that is, towards the pavement bottom. As the temperature continues to decrease, the less aged asphalt concrete located at lower pavement depth will start to become AE-active.



(a (b)

FIGURE 13 (a) Aging profile of asphalt concrete material through pavement thickness, (b) AEA specimens with 2-in. diameter obtained from 6-in. diameter field core (*13*).

Figure 14 shows the AEA test result for functionally graded aged asphalt concrete samples along with a plot of embrittlement temperature versus the corresponding depths in the pavement. In case the maintenance strategy involves milling the pavement surface, using AEA results, one can accurately find the optimum milling depth. For the aged pavement the optimum milling depth is where the embrittlement temperature at that depth matches the low temperature expected in the pavement location. A thin surface treatment could then be added to restore pavement structure and desired surface characteristics. A more cost-effective solution would be to determine the optimum amount of milling and surface replacement that would create a crack-resistant surface. Depending upon a number of variables, milling may be found to be unnecessary, and a thin maintenance resurfacing could serve to achieve a crack-resistant pavement section, by placing the brittle surface at a depth where pavement temperatures would not plunge below the embrittlement temperature of the material.

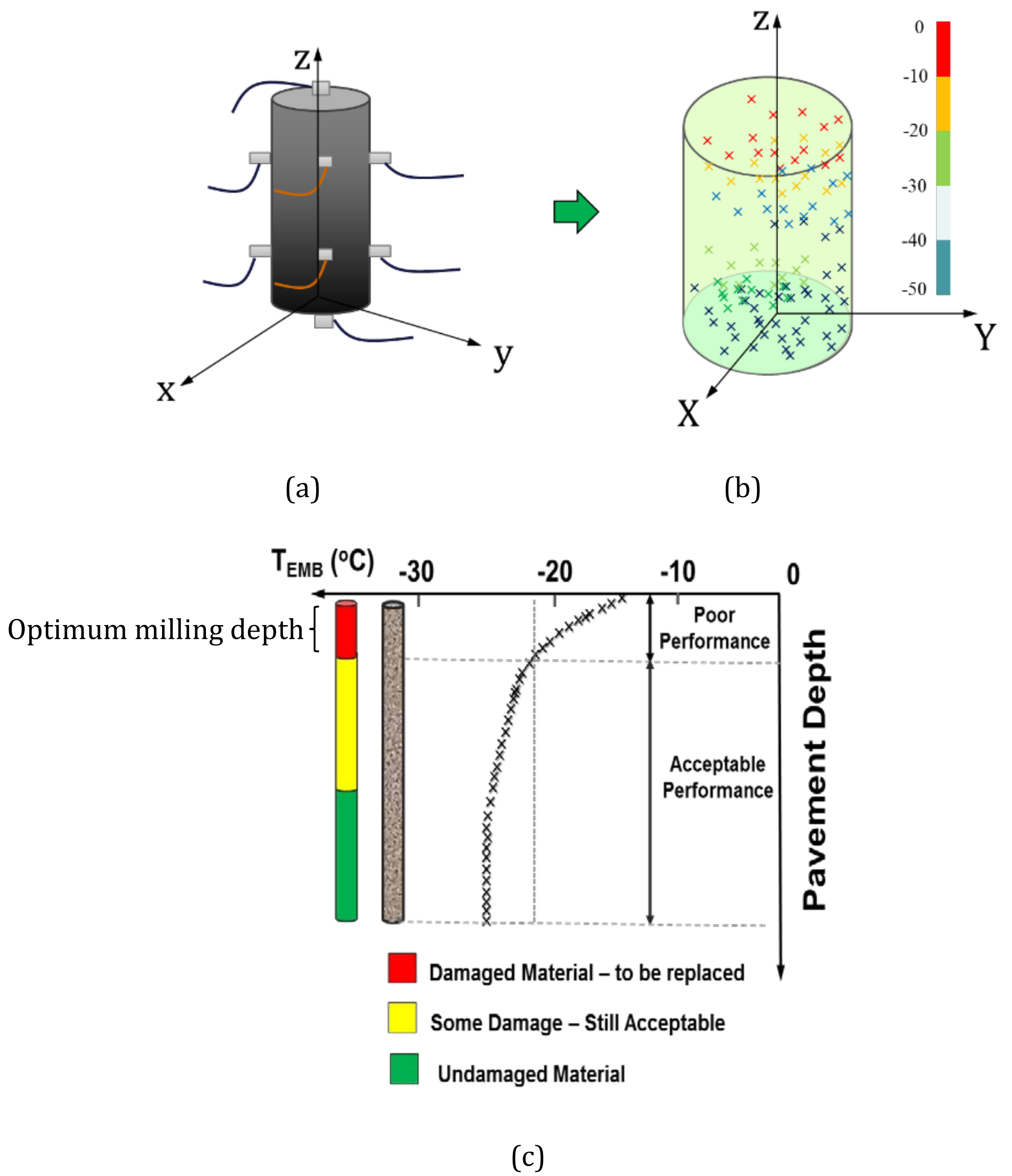
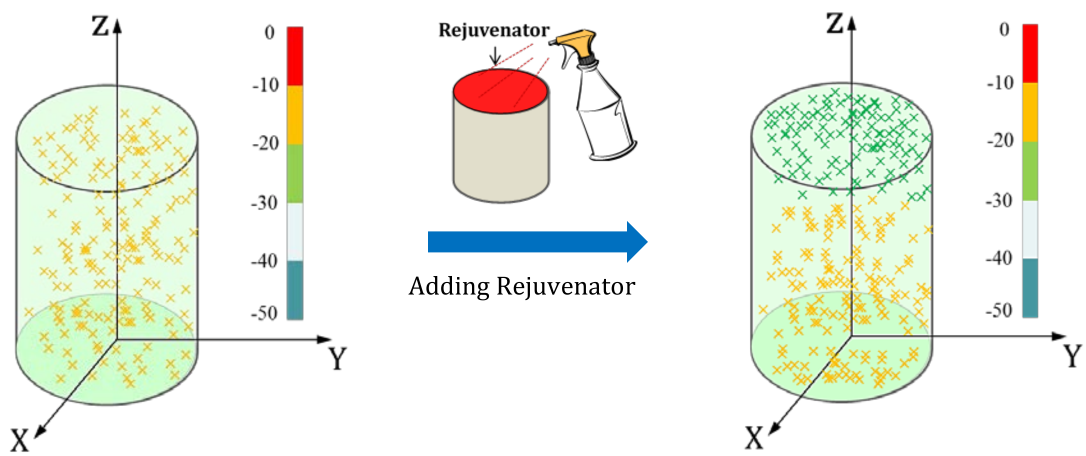


FIGURE 14 (a) AEA sample with 8 AE piezoelectric sensors; (b) typical AEA result: 3D model of embrittlement temperature distribution in the sample; (c) determining the optimum milling depth using embrittlement temperature vs. pavement depth plot.

The AEA could also be used to assess the effectiveness of rejuvenators in softening and restoring crack-resistance to a pavement surface. Currently, there has not been an evaluation approach available to accurately and rapidly assess the depth to which rejuvenators are able to penetrate, and their actual effectiveness in restoring crack resistance to a pavement surface. In this manner, the AEA can be used for at least two stages: (1) as an evaluation tool, to determine the extent of in situ pavement embrittlement, or embrittlement depth, and (2) as a design tool, to assess the effectiveness and proper use of any proposed rejuvenators in achieving the goal of restoring the pavement surface to a crack resistant state. Figure 15 schematically illustrates the AEA test results for an aged asphalt concrete sample before and after applying rejuvenator. The AEA clearly shows the effectiveness of rejuvenator by the change in 3D color-coded embrittlement temperature model of asphalt materials near the sample surface where rejuvenator was applied.



(a) (b)

FIGURE 15 Color-coded 3D models embrittlement temperature of an aged asphalt concrete sample (a) before adding rejuvenator and (b) after spraying rejuvenator to the surface.

The project team believes that, early in the pavement life, the binder possesses the ability to relax stress and to heal microdamage. As the binder ages, this resiliency is lost, and residual stresses and microdamage will begin to accumulate. This in turn can lead to a number of vulnerabilities and distresses, including all forms of pavement cracking (thermal, block, reflective, and top-down), moisture damage, and raveling. This may seem to link a number of key distresses to pavement surface aging and embrittlement, but consider how new asphalt surfaces (i.e., when the ‘current’ binder grade still matches or exceeds the design binder grade) do an excellent job of resisting all of these forms of distress. And conversely, when the pavement surface becomes aged and brittle, and therefore becomes deficient as compared to its design binder grade (i.e., the current low temperature PG grade, or embrittlement temperature, becomes higher than the designed grade), these distresses begin to rapidly develop. This happens in all US climates, though the relative types and amounts of surface distresses vary from region-to-region. Thus, the ability to assess the depth of penetration to which the low temperature binder grade has been lost, and moreover, the ability to remove, restore, or replace (i.e., place a thickness of material above), or some combination of these preservation/rehabilitation approaches, represents a power method to prevent highly coalesced cracks and the associated advanced distress types from happening in the first place. This is predicated on the observation and belief that asphalt pavement surfaces that begin to lose their ability to shed stress and microcracks are vulnerable for the development of more advanced distress types, which become permanent and represent expensive deficiencies in the pavement.

In summary, the AEA can provide highway agencies and pavement evaluation/preservation/materials-testing firms with a powerful tool to accurately assess and monitor pavement condition, and strategically select an appropriate maintenance strategy to restore crack resistance in a cost-effective manner. By avoiding damaging forms of pavement surface cracking, such as top-down fatigue, thermal, and block cracking, pavement structure can be retained (asset preservation), costly rehabilitation can be delayed (saving agency and therefore tax payer dollars in the long run), and user costs can be significantly decreased (recall the estimated 50-to-1 return on investment). In addition, by using this technology to maintain the pavement in a resilient (flexible, healable) and predominantly micro- and macrocrack-free state, the damaging effects of moisture damage and raveling may likewise be delayed or prevented.

Furthermore, by applying thin maintenance treatments at the right time, significant sustainability benefits can be realized by avoiding or delaying the employment of thicker, hot-mixed overlay systems; and allowing the use of thinner treatment systems, and treatments which often involve the use of cold or warm applied asphalt binder systems, thereby reducing the use of new materials, reducing fuel usage, and lowering the carbon footprint of the pavement.

4 TECHNOLOGY TRANSFER AND COMMERCIALIZATION PLAN

Building on the successful outcomes of this research project, the outlook for widespread implementation and commercialization of the developed equipment and test procedures is very promising. Scientific vetting of the technique has gone extremely well, with a nearly perfect acceptance rate of journal and conference paper submissions, as indicted in the reference list. The co-PI, professor Henrique Reis, was also recently invited to provide a keynote address for the 8th International Conference on Cracking and Debonding in Pavements, June 7–9, 2016, where he will describe the cutting edge in advanced measurement systems to support the mitigation of cracking in asphalt materials. This notwithstanding, the road to commercialization of testing equipment in the asphalt industry is not an easy one and should be approached strategically. Experience has shown that it takes more than an “if you build it, they will come” approach. Rather, a strategic implementation plan for a new asphalt test and specification requires sufficient scientific vetting via peer-reviewed publication and presentations, vetting by the Federal Highway Administration (FHWA) mixtures expert task group, development and acceptance of testing standards, and the development of an affordable, simple, market-ready testing and analysis system.

The steps of scientific vetting and development of an affordable, simple test system have been advanced considerably as a result of this research. The development of a graded approach for assessing embrittlement temperature versus depth in field-cored specimens was a time-consuming yet necessary step in the evolution of this new technique. Otherwise, the technique would be very approximate and unable to pinpoint the depth to which a pavement has become prone to brittle behavior and cracking. This would have limited the accuracy of preventive maintenance or rehabilitation strategies deriving from the test result. The remaining future plan for technology transfer and commercialization of the AEA will involve the following steps:

- Field validation of new, graded approach
- Vetting through FHWA mixtures ETG and Development of AASHTO standard
- Finalization of commercial test apparatus.

4.1 Field Validation of Graded Approach

A number of factors will affect the gradient of aging and therefore embrittlement temperature as a function of depth from the pavement surface in practice. This includes in-place morphology of the mix (amount, size and interconnectivity of air voids), binder chemistry, as-constructed mixture properties, age of the surface layer of asphalt concrete, geographical location, existence of surface treatments (and the type and age of the treatment), and climate. To demonstrate the efficacy of the proposed test to properly assess pavement embrittlement temperature versus depth, field validation across a broad range of these factors will be necessary. In addition to testing using the graded AE approach, thin slices of additional field cores should be tested in the AE device to obtain a discrete estimation of embrittlement temperature versus depth from the surface, followed by extraction, recovery, and binder testing of the recovered binder to allow correlation of embrittlement temperature to recovered low temperature binder properties. Testing of field cores in varied climatic regions across the United States is recommended. It may be possible to coordinate a multi-state validation project through either a traditional FHWA pooled fund study, or through the AASHTO Innovation Initiative (AII).

4.2 Vetting through FHWA Mixtures ETG and AASHTO Standard

The FHWA convenes expert task groups (ETGs) in the areas of asphalt binder and asphalt mixtures, typically on a bi-annual basis. This group consists of experts from industry, agencies, and academia, who meet to discuss and vet new tests and specifications for asphalt binders and mixtures, including proposed testing standards to AASHTO. Although regionally popular tests and specifications do sometimes become implemented in the United States, one of the roles of the FHWA and AASHTO is to standardize best practices across the United States in an effort to reap economies of scale and consistencies in research, practice, and industry, but also to promote enhanced safety and durability through sharing of field data emanating from projects constructed using similar design practices and standards. Therefore, it is recommended to vet this new technology through the FHWA Mixtures ETG in order to enable more widespread adoption of the technique, which would provide motivation to industry to invest in final commercialization, marketing, and support of the new test equipment. Principal Investigator William Buttlar will be presenting recent research results obtained on recycled materials at the Spring 2015 FHWA Mixtures ETG, which will serve as a starting point in this process.

4.3 Finalization of Commercial Test Apparatus

Following this research project and based on input received from discussions at the Mixture ETG, finalization of a commercial AE embrittlement tester will be possible. The project team anticipates receiving input on developing initial bias and precision statements, data reporting standards, and perhaps sample pre-conditioning standards. As a jump start to product commercialization, the project team will then pursue research support to enable a round-robin type test demonstration. A possible research mechanism would be through an FHWA Pooled Fund Study, which would involve pooling of funds by US states interested in using the new test device and specification. This stage would also provide a good means for assessing the practicality, repeatability, and robustness of the test equipment, which could then be used to fine-tune the apparatus for the next stage of marketing and more wide-spread implementation. The technique will also be evaluated by the RILEM Technical Committee MCD (mechanisms of cracking and damage in asphalt and composite pavements), which is chaired by Professor Bill Buttlar. This will provide an international perspective on the veracity of the proposed test and specification, and will also open the door for international marketing of the commercial device.

5 CONCLUSIONS

NCHRP IDEA Project 170 involved the development of an acoustic emission-based Asphalt Embrittlement Analyzer (AEA) device as an advanced diagnostic device to assess the degree of aging, crack resistance, and resiliency of near-surface properties in asphalt pavements. A sophisticated computer code was developed to analyze AE signals, to identify microcrack presence and location, and to produce a diagnostic schematic illustrating embrittlement temperature versus location (depth from surface of pavement).

The AEA differs significantly from existing standard mechanical tests (BBR, DTT, IDT, DC(T), TSRST), and likewise differs from more recently proposed tests, such as the ABCD fracture test, the BBR test for asphalt mixtures, and the modified DENT test of Edwards and Hesp (*14*). None of the existing or proposed tests has all of the features of the AEA test, namely:

- Rapid, small, and portable,
- User-friendly computer software with an interactive user interface with the capability to locate AE sources within an 1/8 inch resolution or better,
- Powerful tool, to determine the extent of in situ pavement embrittlement, or "embrittlement depth",
- Suitable for both binders and mixtures,
- Relatively independent of sample size and fracture size effect,
- Relatively independent of sample geometry,
- Suitable for in situ measurements,
- Designed specifically to aid in pavement evaluation for the purpose of determining the optimum timing and method(s) for preventive maintenance and rehabilitation.

In addition, as a design tool, AEA can be used to assess the effectiveness and proper use of rejuvenators in achieving the goal of restoring the pavement surface to a crack-resistant state. The AEA can provide highway agencies and pavement evaluation/preservation/materials testing firms with a powerful tool to accurately assess and monitor pavement condition, and strategically select an appropriate maintenance strategy to restore crack resistance in a cost-effective manner. By avoiding damaging forms of pavement surface cracking, such as top-down fatigue, thermal, and block cracking, pavement structure can be retained (asset preservation), costly rehabilitation can be delayed (saving agency and therefore tax payer dollars in the long run), and user costs can be significantly decreased (recall the estimated 50 to 1 return on investment). In addition, by using this technology to maintain the pavement in a resilient (flexible, healable) and predominantly micro- and macrocrack-free state, the damaging effects of moisture damage and raveling may likewise be delayed or prevented.

Furthermore, by applying thin maintenance treatments at the right time, significant sustainability benefits can be realized by avoiding or delaying the employment of thicker, hot-mixed overlay systems; and allowing the use of thinner treatment systems and treatments which often involve the use of cold or warm applied asphalt binder systems, thereby reducing the use of new materials, reducing fuel usage, and lowering the carbon footprint of the pavement.

Finally, the AEA device could also be used in the original single sensor mode, as a design and evaluation tool to determine the embrittlement temperature of binders and mixtures. Besides providing a low-cost, rapid design and assessment tool, using the AEA in this mode could also yield sustainability benefits through optimized mixture designs that maximize the effective usage of recycled asphalt products from pavement and roofing shingles, including its simultaneous use with warm-mix asphalt products.

The prototype AEA device, now capable of measuring graded in situ embrittlement characteristics, is ready for final commercialization. This will likely involve field validation across a broad range of materials and climates across the US, vetting through the FHWA mixtures expert task group (ETG), development of an AASHTO test standard, round robin testing, and finalization of commercial equipment-based data and experience from these subsequent efforts.

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