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Acoustic emission quantitative evaluation of rejuvenators to restore embrittlement temperatures to oxidized asphalt mixtures

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HIGHLIGHTS

- Acoustic emission approach allows to estimation of oxidative aging in asphalt mixtures.
- Rapid estimation of embrittlement temperatures of asphalt mixtures.
- Provides source location of thermal cracks in asphalt mixtures.
- Acoustic emission approach has potential to evaluate rejuvenator's efficiency.
- Approach is portable and easy to operate when compared to traditional methods.

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ABSTRACT

An acoustic emission (AE) approach to evaluate the effectiveness of rejuvenators in restoring aged asphalt concrete to its low-temperature performance grade is presented. Specimens, oven-aged for 36 h at 135 °C, were treated with rejuvenators (10% of binder weight). After 2, 4, 6, and 8 weeks of dwell time, the specimens were tested using AE while being cooled down to −35 °C. It was observed that after four weeks of dwell time, the rejuvenated-treated specimens had recuperated the original embrittlement temperatures. After eight weeks, the specimens' embrittlement temperature were about three grades (∼18 °C) lower than those of the aged temperatures.

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1. Introduction

Acoustic emission (AE) is a passive inspection technique that uses acoustic waves generated within the material during thermal or mechanical loading for defect detection and materials characterization [1–3]. AE source location techniques have also been widely used in material characterization and health monitoring in large structures such as pipes, and pressure vessels for a number of years. The use of AE to characterize solid material properties has gained popularity in recent decades. Ohtsu et al. [4] showed that the type and orientation of the cracks within a concrete structure can be determined using AE analysis. A similar study by Grosse et al. [5] showed that three-dimensional localization and frequency domain analysis on AE events can be used for crack classification at steel-concrete interface. Acoustic emission has also been used for the evaluation/characterization of asphalt concrete mixtures including its fatigue damage and healing properties [6–8].

Conventionally, the low-temperature performance grading of asphalt binders are based on AASHTO standard protocols [9–11], which require conducting standardized laboratory testing on binder specimens using specialized equipment and specimens with special geometry. These tests however, are time consuming, expensive, and lead to results with high variance. Because asphalt binders and aggregates have different coefficients of thermal expansion, thermal tensile stresses are induced in the mastic during cooling. When the developed thermal tensile stress in the mastic exceeds its strength, thermal cracking develops and strain energy is released in the form of transient elastic stress waves, i.e., AE events. This allows the use of acoustic emission for rapid estimation of the low-temperature performance grading, i.e., embrittlement temperatures, of binders and mixtures, and to conduct rapid field testing using portable AE instrumentation [7,12–20]. The embrittlement temperatures found using the AE

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approach have been proven to agree with those estimated using the AASHTO standard protocols [7], and to have less variance [12–20].

In asphalt concrete, the asphalt binder acts as a thermoplastic and viscoelastic adhesive to hold the aggregates together [21]. One of the major causes of asphalt concrete failures is the weakening of the adhesive bonding between the aggregates and the binder due to oxidative aging [22]. Oxidative aging leads to an increase in stiffness and loss of ductility and cohesion of binders, will lower the resistance of fracture of mixtures as compared to their virgin state. To restore the crack-resistant state of asphalt concrete, measures such as pavement surface milling and the application of rejuvenators aretaken. Asphalt rejuvenators are asphalt additives and modifiers to revitalize, provide sealing, and restore the physical and chemical properties of the aged asphalt concrete [23]. Rejuvenators address the issue of oxidative hardening by softening the aged asphalt binder through restoration of the asphaltenes to maltenes ratio [24]. After applying a thin layer of rejuvenator over the top surface of pavement, the rejuvenator penetrates the asphalt concrete using the pore and tortuosity structure via gravity and capillary action, and diffuses through the asphalt concrete to chemically react with the asphalt binder. The rejuvenator/binder reaction restores the binder's material properties to its original state, i.e., the material properties of the virgin condition. The asphalt binder is softened increasing its adhesive properties so that the asphalt concrete is less susceptible to thermal cracking.

As described by Brown et al. [25], with the exception of visual inspection, there is no standardized method to evaluate the performance of rejuvenators when applied in the field. Currently, the ability of rejuvenators to improve pavements' durability is typically evaluated by: (1) estimating the penetration in samples at 25 °C using asphalt binder extracted from untreated and treated cores; (2) comparing the viscosity at 60 °C of asphalt binder samples extracted from untreated and treated cores, and; (3) comparing the percentage of aggregate loss when untreated and treated samples are subjected to a pellet abrasion test. Mainly because these tests are cumbersome and time consuming, they are not often used. There exists a need for a more reliable method for determining the effectiveness of rejuvenating agents. The main purpose of this study is to illustrate how AE source location can be a powerful tool to characterize and evaluate the rejuvenators' ability to restore mixtures to their original low-temperature performance grading.

1.1. AE source location: a brief literature review

The "zonal location method," is the simplest form of source location. The AE sensors are sparsely installed on the surface of the monitored structure, and each sensor has a specific monitoring range depending on its sensitivity and attenuation of the testing material. The time-of-Arrival (TOA) method [26,27] is one of the most used source location methods, and it uses the travel time the of AE waves to a group of AE sensors, to estimate the distance between the AE source and each of the AE sensors. The location of the source can then be determined using triangulation.

The Time-Difference-of-Arrival (TDOA or Delta-T method) method [28,29], uses the differences in arrival time for a correlated signal detected by a set of spatially distributed sensors. TDOA source location is usually solved via an iterative numerical approach. Aljets and Chong [30] and Scholey [31] proposed a different sensor placement where the sensors are arranged into a close triangular array with few centimeters away from each other. TDOA method is applied to calculate the source location by using the time difference of arrival to the closely arranged sensors. This sensor placement provides the possibility of using a small and portable device with the small sensor arrays as the probe to conduct source location tests in the field [30]. Kundu [32] proposed the use of beamforming techniques coupled with Kundu's optimization schemes to allow accurate determination of the impact point location in anisotropic plates. Kundu further extended the method [33] by proposing a source location technique without requiring the direction dependent velocity profile in the structure and without solving a system of nonlinear equations. The history of the time-reversal method, basic physics, advantages and limitations are also addressed by Anderson et al. [34]. This method was later examined and validated by Ing et al. [35]. The advantage of the time-reversal method is the independency of the computation process on the shape of the structure and the wave velocity model.

Many other source locations schemes have been proposed and applied to seismic source location; some of them can be directly applied to the AE source location. Schumacher et al. [36] suggested that the key parameters used in calculating source location, i.e., locations of sensors, p-wave velocity, and p-wave arrival times are usually not constant; he proposed to represent the errors and uncertainties as probability density functions and to estimate the parameters using a Bayesian probabilistic approach based upon their full posterior probability distributions. Dong and Li [37] improved the accuracy of current source location schemes for micro-seismic events and AE sources. Their innovative method measures the arrival time of the p-wave and s-wave separately, and the source location can be solved by nonlinear fitting Self-Organizing Migrating Algorithms (SOMA) in conjunction with Global Optimization (GO) method without explicitly knowing the wave velocities [37]. Recently, Dong and Li [38] simplified the nonlinear location equations for conventional TDOA method to linear equations and developed a unique three-dimensional analytical solution without having square root calculations. This modified TDOA scheme is similar to the source location method proposed by the United States Bureau of Mines (USBM) [39], which was developed to monitor stability of rooks.

The TDOA, USBM and TOA algorithms are categorized as non-iterative point source location methods. Non-iterative methods solve a set of linear or non-linear equations without using any iterative numerical approach. These methods have the advantage of quick and easy computation process compared to iterative methods which involve using approximations and convergence techniques. While the results obtained using non-iterative source location methods are more prone to errors in the raw data, iterative source location methods provide slower, but a more flexible approach for source location calculations [40]. Geiger's method [41], is one of the most commonly used iterative source location algorithms.

2. Specimen preparation and low-temperature characterization using acoustic emission source location

Gyratory compacted asphalt concrete specimens were prepared using the same mixture design under Superpave guidelines [15]. A nominal maximum aggregate size (NMAS) of 19 mm was used for the mixture with asphalt content of 5.9% by weight of the total mixture. The binder grade PG 64-22 was used in the mixture. The asphalt mixture blend uses aggregates from four stockpiles: 65% of coarse aggregate (CM16), 23% of manufactured sand (FM20), 10.5% of manufactured sand (FM02), and 1.5% of mineral filler (MF). The mass for each kind of aggregate was measured after batching, and those aggregates were put into a foil pan and placed in the oven for 2 h at 155 °C to simulate short-term aging according to AASHTO PP2 protocol. The PG 64-22 asphalt binder and the mixing equipment were also heated in the same oven at 155 °C. Short-term aging simulates the aging which occurs during plant production of the mixture. After the short-term aging, the

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