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Spectral Analysis of Acoustic Emission of Cold Cracking Asphalt

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ABSTRACT

Acoustic emission is one of perspective nondestructive methods for evaluations of pavement materials such as concrete and asphalt. However, this method has not been applied for cold cracking asphalt due to some fracture effects. Methodology of acoustic emission measuring and its parameters evaluation also require some adjustment. This paper is devoted to applications of spectral analysis for investigation of acoustic emission of cold cracking asphalt. Acoustic emission data were analyzed versus temperature and load conditions versus a set of spectral and statistical characteristics. MATLAB codes for UNIX supercomputer were used for data processing. Proposals for future development and practical applications are presented in this work.

Keywords: acoustic emission, spectral analysis, cold cracking, asphalt.

INTRODUCTION

Application of acoustic emission (AE) to evaluation of materials in civil structures is new and challenging task for nondestructive testing in civil engineering. In spite of the fact that AE has been investigated for a considerable period of time and already has been used for some practical tasks there are no standard procedures or final recommendations for measuring equipment and software for asphalt applications. Recently developed AE technique for asphalt testing is based on geotechnical solution for single crack propagation and AE source coordinates measuring during crack propagation. This methodic is more applicable for testing of materials with high level of homogeneity, such as metals, rocks, ceramics etc. Application of AE for asphalt pavement testing is a complicated task because of the material thermo-viscosity, inhomogeneity and anisotropy. Moreover, this technique does not cover such important characteristics of AE as energy and patterns, which could be very informative for fracture analysis of the material. Therefore, combination of source coordinates and energy-pattern characteristics allows describing testing procedure as full scale AE source identification algorithm. The objective of this paper is spectral analysis and implementation of energy-pattern AE characteristic, such as different spectral parameters for asphalt testing procedure.

STATE-OF-THE-ART OF ACOUSTIC EMISSION OF COLD CRACKING ASPHALT

Research of cold cracking in asphalt pavements is overcoming a new stage of development – nondestructive monitoring of cold weather conditions and fracture estimations in asphalt pavements. This challenging task has initiated use of contemporary nondestructive techniques for cold cracking asphalt analysis. Application of AE for these purposes was mentioned in some publications [1-10]. The main idea of this research is based on necessity of monitoring of AE coordinates as tracks of crack propagations through asphalt during mechanical loading under specific cold temperature conditions

[11-14]. Determining the low-temperature fracture toughness of asphalt mixtures is presented in paper [15-17]. Some imported parameters of determination of asphalt binders viscosity from other rheological parameters is demonstrated in the work [18-19].

EXPERIMENTAL SET-UP AND ASPHALT SPECIMENS

The experimental design included ten specimens from different parts of MNROAD asphalt pavement with extracting from cores by cutting slices about one inch thick. The main goal of this research is investigation of AE response to cold temperature cracking under compression loads. Special one-inch long notches were made on the specimens for crack growing initiation (Figure 1).

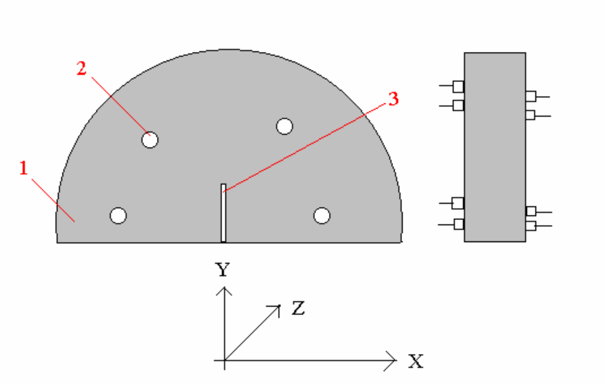


Figure 1. Experimental specimen design: 1- asphalt body; 2- miniature transducers; 3- artificial notch.

AE testing equipment was based on desktop computer station and National Instrument data acquisition boards DAQPad – 1200 and NI 5112 models under operation with LabView and MatLab software. AE transducers of Physical Acoustic Corporation, model S9225 were certified according ASTM Standard E976 "Guide for Determining the Reproducibility of Acoustic Sensor Response" (Figure 2).

Figure 2. Miniature acoustic emission transducer of Physical Acoustic Corporation, model S9225

The main characteristics of AE transducers are presented in the Table 1.

Table 1

AE TRANSDUCER CHARACTERISTICS

Model	Dimensions (diam. x height)	Weight	Operating	Peak	Operating

	mm / inches	(grams)	Temperature (°C)	Sensitivity V/(m/s) [V/μbar] (dB)	Frequency Range (kHz)
S9225	3.6 x 2.4 / [.15 x .1]	2.5	-54 to 121	48+ [-77.5]	250 - 2000

Amplitude-frequency characteristic for these transducers is presented in the Figure 3.

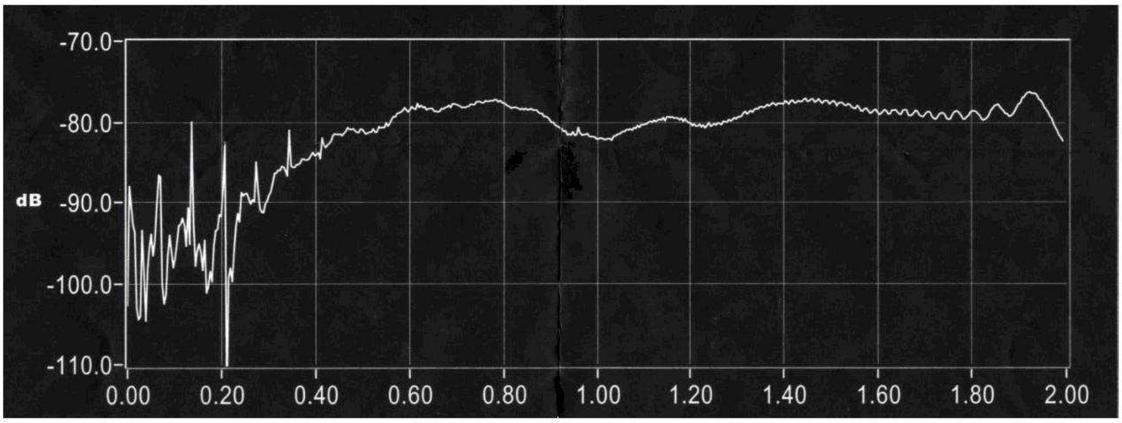


Figure 3. Typical amplitude (dB) – frequency (MHz) characteristic of S9225 AE transducers.

This miniature design of AE transducers provides new opportunities for testing because they do not contain any specific frequency resonance and their amplitude-frequency characteristic is practically flat and wideband at the range 0.2-2 MHz. These new features allow using these transducers for energy-pattern analysis of AE based on signal processing techniques.
Transducers were connected to preamplifiers with 40-60 dB gain. Block of preamplifiers is displayed in the Figure 4.

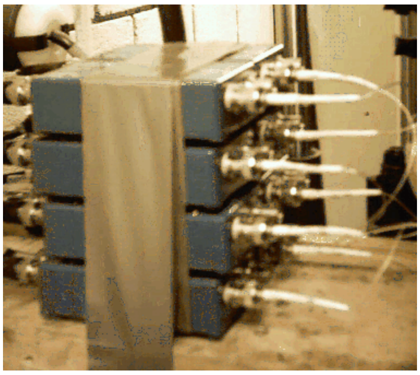


Figure 4. Block of eight preamplifiers with 40 dB gain.

Load testing machine and AE monitoring system are shown in the Figure 5.

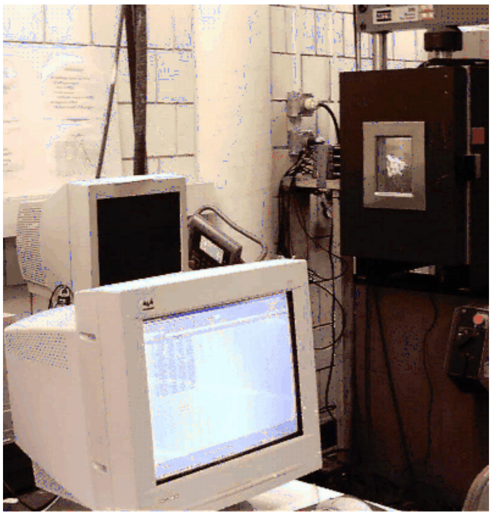


Figure 5. Load testing machine and AE monitoring system.

The following main parameters of data acquisition measuring system were chosen:

- Threshold level is 10-50 μV;
- Sample rate is 20 MHz;
- Quantity of channels is 8;
- Record of AE data is continues;
- Out file for AE data is LabView format;
- Out file for AE coordinate is in *.dat format.

Position of asphalt specimen in testing chamber is presented in the Figure 6.

Figure 6. Asphalt specimen in the testing chamber.

METHODOLOGY OF AE ANALYSIS AND EXAMPLES

Methodology of AE analysis includes tow separated lines of research:

- AE coordinates calculations based on differences of times of pulses propagations form sources to numbers of AE transducers fixed to the specimen's surface;
- Recording of AE (pulses) and computerized analysis of their characteristic, such as different kinds of spectrums.

Methodologies of AE coordinates calculation were published in several journal publications [] and were not considered in this work. Methodology of computational analysis of AE could be described here as applications of digital signal processing for characterization of different parameters of AE process versus mechanical and temperature loads to asphalt specimens. For these purposes it is important to describe cases when AE pulses are of very low amplitudes and could be mistakably chosen as noise, and when AE pulses could be analyzed as a sum of AE process and background noise together.

It is possible to classify AE in accordance with the three main types of acoustical signals obtained during material testing: acoustic noise, acoustic pulse and their combinations. Typical example of acoustic noise (or a sum of noise and low amplitude AE pulse) is shown in the Figure 6:

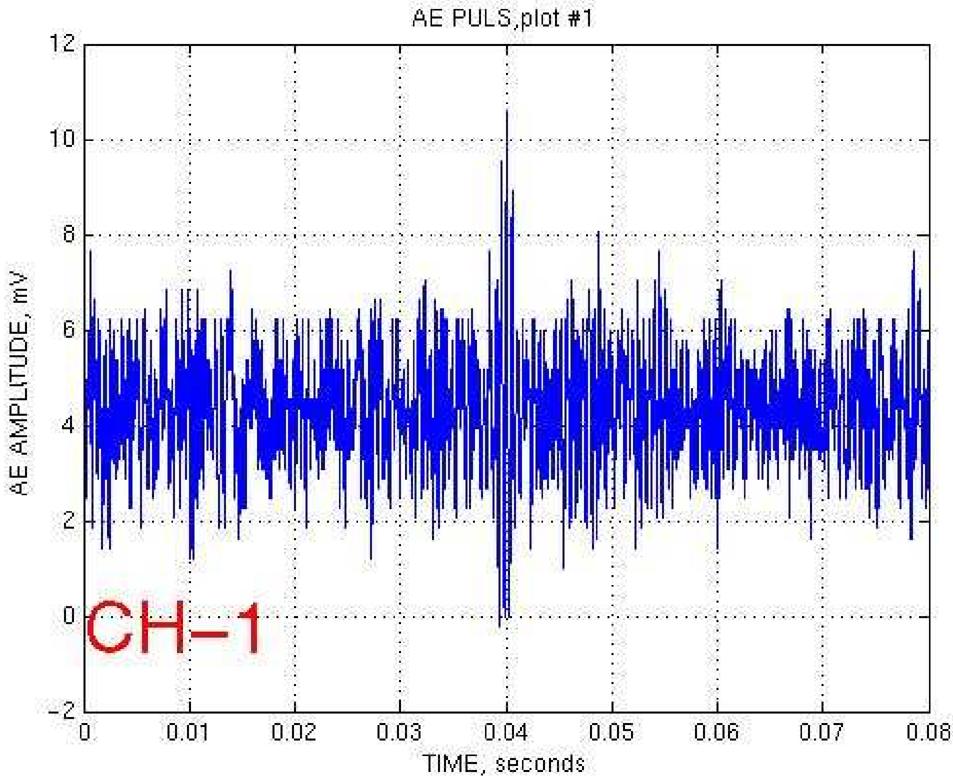


Figure 6. Typical example of acoustic noise or a sum of noise and low amplitude AE pulse (channel #1).

This acoustic noise is a combining of electrical noise of measuring equipment, environmental noise and low level AE response from material.

Typical example of AE pulse with noise is presented in the Figure 7:

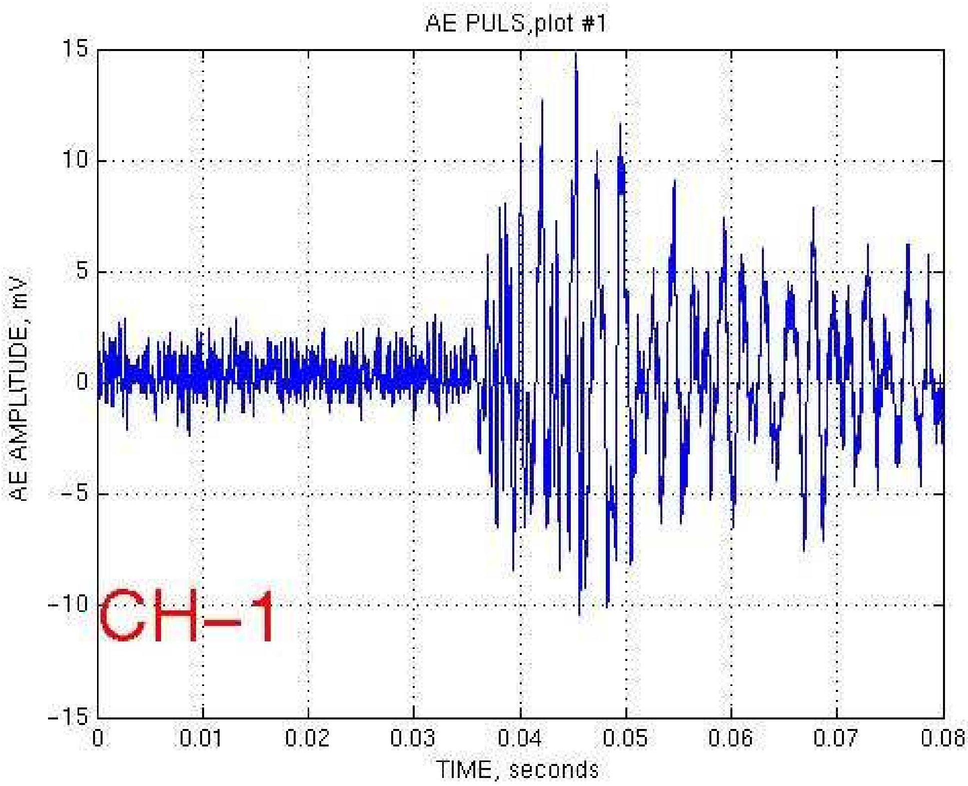


Figure 7. Typical example of AE pulse with noise (channel #1)

SPECTRAL ANALYSIS OF ACOUSTIC EMISSION

Signal processing of AE is based on spectral analysis of events and AE process as average characteristics of different parameters, which were obtained through statistical analysis of these events.

The discrete Fourier transform, or DFT, is the primary tool of digital acoustic signal processing. The foundation of the DFT is the fast Fourier transform (FFT), a method for computing the DFT with reduced execution time. Many of the spectral analysis functions (including *z*-domain frequency response, spectrum and cepstrum analysis, and some filter design and implementation functions) incorporate the FFT. MATLAB provides the functions of direct spectral transformations *fft* and reversed spectral transformations *ifft* to compute the DFT and return these data, respectively. For the input sequence of acoustic signal $U(t)$ and its transformed version as spectrum $F(\omega)$ the two functions implement the following relationships

$$F(k+1)=\sum_{n=0}^{N-1}U(n+1)W_N{}^{kn}$$
$$U(n+1)=\frac{1}{N}\sum_{k=0}^{N-1}F(k+1)W_N{}^{-kn} \quad (1)$$

where

$$W_N = \exp[-j\cdot(\frac{2\pi}{N})] \quad (2)$$

and $k = 0,1,2...N-1, n = 0,1,2...N-1$ - numbers of spectral and timing data in analysis where $\omega = 2\pi f$ and f - frequency of AE transformation.

Generally, FFT brings complex variant of spectral data, which contains as real part of acoustic signal, as imagery part of signal spectrum $F(\omega)$. The real part of signal spectrum is presented by amplitude spectrum $A(\omega)$ and imagery part is presented by phase spectrum $\Phi(\omega)$ that could be described as following

$$A(\omega) = \mathrm{Re}(F(\omega))$$
$$\Phi(\omega) = \mathrm{Im}(F(\omega)) \quad (3)$$

and their relation is presented by angle spectrum $\Theta(\omega)$

$$\Theta(\omega) = \frac{A(\omega)}{\Phi(\omega)} \quad (4)$$

Spectral analysis of acoustic signals allows to present mixture of noise and AE event in frequency domain and to build a specific imaging for energy-pattern characteristics of AE.

An example of spectral characteristics of AE event is given below in the Figure 8:

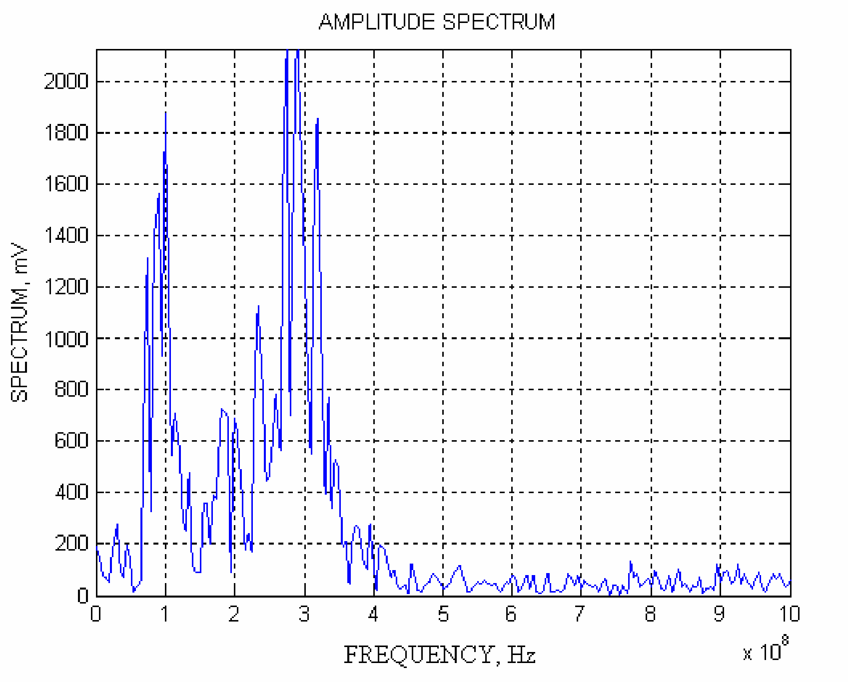


Figure 8. Amplitude spectrum of AE pulse with background noise

There are two important characteristics of AE patterns: phase angle $\Theta(\omega)$ and phase spectrum $\Phi(\omega)$, which indicate inner relations in signal and are very helpful for wavelets imaging and other types of visualization.

Phase spectrum is presented in the Figure 9:

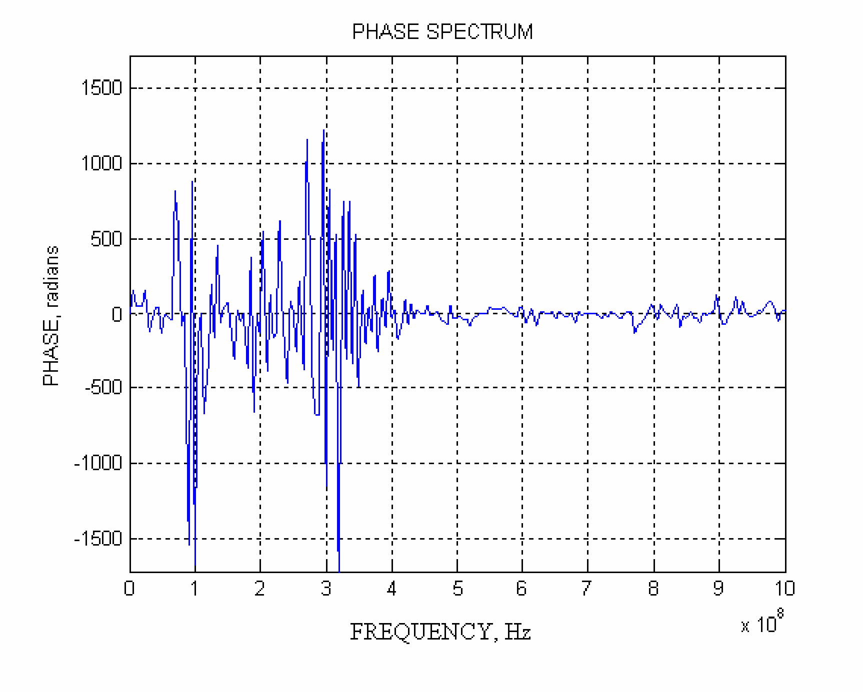


Figure 9. Phase spectrum of AE pulse with background noise.

Modern signal processing allows to present acoustic signals in time and frequency domain in one graphical image as wavelet transformed AE.

Wavelet presentation of the spectrum is given in the Figure 10:

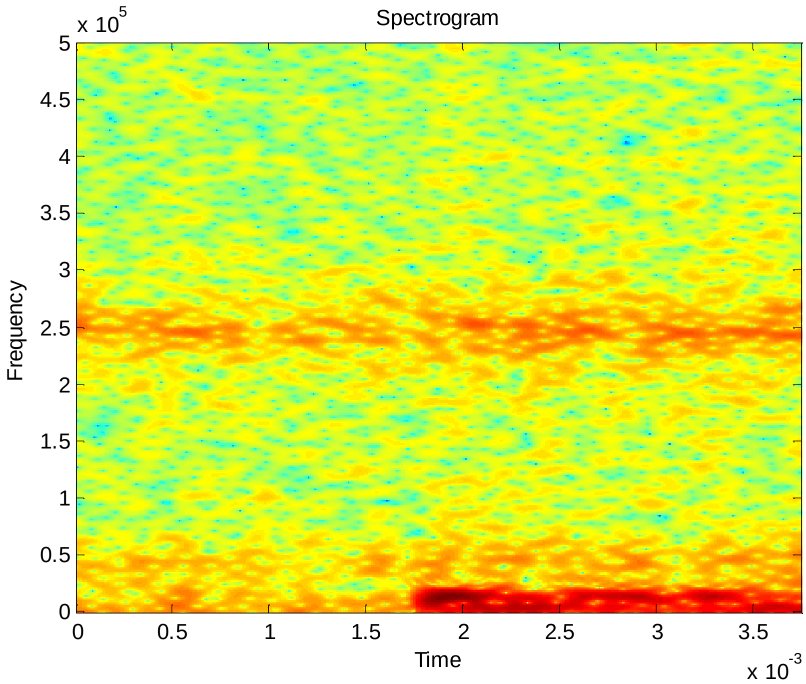


Figure 10. Time - frequency wavelet transform of AE pulse with background noise.

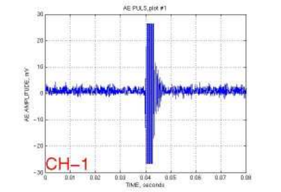
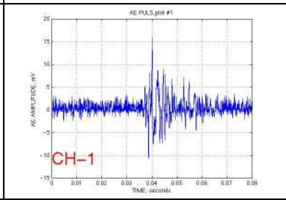
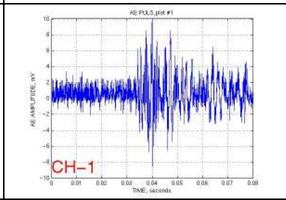
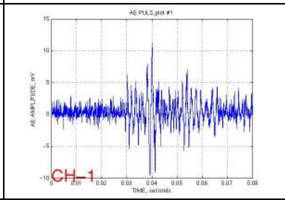
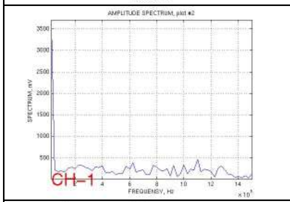
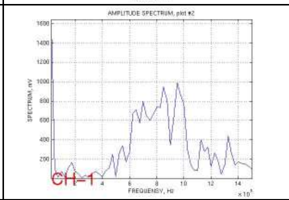
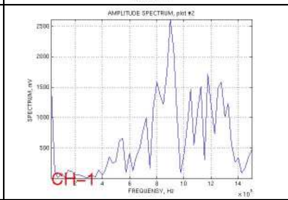
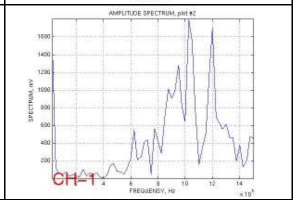
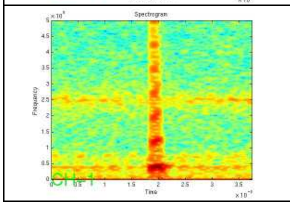
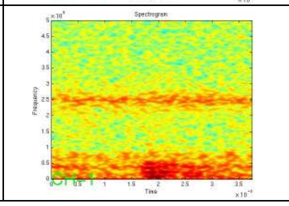
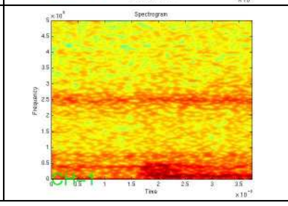
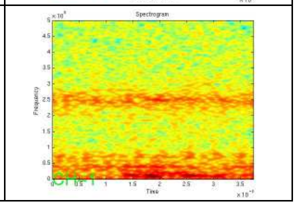
SPECTRAL ANALYSIS OF ACOUSTIC EMISSION OF COLD CRACKING ASPHALT

Effect of the cold cracking of asphalt was investigated for a number of asphalt specimens under specific temperature conditions and mechanical loads. Vertical and horizontal displacements, level of loading and temperature were recorded during test time. AE signals was simultaneously cached and collected by computer based acquisition system and analyzed using specially prepared MATLAB codes at UNIX platform of supercomputer. Application of supercomputing was necessary because sizes of AE files did not allow analyzing them at PC due to limits of operational memory and speed of calculations. Comparison of recorded loading data and AE signals were in relative time because two different systems of time measurement were used, but they had the same “start” and “finish” mark of time. An example of AE measurements and calculated spectrums are presented in the Table 2 for asphalt specimen (code 34-13-T1)

Table 2

SPECIMEN 34-13-T1

RELATIVE LEVEL OF LOADING TIME

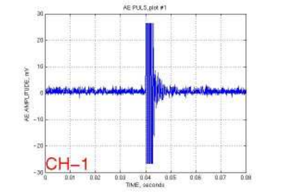
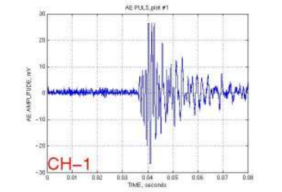
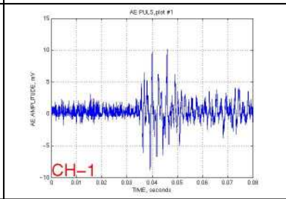
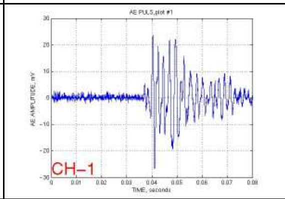
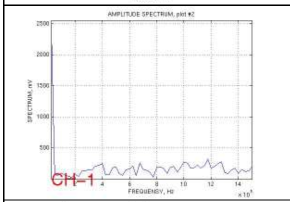
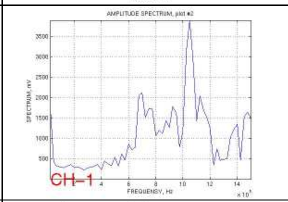
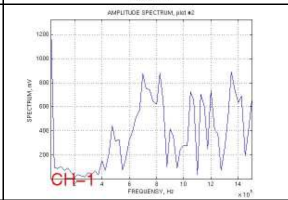
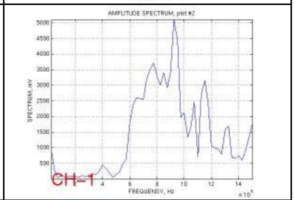
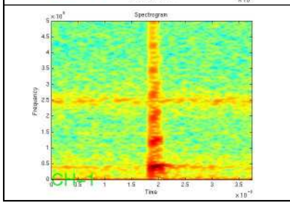
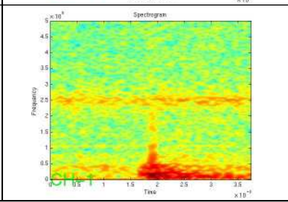
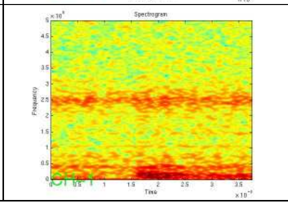
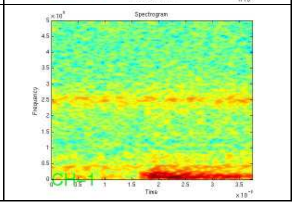
0.2	**0.4**	**0.6**	**0.8**
			
			
			

And for asphalt specimen (code 35-17-B1) in the Table 3

Table 3

SPECIMEN 35-17-B1

RELATIVE LEVEL OF LOADING TIME

0.2	0.4	0.6	0.8
			
			
			

COMPARISON OF LOAD HISTORY AND SPECTRAL ANALYSIS DATA

Comparison of different AE parameters with loading history gives possibilities to evaluate asphalt behavior in-situ. An example, graph of loading forces versus time and maximum amplitude of spectrum versus time, is shown in the Figures 11 for 34-13-T1 specimen and the Figure 12 for 34-13-T1 specimen:

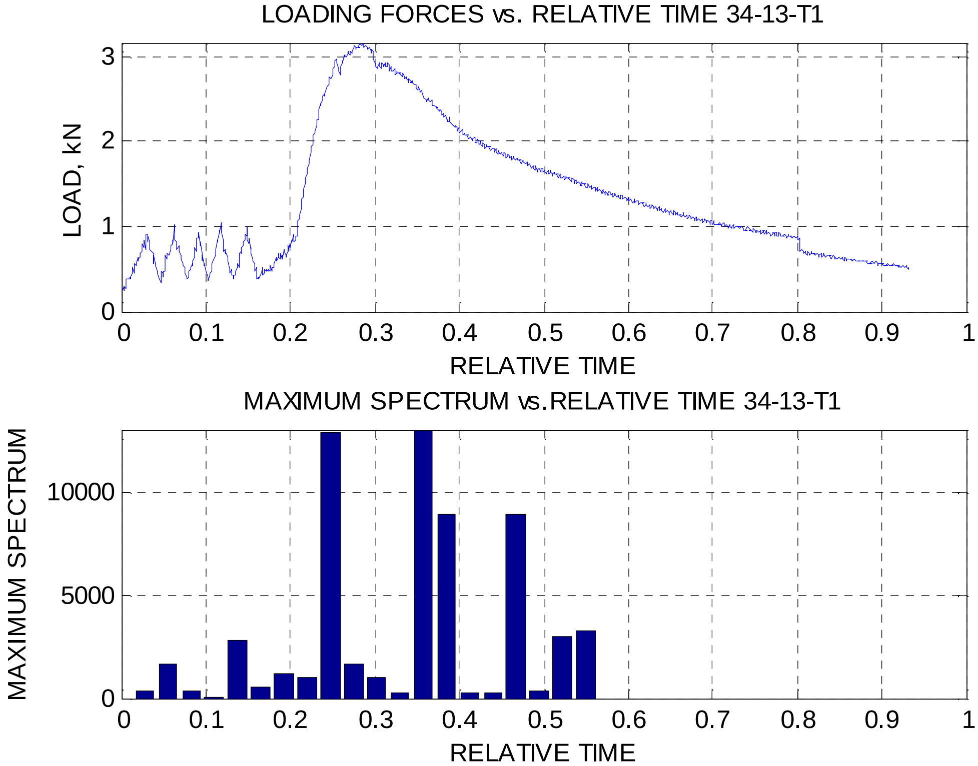


Figure 11. Loading of specimen and maximum of AE amplitude spectrum vs. relative time (specimen 34-13-T1)

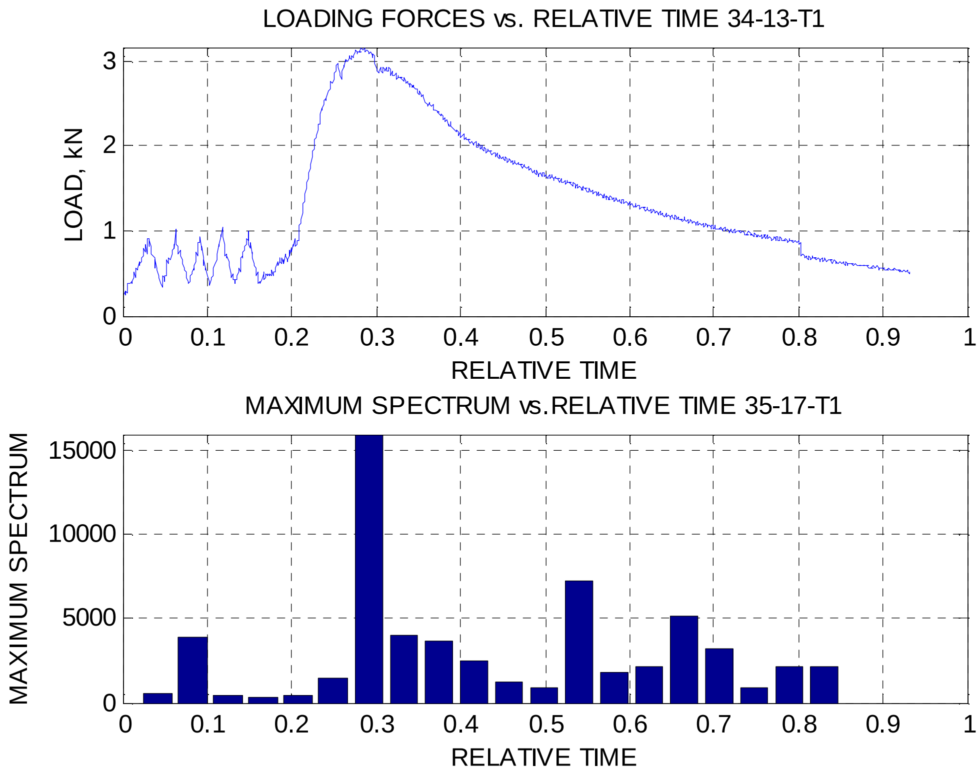


Figure 12. Loading of specimen and maximum of AE amplitude spectrum vs. relative time (specimen 35-17-T1)

PROPOSED MODELS AND APPLICATION FOR PAVEMENT TESTING

Evaluation of AE spectrums could be combined with source coordinates calculations in 3D. In this case it is possible to build an integrating evaluation model, which includes as spectral patterns of AE, as distance to sources and their coordinates. This combination could allows to calibrate receiving AE spectrum for specific material wave attenuations and estimate losses. Precision of coordinate calculations affected sensitivity of method. Increasing of precision of method will give more reliable data for field AE testing and will allow to apply this method immediately for practical tasks. However, it is possible to note that several steps should be done before this method will be ready for practical applications in industry:

a. AE signals / noise ratio should be optimized by filtering and using some new techniques, such as wavelets transformations;
b. AE coordinates data should be treated as stochastic process with probabilistic approach for analysis;
c. AE transducers should have permanent position and stable acoustic contact with the specimen during all steps of investigation;
d. AE coordinates evaluation algorithm should be optimized from maximum likelihood method to direct geometric arrays algorithm [].

COMBINATION OF COORDINATES CALCULATION WITH ENERGY-PATTERN CHARACTERISTICS: NEW ALGORITHMS AND DATA VISUALIZATIONS

Full scale AE analysis algorithm should include two parts: coordinates calculation and energy-pattern analysis for each AE event. In this case it is possible to include attenuation of propagating waves to backcalculation analysis of fracture mechanism. The general model for material evaluation by AE full scale testing could be described as functional

$$MP = F[x, y, z, f(p_1, p_2 ... p_k)] \qquad (5)$$

where x, y, z – coordinate of AE sources;
$f(p_1, p_2 ... p_k)$ - function of AE parameters;
$f(p_1, p_2 ... p_k)$ - effective AE parameters, which were chosen for analysis.

Some new algorithm and 3D AE source coordinate evaluation technique is described in the papers [9,10].

CONCLUSIONS

Analysis of possibilities of AE application for asphalt pavement testing shows that existing methods and equipment should be improved, standardized and integrated to one common architectural testing design. Full scale AE testing should include AE coordinate evaluation as well as energy-pattern of AE sources evaluation. Some contemporary techniques, such artificial intelligence, wavelet transforms and stochastic modeling should be involved in AE testing procedure for better performance, repeatability of results and decision making. The received experimental results show real possibilities of AE application for diagnostics of pavements in situ.

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