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Research paper



Evaluation of Low Temperature Cracking of Asphalt Mixture Modified with PPA Using Acoustic Emission Technique

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Abstract

In this study, the behavior of asphalt mixture was studied using non-destructive Acoustic Emission (AE) technique at low temperatures. For this purpose, two types of bitumen 60/70 and 85/100 with two types of limestone and Silica aggregate were used to construct asphalt mixtures. Polyphosphoric acid (PPA) was used to modify the bitumen in the dosage of 0, 0.5, 1.0 and 1.5% of bitumen weight. Semicircular bending test (SCB) under a steady increasing strain at a rate of 3mm/min was conducted at 0, -10-, and -20 °C. Two AE channels were used to record the Sinusoid output around the crack of SCB sample during crack growth. Analysis of the results obtained from this study using SPSS software indicates that there is a significant relationship between the failure energy of SCB samples and the number of impacts received from AEs. Furthermore, AE energy has a good agreement with the sample failure energy. According to the failure criterion, asphalt mixtures containing 85/100 bitumen modified by 1.0% of PPA and limestone aggregate exhibit more crack resistance among other compositions.

Keywords: *Acoustic emission, asphalt mixture, crack, fracture energy, low temperature Behavior.*

1. Introduction

Low-temperature cracking is a major distress of asphalt mixtures and occurs more often in areas with cold weather or high-temperature variations of day and night [1]. As the temperature decreases, the asphalt mixture shrinks and generate a tensile stress in structure because of the friction present in the pavement layers [2]. This cracking appears in two forms of low-temperature cracks and thermal fatigue cracks. Low-temperature cracks occur in regions with cold climate, while the potential of thermal fatigue cracking is high in the pavement of warm climate which are made with stiff bitumen [3]. Generally, low-temperature cracks are dependent on the asphalt mixture properties (bitumen, type of aggregates, etc.), the environmental factors (temperature, traffic, etc.) and the geometric conditions of the pavement (layer thickness, friction coefficient between two layers of pavement, etc.). To reach to a proper design of asphalt mixtures it is necessary to consider all of these factors [4, 5]. Bitumen is one of the most important components contributing to low-temperature cracking in the asphalt mixture. At low temperatures, bitumen become brittle and fragile, applied strains causes the bitumen to crack because of bitumen intolerance, therefore crack starts appearing in the asphalt mixture. The lower viscosity (higher penetration grade) of bitumen leads to a decrease in the potential for cracking due to low temperature.

In a study, it has been shown that bitumen has a more significant role in low-temperature cracking than other distress of asphalt mixture (such as rutting, fatigue, and moisture damage). Also, the temperature range of bitumen workability (performance grade) is considered as an important factor in the asphalt mixture production and crack resistance [6]. According to previous studies, the effect of the aggregates type on this distress depends on factors such as abrasion resistance, the ability of bitumen absorption and roughness of the aggregate texture [4, 7]. The higher abrasion resistance of aggregate, the greater resistance of low-temperature cracking of asphalt mixture. Also, the greater bitumen absorption capacity reduces the low temperatures resistance of asphalt mixture because of the reduction in the bitumen film covering the aggregates. In addition, using broken aggregate causes more locking in asphalt mixtures component. Therefore, the combination of crushed aggregate and soft bitumen produce an asphalt mixture with more resistance to low-temperature cracking [8]. The effect of temperature on low-temperature cracking has been clarified by previous research and indicate that the lower temperature of asphalt mixture causes the greater potential of cracking.

In mechanical engineering, many techniques are used to identify the crack and its propagation pattern in industries, one of which is the acoustic emission (AE) [9]. This is a relatively simple and low-cost test hence, this technique is used in the present research, to evaluate the growth of cracks in asphalt mixtures at low temperatures under certain loading conditions. Finally, the best indicators of this technique will be presented which have more potential to predict asphalt mixture cracking.

2. Acoustic emission system

2.1. Acoustic emission mechanism

Acoustics emission is a phenomenon that results from the generation and emission of an elastic wave in the material in the ultrasonic range (1KHz - 20 MHz). These waves result from the sudden release of elastic energy from an existing source in a material because of various mechanisms of deformation and failure. The released waves in the body reach the surface and cause vibrations on the material surface. These vibrations can be captured by sensors of an

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acoustic emission system which are made of piezoelectric material. Hence the information of the waves source can be recorded. As shown in Fig. 1, the components that have discontinuity, release their energies as soon as they are subjected to stress. This energy is released as high-frequency waves of stress in the structure. The emitted wave characteristics depend on the source, the loading intensity, and the emission surroundings properties. After that, these waves are received by sensors and converted to electrical energy by these sensors. These voltages are amplified by electronic circuits and analysed by timing circuits as acoustic emission data. The analysis of these data includes the interpretation of the frequency, the voltage intensity, and the received voltage corresponds with the position of the transmitter source [10].

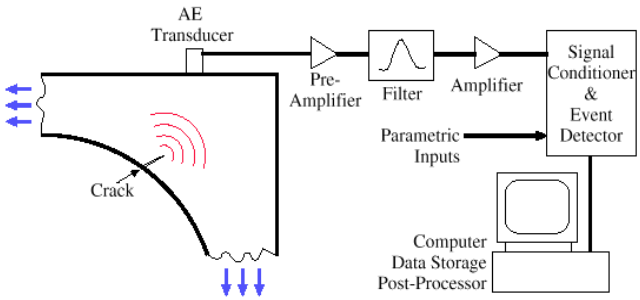


Fig. 1: Velocity variations Schematic of acoustic emission system [10].

The main difference between the acoustic method and other non-destructive test methods is the passive nature of this method, while other methods are active in most cases. For example, an ultrasonic or radiographic method requires applying external energy or a change in the material in order to record information about the desired material. While in the acoustic method, the released energy of the material is required. In other words, in acoustic method the sound generated from an object due to energy release is recorded while in the ultrasonic methods the sound reflection of a noise input is detected. Acoustic emission method is one of the newest methods in the non-destructive testing field, with its unique capabilities, which has attracted the attention of researchers. Some of the acoustic emission features include 1- Detection mechanisms of various failure in materials such as crack growth, fatigue and creep of structure, 2- Detection of leakage in tank and pipelines, 3- Periodic inspections of engineering structures and etc.

2.2. Describing parameters of acoustic emission signals

The most important parameters describing and measuring the acoustic emission signals are shown in Figure 2. These parameters are the number of counts, signal frequency, amplitude, signal energy, rise time, and duration as described below:

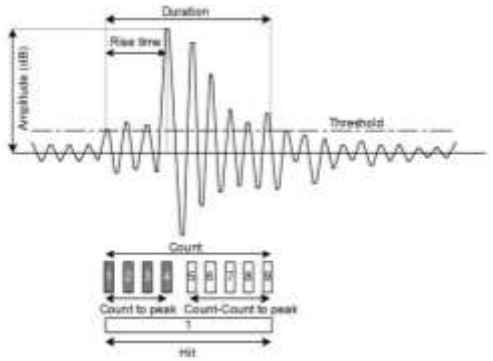


Figure 2: Acoustic emission signals and its describing parameters [11].

Hit: It refers to any acoustic event or acoustic waveform registered in the system.
Domain: The maximum voltage of an acoustic signal is called the amplitude. It is one of the most important parameters in describing the signal because this parameter determines the detectability of the signals and is proportional to the real magnitude of occurred hit in the source. This parameter is usually expressed in decibel units.
Counts: The number of pulses that pass through a certain threshold. This parameter is one of the oldest and simplest parameters of acoustic emission test.
Signal energy: This parameter measures the acoustic signal value. It is equal to the area under the amplified signal curve. This parameter has the preference in many ways to counts and even the duration, because it depends on both the amplitude and the signal duration, while it has a lower dependence on the frequency and activation threshold.
Duration: The time taken from the first acoustic pulse passing transient from the excitation threshold to the last pulse of the threshold. This parameter is measured by the microsecond scale and depends on the magnitude of the acoustic event and the acoustic and reflective properties of the material. This parameter is useful for identifying in long processes.
Rise Time: The time taken from the first pulse transient from the excitation threshold to the maximum signal point. This parameter depends on the properties of the wave propagation in the material and is used to correct the signal and remove the noise.
Rise angle (RA): RA is the ratio of the rise time to the maximum amplitude [12].

2.3. Parametric analysis of acoustic data

The waveform can be considered together with the parametric data as two basic categories of recorded AE data. In the basic parameter analysis, the characteristics and changes in the parameters of the acoustic signals are evaluated for assessing the damage corresponding to the applied stress conditions. Therefore, the parametric data is more accessible and more functional [13]. These parameters are shown in Figure 3:

Variables	Parameter	Obtained information
Time domain	Rate	Rate of damage occurring
	Peak amplitude	Intensity of source event, orientation
	Relative arrival time	Source location
	Duration	Energy of source event
	Count	Energy of source event
	Waveform	Structure of source event
	Energy	Energy of source event, type of damage
Frequency domain	Frequency spectrum	Nature of source event
Time-frequency domain	Spectrogram	Energy distribution of source event through time
	The time variation of each frequency component	The intensities of source frequency component

Figure 3: Various Parametric analyzes and their methods [13].

2.4. Application of Hits in microdamage analysis

This technique can capture the microcracks from the beginning of distress to the large cracks in the failure state. Figure 4 shows the growth of the cumulative number of hits versus time. In this figure, the cumulative increase in the number of hits indicates an increase in the damage level. Rau et al. investigated the use of hits rate and applied stress in the quasi-fragile materials. Their study results indicate that the microcracks are formed with the loading and simultaneously the number of recorded hits also increase. Therefore, this parameter can be used to investigate damage [13,14].

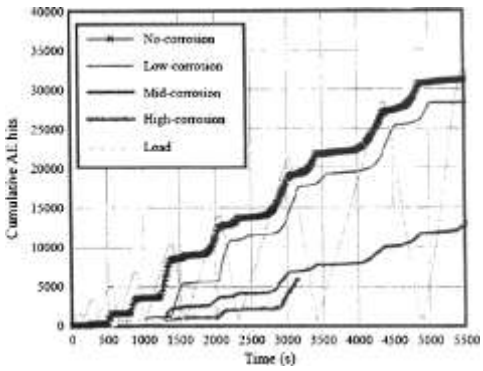


Fig. 4: cumulative hit diagram vs. time for the reinforced concrete beam [13].

Regarding the previous studies, we tried to compare the above parameters with the fracture energy of laboratory samples (as a criterion of failure), and the parameter which has a significant relationship with the failure energy, to be presented.

3. Fracture energy

As mentioned above, the fracture energy is considered as a distress criterion. The value of this parameter for the laboratory samples of this study (semicircular bending) can be calculated determined using the following equation [15]:

$$G_f = \frac{W_f}{A_{lig}} \quad (1)$$

Where G_f is the fracture energy, A_{lig} is the Ligament area and W_f obtained from the following equation:

$$W_f = \int P du \quad (2)$$

This integral is equal to the area under the P-u curve (load-displacement) calculated by MATLAB software.

4. Sample preparation and laboratory tests

4.1. Optimum percentage of bitumen

The control sample of asphalt mixtures were constructed using two kinds of limestone and silica aggregate and two types of bitumen with a penetration degree of 85/100 and 60/70 according to Marshall mix design (ASTM D1559). The combination of 60/70 bitumen with the limestone and silica were labeled L60 and S60, respectively. Similarly, samples made of 85/100 bitumen with the limestone and silica were named L85 and S85.
According to the ASTM D1559, the optimum percentage of bitumen for control mixtures of S60, S85, L60, and L85 were 6.1%, 5.7%, 5.2% and 4.6%, respectively.

4.2. Bitumen modification

In this study, poly phosphoric acid (PPA) was used as a modifier to improve the bitumen properties. For this purpose, neat bitumen was blended with 0, 0.5, 1.0 and 1.5 wt.% of PPA at 140 °C in low shear approximately of 450 rpm for 1 hour. Each set of control samples (L60, L85, S60 and S85) which contained 0%, 0.5%, 1.0%, and 1.5% of PPA were labeled as L60-0, L60-5, L60-10, L60-15 and as well as L85-0, L85-5, L85-10, L85-15, S60-0, S60-5, S60-10, S60-15, S85-0, S85-5, S85-10, S85-15, respectively. It should be noted that PPA does not have a significant effect on the bitumen optimum percentage of all control mixtures.
The cylindrical samples of asphalt mixture (4 inches in diameter and 3 inches in height) were divided into semicircular with 4-inch in diameter and thickness of 2.5cm. Finally, a crack with 0.5mm in thickness and 2.5cm length was created at the center of the SCB samples.

5. Test method

The SCB specimens were tested by UTM25 under three-point loading as shown in Fig. 5 at a displacement rate of 3 mm/min with different temperatures of 0, -10 and -20 °C. The acoustic data were recorded using AEWin software and PCI-2 system with a recording rate of 1 MS/s. Two channels of piezoelectric AE with large bandwidth were attached around the cracked using silicone grease. The recorded data of sensors was amplified by a pre-amplifier with a coefficient of 40 dB. Furthermore, a threshold of 37dB was also considered to remove background noise through the test. It should be noted that four SCB samples were used to repeat the test of each test criteria.



Figure 5: Schematic of samples loading and attachment of the AE channels around the crack.

6. Results and discussion

The results of the three-point bending test, are presented in Fig. 6 as the force-displacement diagram, for 4 repeats of S60 and S85 mixtures (for example) at -10 °C:

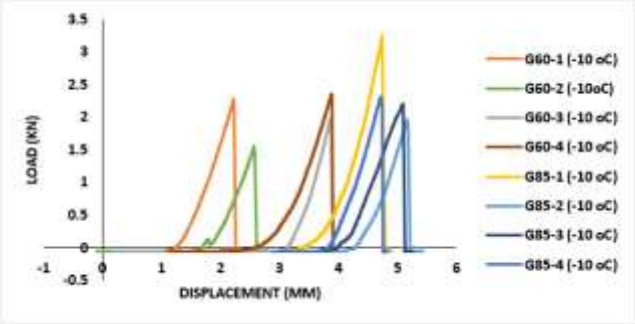


Fig. 6: Force-displacement diagram for S60 and S85 at -10 °C

All results of this test are shown in figure 7:

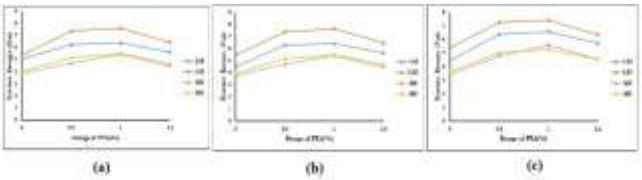


Figure 7: Fracture energy of asphalt mixtures: (a): at 0 °C, (b): at -10 °C, (c): at -20 °C.

As it can be seen in Figure 7, the asphalt mixture including limestone has more crack resistance because of higher fracture energy value. The same result can be observed in the specimen which are constructed by bitumen of 85/100 penetration. This result indicates that the asphalt mixture containing the softer bitumen and crushed aggregate, has more resistance against crack damage, compared to other combinations. This result has been presented in the study of Zaumanis, Mashaan and Pasetto which approve the experimental output of this research [16, 17, 18]. On the other hand, using PPA has a significant effect on the potential of crack resistance, especially in the dosage of 1%. According to these results of three-point bending test, the mixtures of L85-10, L85-5, and L85-15 exhibit more crack resistance among other compositions. Therefore, using the upper dosage of PPA (e.g. 2% and higher) decreases the effect of modifier on the crack resistance.
The output of the AE parameters is presented in Table 1, all of which are the average result for four tests.

Table 1: The average results of AE parameters

Sample	Test Temperature	Avg. of Hit (X_1)	Avg. of AE Energy (105 aj) (X_2)	Duration (μs) (X_3)
L60-0	0	14	6.325	18
	-10	12	6.084	12
	-20	10	5.936	42
L85-0	0	19	7.740	17
	-10	16	7.306	33
	-20	15	7.013	26
G60-0	0	10	5.182	35
	-10	8	4.906	22
	-20	5	4.664	39
G85-0	0	10	5.730	45
	-10	9	5.598	27
	-20	7	5.208	30
L60-5	0	18	8.060	33
	-10	16	8.007	20
	-20	14	8.066	31
L85-5	0	25	10.072	28
	-10	21	9.928	19
	-20	19	9.061	44
G60-5	0	13	6.017	18
	-10	10	6.043	19
	-20	6	6.970	24
G85-5	0	11	7.585	26
	-10	11	7.776	33
	-20	9	7.906	41
L60-10	0	10	8.839	28
	-10	18	8.894	32
	-20	17	8.723	21
L85-10	0	11	10.862	37
	-10	16	10.440	13
	-20	14	9.879	20
G60-10	0	14	7.515	18
	-10	13	7.221	19
	-20	26	7.787	43
G85-10	0	8	7.957	37
	-10	12	7.933	22
	-20	15	7.760	19
L60-15	0	14	7.551	11
	-10	17	7.512	32
	-20	11	7.606	22
L85-15	0	18	9.032	41
	-10	16	8.545	19
	-20	19	8.188	18
G60-15	0	13	6.009	24
	-10	7	5.745	36
	-20	10	6.103	25
G85-15	0	13	6.651	21
	-10	10	6.486	42
	-20	12	6.435	38

It is now necessary to determine the correlation between the fracture criterion (fracture energy) and the output parameters of the AE device to find the best indicator of AE parameters in order to predict the potential of crack resistance of asphalt mixture. Hence, the root mean squared error (RMSE) was considered for this selection. the RMSE value is obtained as follows:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(E_i - X_i)^2}{n}} \quad (3)$$

Where X_i and E_i are the AE parameter and fracture energy value of the ith sample, respectively. The lower RMSE value represents the more significant relationship between the fracture energy and the AE parameter. The results of this analysis are presented in Table 2:

Table 2: RMSE values of AE Parameters

AE parameter	Avg. of Hit (X_1)	Avg. of AE Energy (X_2)	Duration (X_3)
RMSE of Parameter	8.817	2.031	24.021

The results of the errors indicate that there is a significant relationship between the AE energy parameters and the hit number with the fracture energy of the samples. The "Duration" parameter has the highest error value and this result can be interpreted to show that this parameter is effective for long-term experiments. On the other hand, samples of SCB have been tested at a negative temperature and therefore behave as an elastic material, while there is very short time to sample failure. So, this parameter failed to describe the failure criterion as well as other AE parameters. The lowest RMSE value is related to the AE energy parameter, which is equal to 2.031. Therefore, it can be concluded that the AE energy parameter will be more able to determine the potential of asphalt mixture failure at low temperature. According to this parameter, the L85-10 sample containing limestone aggregate, 85/100 bitumen, and 1% polybasic acid has a higher value of AE energy, thus exhibiting higher resistance to low temperature cracking.

7. Conclusion

In this study, the effect of poly phosphoric acid on the low temperature cracking of asphalt mixture was investigated using acoustic emission technique. Three-point bending test was conducted on the SCB sample of asphalt mixtures at different low temperature of 0, -10, and -20 °C. The following conclusions can be derived from this study:

1- The results of three-point bending test show that the samples constructed with crushed aggregate and softer bitumen have more resistance against crack damage of low temperature cracking.

2- Using PPA has a significant effect on the crack resistance improvement of asphalt mixture, especially in the dosage of 1%.

3- The asphalt mixtures of L85-10, L85-5, and L85-15 exhibit more crack resistance among other compositions. Therefore, using the upper dosage of PPA (e.g. 1.5% and higher) decrease the effect of modifier on the crack resistance.

4- Statistical analysis indicates that the parameter of AE energy and hit number have the lowest RMSE. So, these parameters can be suitable to predict the potential of asphalt mixture cracking.

5- According to the AE technique and three-point bending tests, it can be concluded that 1% of PPA is the optimum dosage of bitumen modifier.

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