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Assessment of fatigue damage in asphalt mixture using an acoustic emission approach

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Abstract. Fatigue failure is the main damage forms of asphalt mixture. Acoustic emission (AE) is an effective technique for continuously monitoring the development of fatigue damage in asphalt mixture. Firstly, the AE characteristic and mechanical behaviour of asphalt mixture and their relationship were investigated by performing four-point bending fatigue test and AE test. Furthermore, the parameters of continuum damage mechanics model that describes the deterioration process of asphalt mixture were calibrated in according with the AE technique. Finally, simulation analysis on the four-point bending fatigue test of asphalt mixture is performed. The results indicated that the AE parameters could reflect the changes of mechanical characteristic. The variation of AE energy and dissipated energy had a similar tendency. There is a strong correlation between the result of continuum damage mechanics model and mechanical test. The numerical results show that the definition of damage variable based on AE energy is reliable and reasonable. This research would provide a new idea for the application of AE technique on diagnosing the fatigue damage evolution process of asphalt mixture.

1. Introduction

Asphalt mixture is one of the most widely used materials in pavement construction. The repeated traffic loads combined with the effects caused by environmental factors could lead to the pavement degradation, which, in the long-term, may cause the fatigue failure of the pavement during their service life. Therefore, exploring the material fatigue performance is an important issue. In depth study of the characteristics and evolution rule of material fatigue damage is the key to improve the pavement service life. The core of this problem is to find a damage factor that can represent the evolution process of damage.

Nowadays, there are plenty of research works reported in the literature about the definition of damage factor. Such as: stiffness modulus, the equivalent strain rate, the number of cycles, dissipative energy, pseudo strain energy density function and so on[1,2]. However, asphalt mixture is a composite material, its failure process is complicated. The above indicators just reflect the change in some macroscopic physical properties. A reasonable method should reflect the local micro-damage and structure degradation process of asphalt materials in real time and dynamic. Acoustic emission testing is a nondestructive detecting technology, and it is able to perceive the failure process of material by transient elastic wave. The waveform of AE signal is collected by the detection device and can be processed and transformed into the various basic acoustic emission parameters. These parameters reflect the activity and development trend of acoustic emission sources during the acoustic emission process. The AE technique has been widely used for the non-destructive evaluation of engineering materials, such as coal, rock and cement concrete. At the same time, the parameters, such as AE energy, ringing counts and AE events, has been utilized to evaluate the damage process of these materials[3,4]. AE technique also can be used to study the performance of asphalt mixture. Now, most of the research about asphalt mixture

focused on the crack initiation and propagation of asphalt mixture in low temperature, and these results revealed that AE technique holds great potential for the low temperature performance of asphalt mixture[5,6]. Thus, using AE technique to describe the asphalt mixture fatigue damage evolution process is an important research work.

The main objective of this paper is to establish the damage factor by AE technique, and explore the fatigue failure characteristics of asphalt mixture. All of these are based on the research of the failure process and corresponding acoustic emission characteristics. The study would give an insight into the asphalt mixture fatigue damage evolution process by using AE technique.

2. Materials and methods

2.1 Bitumen and aggregate
The 70 penetration grade bitumen was used in the investigation. The type of aggregate is limestone. The AC-20 asphalt mixture with a nominal maximum aggregate size of 19mm were prepared for material performance test. Table 1 summarizes the detailed property parameters of the bitumen and aggregates.

Table 1. Properties of bitumen and aggregate

Bitumen			Aggregate		
Density (kg/m^3)	Viscosity at 135℃ $(Pa{\cdot}s)$	Viscosity at 175℃ $(Pa{\cdot}s)$	Particle size (mm)	Apparent relative density (g/cm^3)	Water absorption $(\%)$
			9.5-20	2.715	0.25
1.034	0.405	0.082	4.75-9.5	2.711	0.30
			2.36-4.75	2.710	0.43
			0-2.36	2.716	1.38

2.2 Sample preparation
The asphalt mixture design in the study was designed using the Marshall mixture design method. The void fraction is 4.5%, and other relevant parameters are presented in table 2.

Table 2. Marshall test results at optimal binder content

Properties	Bulk density (kg/m^3)	Theoretical maximum gravity (kg/m^3)	Volume of air void $(\%)$	Voids in mineral aggregate $(\%)$	Voids filled with asphalt $(\%)$	Marshall stability (kN)	Flow value $(0.1mm)$
Test results	2.406	2.520	4.5	13.6	66.8	13.42	37.1

The standard testing sample like a beam with the dimension of 380 mm × 63 mm × 50 mm were cut from the rutting plate with the dimension of 400 mm × 300 mm × 70 mm. In order to guarantee the reliability of test results, four specimens were prepared, according to the requirements of parallel tests in the test specifications.

2.3 Four-point bending fatigue test
In this research, the UTM-30 mechanics testing system was used for the four-point bending (4PB) fatigue test. The 4PB fatigue test, as described in the AASHTO T321-17, were performed under the stress-controlled mode of loading with the stress amplitudes of 5000 kPa at a temperature of 10 ℃. A repeated sinusoidal load was applied at a frequency of 10 Hz without rest periods. According to the specifications, the stiffness at the 50th cycle of loading is considered the initial stiffness (E_0), and the number of load repetitions required to reduce initial stiffness of a specimen to 50% was traditionally used as the fatigue failure point.

2.4 Acoustic emission testing
The Micro-Ⅱ Express digital AE system was used for acquiring sound emissions in asphalt mixture specimens. The AE sensors used were resonator sensors with an operating frequency range of 25-750

kHz and the signals were pre-amplified using a 40dB preamplifier. To further amplify the signals and help AE sensors stick to the specimen, grease was used for gaining good acoustic coupling on the surface of the sensor. Depending on the results of the environmental noise tests, the threshold of 30 dB was adopted, and the mechanical and electrical noises were screened. The sampling rate for the system was set to 1MHz to ensure all sensor output data was being recorded. The time parameter, includes peak definition time (PDT), hit definition time (HDT) and hit lock-out time (HLT), is intimately linked to the specimen size and wave propagation. In consideration of these factors, these time parameters were set to 30μs, 130μs and 300μs, respectively. Once the input parameters were set and the load was applied to the specimen, the waveform of AE signal is collected by the AE system, and several AE parameters were calculated from the waveform. These AE parameters were used for the material performance evaluation.

3. Results and analysis

3.1 Mechanical properties of asphalt mixture

During the test, some mechanical parameters, such as initial flexural stiffness(S_0), cumulative dissipated energy (U_f), stress (σ) and corresponding strain (ε), were recorded and used for the asphalt mixture performance evaluation. Figure 1(a) showed the time history of stress and corresponding strain during the 1st replicate of the 4PB fatigue test. It reflects the process of strain accumulation under the constant stress cyclic loading of 5000kPa. Figure 1 (b) illustrated that the test is terminated after the stiffness modulus of asphalt mixture decreases to 50% of the initial value. It reflects the process of degeneration of the material property.
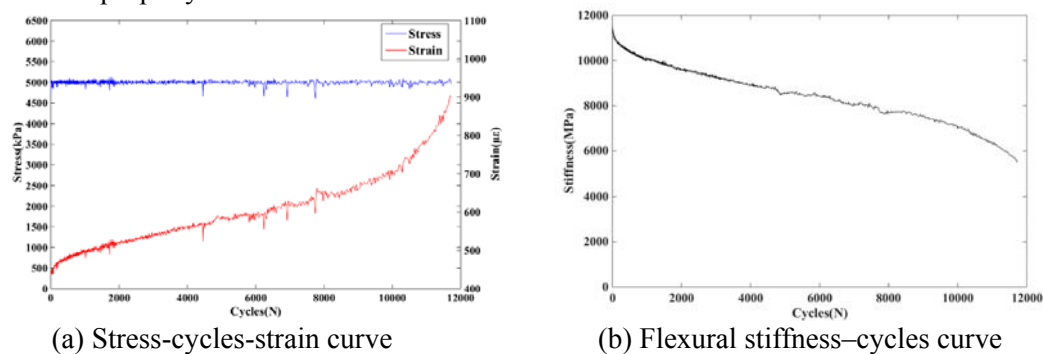

(a) Stress-cycles-strain curve   (b) Flexural stiffness–cycles curve

Figure 1. Evolution curves of mechanical parameter

However, the fatigue damage process of asphalt mixture cannot be well reflected by the attenuation of stiffness modulus alone. It is well known that the energy is represented by the area under the stress-strain curve. If the loading and unloading curves coincide, the energy put into the material is recovered after the load is removed. As shown in figure 2, the strain is not recovered when the load is removed from the material, which means that there is energy lost in the material, energy that was dissipated through mechanical work, heat generation, or damage to the material to its original shape. Hence, the area of an ellipse is the dissipated energy of the material caused by one load cycle[7]. The total dissipated energy is the sum of each loop dissipated energy during the test.
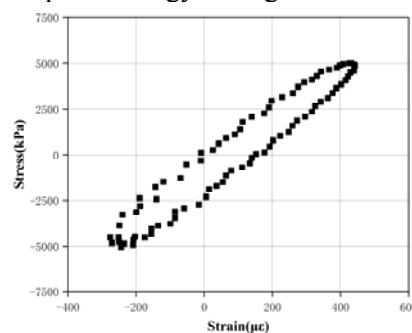

Figure 2. Dissipative energy calculation model

Dissipation energy which based on thermodynamics theory is an important parameter to describe fatigue damage. It gives full expression to the influence of cyclic stress and strain. Hence, many researchers suggest that the damage factor of asphalt mixture can be defined on the basis of dissipation energy, and it can accurately reflect the change of mechanical properties of asphalt mixture. Liu[8] proposed to the definition of damage factor by using the ratio of dissipation energy at a certain time to total dissipation energy, which can be calculated as in equation (1).

$$D_i = \frac{U_i}{U_f} \qquad (1)$$

Where,

D_i —— the cumulative damage value of asphalt mixture after the i th cycle,

U_i —— the cumulative dissipation energy value of asphalt mixture after the i th cycle,

U_f —— the cumulative dissipation energy value of asphalt mixture at the end of test.

3.2 Acoustic emission characteristics of asphalt mixture

The release rapid of local energy in the form of transient elastic wave, generally known as acoustic emission. The process of deformation, crack initiation and expansion of asphalt mixture until the ultimate failure all generates the AE signal. The waveform of AE signal is collected by the detection device and can be processed and transformed into the various basic acoustic emission parameters. Among them, the AE energy and amplitude are always used in damage analysis because it reflects the strength of the signal.
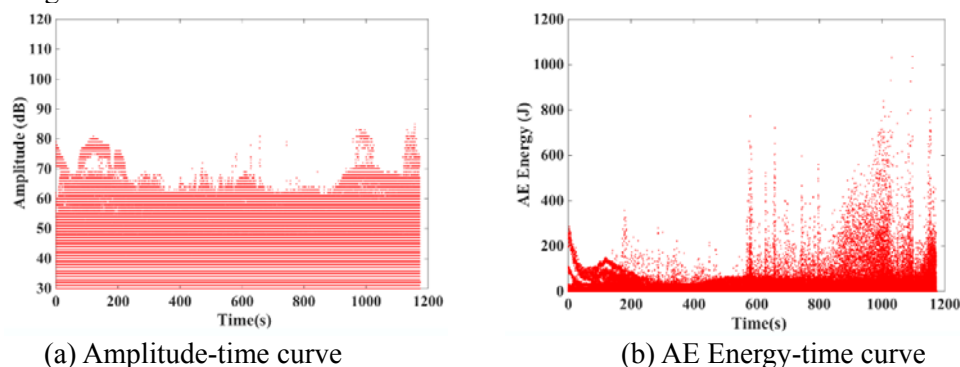

(a) Amplitude-time curve   (b) AE Energy-time curve

Figure 3. Evolution curves of AE parameters over time

The initial cracks or voids within the asphalt mixture will be compacted and closed during the initiation of loading. As shown in figure 3, it is found that the value of AE Energy and Amplitude is high in the initial stage. This corresponds to where the initial deformation has been formed. It indicated that the material caused damage at this stage. In addition to, the state parameter revealed the paroxysmal characteristics at about 600 seconds. That might be because the internal structure of materials is adjusting in this moment. Prior to test termination, peaks in the AE energy parameter predominantly appeared. In the area of 1000 to 1200 seconds, the strain has increased drastically. At this time, the acoustic emission energy can reach the peak value of 1036 J, and the corresponding signal amplitude exceeds 85 dB. It means that the material has been badly damaged. Based on the foregoing, there is no denying that the variation of AE parameter is linked closely with material mechanical behavior.

3.3 Relationship Between Dissipative Energy and Acoustic Emission Energy

It is also known that the release of strain energy produced the AE signal. The AE energy reflects the strength of the signal. At the same time, dissipated energy is also a form of strain energy, and is linked closely with material damages. Thus, it is not difficult to find that there is a relationship between AE energy and dissipative energy, and the AE energy is closely related to damage. In fact, the variation of cumulative AE energy and cumulative dissipated energy had a similar tendency, as shown in figure 4.
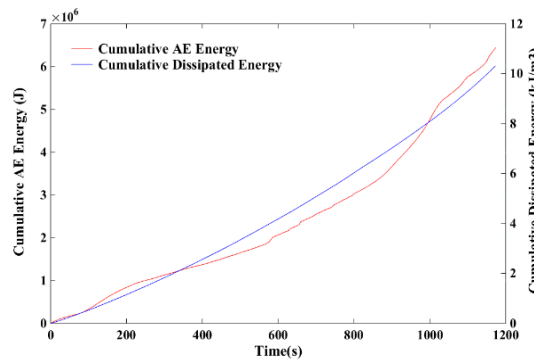
Figure 4. Evolution curve of AE energy and dissipated energy over time

The results showed that the energy of an acoustic emission signal is proportional to the dissipative energy associated with the damage. Therefore, the equation (2) which reflected the linear relationship between cumulative AE energy and cumulative dissipated energy was proposed.

$$W = 1744 \times U \tag{2}$$

Where,

W —— the cumulative AE energy,

U —— the cumulative dissipation energy.

Using equation (1) and (2), the damage factor D of asphalt mixture can be calculated from AE energy through equation (3).

$$D = \frac{W(\varepsilon)}{W_m} \tag{3}$$

Where,

$W(\varepsilon)$ —— the cumulative AE energy in a certain amount of strain,

W_m —— the cumulative AE energy for a specimen that is failure.

3.4 Damage evolution properties

As for cyclic loading tests, damages happen all the time. The damage constitutive laws which is based on the definition of the effective stress concept is established as in equation (4).

$$\sigma = (1 - D)E\varepsilon \tag{4}$$

Where,

σ —— the nominal stress,

D —— the damage factor,

E —— the elastic stiffness of the undamaged material,

ε —— the total strain.

There are many methods of the definition of damage factor. Among them, the continuum damage mechanics (CDM) is a combination of the internal state variable theory and the thermodynamics of irreversible processes. This approach is appealing because it has the intrinsic simplicity and versatility, as well as its consistency. The Weibull distribution is an important method in the CDM. The rate of evolution of a scalar damage factor D is given by the Weibull distribution function as in equation (5).

$$\frac{dD}{d\varepsilon} = f(\varepsilon) \tag{5}$$

Where f (ε) is the Weibull distribution function given by the function as in equation (6).

$$f(\varepsilon) = \frac{\alpha}{\beta} \frac{(\varepsilon - \varepsilon_0)^\alpha}{\beta} \exp\left[-\frac{(\varepsilon - \varepsilon_0)^\alpha}{\beta} \right] \tag{6}$$

Where,

α and β —— the parameters related to material size and deformation characteristics,

ε_0 —— the initial strain, which is obtained through test.

By integrating equation (5), the expression of damage factor can be obtained as in equation (7).

$$D = 1 - \exp\left[-\frac{(\varepsilon - \varepsilon_0)^{\alpha}}{\beta}\right] \tag{7}$$

The parameters (α and β) of the Weibull distribution function were usually estimated by the constitutive laws. However, the damage factor with AE energy provides another alternative. It can be used to calibrate the parameters in the Weibull distribution function. By fitting test data, the fitted value for α and β are 1.45 and 5630, respectively. The correlative degree between test result and Weibull distribution function is 0.94, as shown in figure 5. It presents that Weibull distribution function is only consistent with the front part of the 1st replicate test. This is due to the definition of fatigue failure criterion.
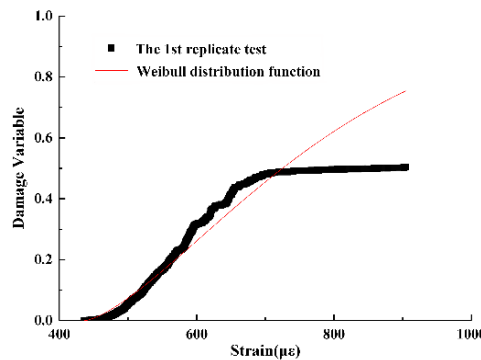

Figure 5. Fitting curve of damage factor with AE parameters

There is a strong correlation between the result of continuum damage mechanics model and mechanical test. It means that the damage factor based on AE energy is reliable and reasonable. Thus, a damage factor equation was applied to describe the asphalt mixture damage with AE energy, which can be calculated as in equation (8). Because of the definition of fatigue failure criterion, damage factor has an upper limit of 0.5, and so it has been corrected by a constant.

$$D = \frac{W(\varepsilon)}{2 \times W_m} = 1 - \exp\left[-\frac{(\varepsilon - \varepsilon_0)^{1.45}}{5630}\right] \tag{8}$$

3.5 Finite element analysis

The FE simulation reproduces the boundary conditions that the specimen is subjected to in the 4PB device. As mentioned previously, the beam was loaded with a sine waveform, and other conditions were set in accordance with test. In addition, 12000 MPa and 0.4 are the material properties of Young's Modulus and Poisson's ratio respectively. The mesh used is based on a regular three-dimensional square grid with elements of 5 mm.

A user defined material subroutine (UMAT) was developed to calculate the bending responses with a commercial finite element software ABAQUS 6.14. In particular, the modulus of material for every cycle had to be redefined. At the end of each step, the maximum strain would be used to calculate the damage factor based on the Weibull's function model, and the modulus would have been corrected. Figure 6 showed the curves from experiments and FEM computation. It was found that the experimental results are consistent with the finite element results. The mechanical properties of the asphalt mixture decreased with the rise of the strain levels. The numerical computational method provides a reference for the research of fatigue damage in asphalt mixture.
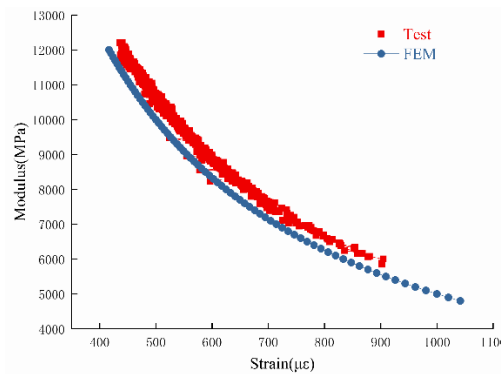
Figure 6. Comparison of test curve with FEM simulation curve

4. Conclusions
The findings and conclusions are as follows:

(1) The variation of AE parameter is linked closely with material mechanical behavior. AE energy as an important parameter can be utilized to evaluate the fatigue failure characteristics of asphalt mixture.

(2) Based on the AE technique, a novel calibration method to determine the CDM model parameters is proposed.

(3) An effective numerical computational method is developed to explore the evolutional law of damage in asphalt mixture.

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