

Article

Fracture Damage Properties of SBS-Modified Asphalt Mixtures Reinforced with Basalt Fiber after Freeze-Thaw Cycles Using the Acoustic Emission Approach

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Abstract: This paper focuses on the fracture damage characteristics of styrene-butadiene-styrene (SBS)-modified SMA-13 specimens with basalt fiber under various freeze-thaw (F-T) cycles. SBS-modified stone mastic asphalt (SMA)-13 specimens with basalt fiber were prepared, first, using the superpave gyratory compaction method. Then, asphalt mixture specimens processed with 0–21 F-T cycles were adopted for the high-temperature compression and low-temperature splitting tests. Meanwhile, the acoustic emission (AE) test was conducted to evaluate the fracture characteristics of the asphalt mixture during loading. The results showed that the AE parameters could effectively reflect the damage fracture characteristics of the asphalt mixture specimen during the high-temperature compression and low-temperature splitting processes. The fracture damage of the asphalt mixture specimens during compression or splitting are classified into three stages based on the variation of the AE signals, i.e., when the load level is below 0.1–0.2 during the first stage and the load level is 0.1–0.9 or 0.2–0.8 during the second stage. The AE signal amplitude and count show clear correlations with the compression and splitting load levels. Meanwhile, the AE signal clarifies the formation, development, and failure of internal damage for the asphalt mixture specimens during the compression and splitting processes. The intensity (value and density) of the AE signal parameters of asphalt mixture decreases with increasing F-T cycles. It is evident that the F-T cycle has a significant adverse effect on the mechanical strength of asphalt mixture, which makes asphalt mixtures more likely to cause early failure.

Keywords: asphalt mixture; basalt fiber; fracture characterization; acoustic emission; freeze-thaw

1. Introduction

Asphalt pavement has been widely used in the construction of high-grade highways due to its advantages such as good driving performance, high comfort, low noise, and convenient construction and maintenance [1,2]. During the long-term service process of asphalt pavement, complex and diverse service environments, as well as increasing traffic and load, have lead to more and more pavement diseases, which cause damage and greatly shortening the service life [3,4]. Especially in northern China and other seasonal frozen areas, due to severe climate changes and traffic load, asphalt pavement is severely damaged and shows accelerated damage [5–7].

Basalt fiber is produced from natural basalt material after melting at a high temperature. It is generally brown with a metallic luster. Basalt fiber, which is a new type of environment-friendly and high-performance inorganic fiber material, has the advantages of high strength, low water absorption, acid and alkali resistance, high temperature resistance, and environmental protection [8–11].

Researchers have carried out many related experimental studies on basalt fiber-modified asphalt mixtures. Moreover, basalt fibers have been gradually used in asphalt pavements to replace polyester fibers and lignin fibers. It is also evident that its strong affinity improves the road performance of asphalt pavements and effectively improves the durability of asphalt mixtures [12–14].

Asphalt pavements, in seasonal frozen areas, are in a condition of repeated freeze-thaw (F-T) cycles for a long time, and therefore continuously accumulate internal damage due to the coupling effects of moisture and temperature, which results in F-T damage. Researchers have also conducted many studies on F-T damage of bituminous mixtures and discussed the F-T damage characteristics through comparing various F-T cycles [15,16]. Huang et al. [17] discussed the influences of F-T cycles of AC and SMA asphalt mixtures and investigated the three-dimensional failure criterion of asphalt mixtures during the F-T cycle through triaxial tests. The results showed that SMA had better F-T resistance. Cheng et al. [18] improved the use of diatomite and basalt fibers in asphalt mixture for a seasonal frozen area and analyzed the influences of F-T cycles on its strength and strain energy through indirect tensile tests. Gong et al. [19] selected nanomaterials to improve the F-T resistance of bituminous mixtures and established a gray prediction model based on volume parameters and mechanical properties to investigate the F-T resistance of modified asphalt mixtures. You et al. [20] used an interfacial bond strength test to evaluate the impact of durability of bituminous mixture under the condition of repeated F-T cycles, and fully considered the change in the bonding performance between aggregates and asphalt during the period of F-T cycles. Lachance et al. [21] investigated the viscoelastic characteristics of modified bituminous mixtures under various F-T cycles and explored the effects of aggregates on their viscoelastic properties based on complex modulus tests. Hong et al. [22] tested the dynamic modulus and mass loss of asphalt pavement in the cold region, evaluated the strain-stress behavior of the test piece, and analyzed its F-T durability. Kavussi et al. [23] used rubber particles to modify asphalt mixture. On the basis of the response surface method, the influence of F-T cycles on water stability and fatigue performance was evaluated. This study considered that rubber particles were more effective for improving the fatigue resistance of asphalt mixture.

Acoustic emission (AE) technology is a phenomenon in which a material or structure releases strain energy in the form of elastic waves [24,25]. When damage occurs inside the material or structure, especially during the mechanical loading of the material or structure, it is often accompanied by the generation of local elastic waves [26,27]. This can be used as a means for structural health detection, detecting damage such as cracks, monitoring or positioning the damage of materials or structures, and characterizing their damage [28,29]. Jiao et al. [28,29] utilized the acoustic emission approach to investigate the damage fracture characteristics of porous asphalt mixture or pervious asphalt with different additives under the compression or splitting loading, respectively. Sun et al. [30] studied the application of rejuvenators in aged asphalt mixtures and evaluated their low-temperature performance by using acoustic emission. Qiu et al. [31] used three-point bending tests and AE tests to study the continuous damage evolution characteristics of asphalt mixtures. The dynamical damage evolution was evaluated based on the wavelet transform and fractal theory. Hill et al. [32] studied the warm mix asphalt prepared by using reclaimed asphalt pavement instead of aggregates and evaluated the high-temperature rutting, low-temperature cracking resistance, and moisture stability of asphalt mixtures with four additives combining acoustic emission test.

Therefore, based on the above research, the following studies were conducted and described in this paper: First, styrene-butadiene-styrene (SBS)-modified SMA-13 specimens with basalt fiber were prepared. Then, a high-temperature compression test and a low-temperature splitting test were conducted. At the same time, the fracture characteristics under compression and splitting loadings were studied using the AE test. Meanwhile, the AE signal parameters including amplitude and count were recorded and analyzed to evaluate the fracture damage under various F-T cycles. The purpose was to correlate the fracture damage with AE signal and study the effect of F-T cycles on SBS-modified asphalt mixture specimens with basalt fiber through a high-temperature compression

test and low-temperature splitting test, and to study the fracture damage for the seasonal frozen area, which is affected by seasonality, i.e., freezing in winter and melting in summer.

2. Experimental Materials and Methods

2.1. Experimental Materials

The asphalt used, in this study, was SBS-modified asphalt, which was produced by Zhonghai Asphalt Co., Ltd. (Yingkou, China). The coarse and fine aggregates were crushed basalt, produced from Jiutai City, Jilin Province. The filler used was limestone powder, which was from Siping City, Jilin Province. In addition, eco-friendly basalt fiber was used to reinforce the asphalt mixture. The technical properties of all the above materials are listed in Tables 1–4, which meet the requirement of the specifications JTG F40-2004 [33].

Table 1. Technical properties of styrene-butadiene-styrene (SBS)-modified asphalt.

Test Items	Unit	Standards	Requirements	Values
Penetration	0.1 mm (@ 25 °C, 100 g, 5 s)	T0604	60~80	71
Ductility	cm (@ 15 °C, 5 cm/min)	T0605	≥30	45
Softening point	°C	T0606	≥55	60.5
Density	g/cm ³	T0603	—	1.018
Flash point	°C	T0611	≥230	262
RTFOT				
Mass loss	%	T0609	±1.0	−0.094
Penetration ratio	% (@ 25 °C)	T0609	≥60	66.9

Table 2. Technical properties of basalt coarse aggregates.

Test Items	Unit	Standards	Requirements	Values
Crushing value	%	T0316	≤26	13.6
Los Angeles abrasion value	%	T0317	≤28	17.9
Apparent specific gravity	13.2 mm 9.5 mm	T0304	≥2.6	2.836
	4.75 mm			2.805
	13.2 mm	T0304	≤2.0	2.726
Water absorption	9.5 mm			0.6
	4.75 mm			0.28
Soundness	%	T0314	≤12	0.7
Elongated particle content	%	T0312	≤15	5
Passing 0.075 mm sieve	%	T0310	≤1	9.2
				0.3

Table 3. Technical properties of basalt fine aggregates.

Test Items	Unit	Standards	Requirements	Values
Apparent specific gravity	—	T0328	≥2.5	2.723
Water absorption	%	T0304	—	0.64
Angularity (flow time)	s	T0345	≥30	39.9
Sand equivalent	%	T0334	≥60	68

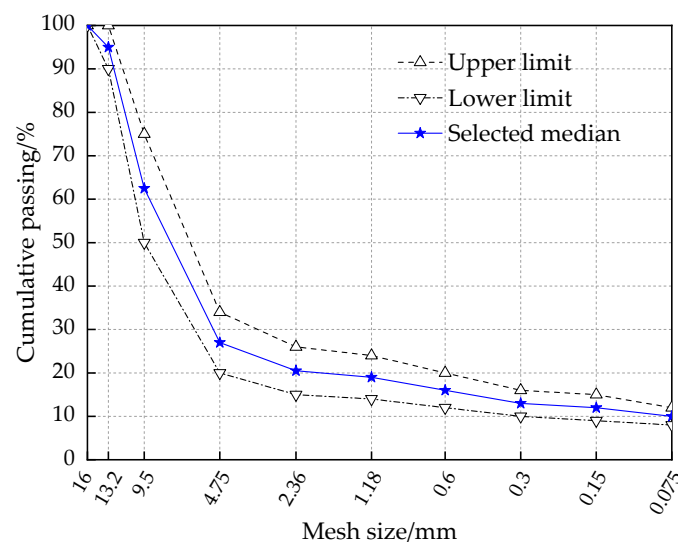
Table 4. Technical properties of limestone mineral filler.

Test Items	Unit	Standards	Requirements	Values
Apparent density	t/m ³	T0352	≥2.5	2.712
Hydrophilic coefficient	—	T0353	<1	0.63
Water content	%	T0103	≤1	0.3
Plastic index	%	T0354	<4	2
Granular composition	<0.6 mm	T0351	100	100
	<0.15 mm		90~100	92.5
	<0.075 mm		75~100	81.8

2.2. Experimental Methods

2.2.1. Specimen Preparations

Stone mastic asphalt (SMA) is a commonly used asphalt mixture type in China, and SMA is extensively adopted for highways. Following the Chinese specification JTG E20-2011 [34], the median gradation of SMA-13 was selected, in this study. The corresponding gradation curve is plotted in Figure 1. The SMA-13 specimens were designed and prepared using the superpave gyratory compaction (SGC) method, and the detailed procedure can be investigated in the previous study [35]. The bitumen percentage was 5.7% by weight of aggregates and the basalt fiber content was 0.34% by mass of SBS-modified asphalt. For the SGC parameters, the number of gyrations was set as 100 under the pressure of 600 kPa and gyration angle of 1.25°. In this study, the procedure of the SMA-13 specimen by the SGC method is shown in Figure 2, which generally consisted of three basic steps.

**Figure 1.** Gradation of stone mastic asphalt (SMA)-13.**Figure 2.** Preparation procedure of AC-13 by the superpave gyratory compaction (SGC) method.

2.2.2. Experimental Procedure for Fracture Properties of Asphalt Mixtures

First, the asphalt mixture specimens were processed by 0, 3, 6, 9, 12, 15, 18, and 21 F-T cycles according to the previous studies [6,7,15,16]. Before the F-T cycle processing, the specimens were sealed separately with a plastic bag, and then 15 mL of water was poured into each of the bags. Then, the test specimens were immediately put into the refrigerator. Each F-T cycle included freezing the test specimens in an $-18\text{ }^{\circ}\text{C}$ refrigerator for 16 h, and then thawing them in $25\text{ }^{\circ}\text{C}$ water for 8 h.

The uniaxial compression test is a commonly used experimental method for determining the compressive strength of bituminous mixtures, while the low temperature cracking test is a common and simple test method for assessing the crack resistance of bituminous mixtures at low temperatures. For the purpose of further investigating the influence of the F-T cycles on the damage of the SMA-13 asphalt mixture specimens, the AE technology was also used during the high-temperature uniaxial compression and low-temperature splitting tests. For the AE test, a few AE parameters were measured from the AE signals. On the basis of these parameters, the AE signal characteristics of the SBS-modified asphalt mixtures that were reinforced with basalt fiber tested during the compression or splitting test were used to characterize their damage mechanisms.

(1) High-Temperature Uniaxial Compression Test

In this paper, an electro-hydraulic servo pressure material testing machine (Jinli Test Technology Co., Ltd., China) was selected to perform the uniaxial compression test at $50\text{ }^{\circ}\text{C}$ for basalt fiber-modified asphalt mixtures subjected to F-T cycles. Figure 3 illustrates the scene of the uniaxial compression test combined with the AE test. The testing system included a loading control system, a data acquisition and processing system, an environmental chamber, and so on. The AE system with six channels consisted of one AE sensor attached on the asphalt mixture specimen with a kind of sound-transmitting coupling agent, preamplifier, as well as an acquisition and data analysis system. For the purpose of obtaining the stress–strain relationship curve of the asphalt mixture specimens, the displacement control during compression was used for loading at a constant strain rate. Before the tests, asphalt mixture specimens were kept in an environmental chamber at $50 \pm 0.5\text{ }^{\circ}\text{C}$ for more than 4 h to ensure uniform temperature distribution inside the specimens, and the test loading rate was set to 1 mm/min. Following the specification JTG E20-2011 [34], the compressive strength, failure strain, and compression failure stiffness modulus were calculated using the following equations, respectively.

$$R_c = 4P_c/\pi d^2, \quad (1)$$

$$\varepsilon_c = \Delta l/l, \quad (2)$$

$$S_c = R_c/\varepsilon_c, \quad (3)$$

where R_c is the compressive strength, P_c is the maximum force of the compression test, d is the diameter of the asphalt mixture specimen, Δl is the deformation in the compressive test, ε_c is the compressive failure strain, and S_c is the compression failure stiffness modulus.

(2) Low-Temperature Splitting Test

In this paper, an electro-hydraulic servo pressure material testing machine produced by the Jinli Test Technology Co., Ltd. was also selected to perform the low-temperature splitting test at $-10\text{ }^{\circ}\text{C}$ for the basalt fiber-modified asphalt mixtures subjected to repeated F-T cycles. Figure 4 shows the scene of the low-temperature splitting test combined with the AE test. Before the tests, the asphalt mixture specimens were kept in the environmental chamber at $-10 \pm 0.5\text{ }^{\circ}\text{C}$ for at least 6 h to ensure uniform temperature distribution inside the specimens. The displacement control was used for loading at a constant strain rate and the test loading rate was also set to 1 mm/min. Following the specification JTG

E20-2011 [34], the splitting strength, failure strain, and failure stiffness modulus were calculated using the following equations:

$$R_T = 0.006287P_T/h, \quad (4)$$

$$\varepsilon_T = X_T \times (0.0307 + 0.093\mu)/(1.35 + 5\mu), \quad (5)$$

$$S_T = P_T \times (0.27 + 1.0\mu)/(h \times X_T), \quad (6)$$

where R_T is the splitting strength, P_T is the maximum force of the splitting test, h is the height of the asphalt mixture specimen, μ is the Poisson ratio, $\mu = 0.25$ when the test temperature is below 10 °C according to the specification JTG E20-2011 [34], X_T is the deformation in the horizontal direction, ε_T is the splitting failure strain, and S_T is the compression failure stiffness modulus.

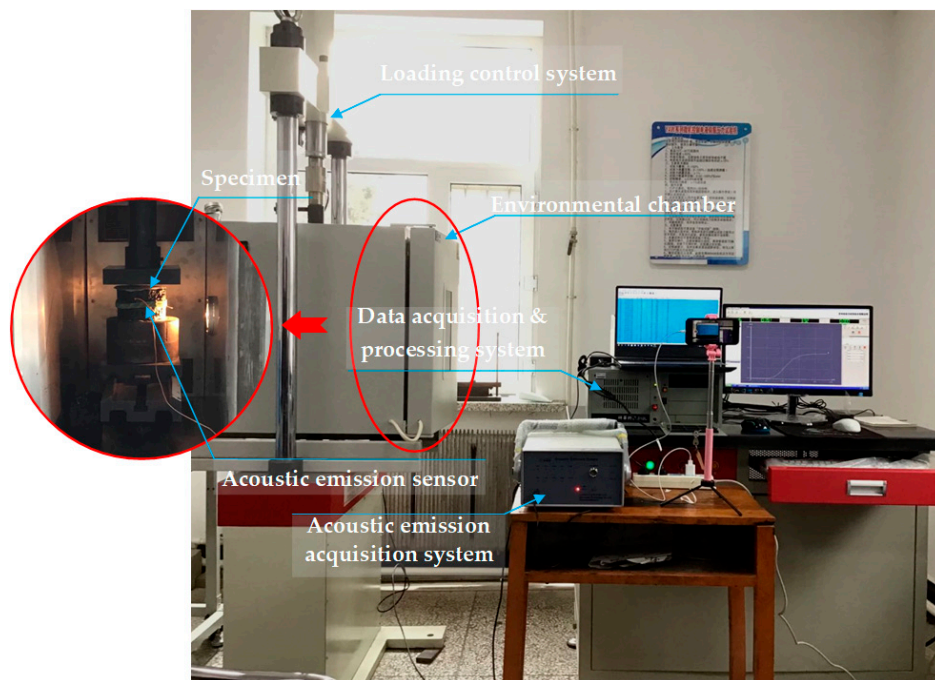


Figure 3. High-temperature uniaxial compression test used in this study.

(3) Acoustic Emission (AE) Technology

Acoustic emission (AE) technology is a phenomenon in which a material or structure releases strain energy in the form of elastic waves. When damage occurs inside the material or structure, especially during the mechanical loading of the material or structure, it is often accompanied by the generation of local elastic waves. This can be used as a means for structural health detection, detecting damage such as cracks, monitoring or positioning the damage of materials or structures, and characterizing their damage [28,29].

The commonly used AE parameters are signal amplitude, count, duration, energy, rise time, and so on. The characteristic parameters of AE signals are shown in Figure 5. According to previous studies, signal amplitude and count can effectively characterize the fracture performance of bituminous mixtures [28,29]. In this study, the AE signal amplitude and count parameters were also selected to characterize the fracture damage characteristics of basalt fiber-modified asphalt mixture under various F-T cycles. As can be seen from Figure 5, the signal amplitude represents the maximum volt of the AE signal, and the signal count is the cumulative number of times that the AE signal strength is greater than the threshold point. Then, these two parameters (i.e., amplitude and count) can usually reflect the signal strength during the AE test.

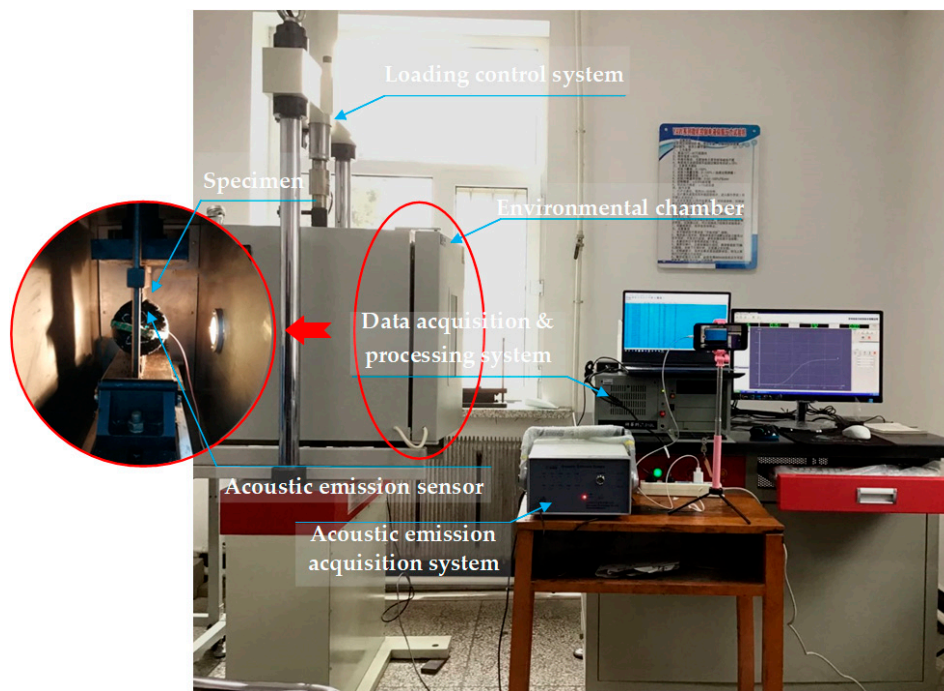


Figure 4. Low-temperature splitting test used in this study.

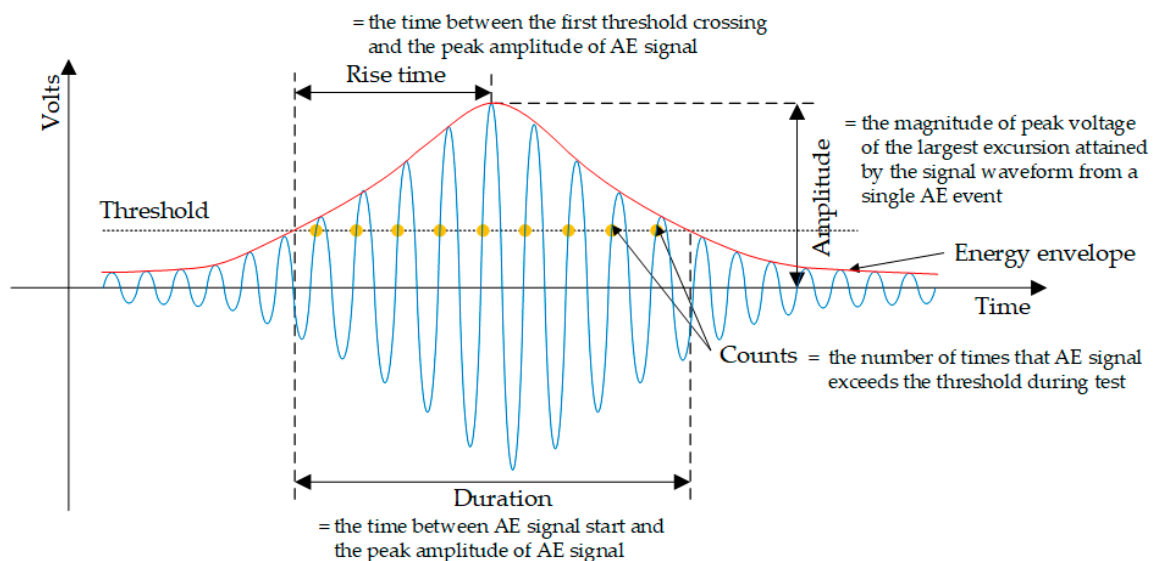


Figure 5. Acoustic emission (AE) signal and parameters.

3. Results and Discussion

3.1. Compression Fracture Characterization Analysis of SBS-Modified Asphalt Mixtures with Basalt Fiber under Various F-T Cycles

In seasonal frozen areas, there are many factors influencing the performances of asphalt pavement, such as traffic loading, temperature, and so on. For each F-T cycle group, two replicate SGC asphalt mixture specimens were prepared and processed for 0–21 F-T cycles. In order to characterize the high-temperature performance of the asphalt mixture, the mean values of the uniaxial compression test, as a commonly used test method, were used for the determination of the compressive strength of the asphalt mixtures under various F-T cycles. At the same time, the AE technology, as a damage detection technology, was applied to the fracture of asphalt mixtures.

3.1.1. Signal Amplitude

For the purpose of analyzing the effects of F-T cycles on the compression fracture damage, the relationships between signal amplitude and load level versus time during compression were obtained for the SBS-modified asphalt mixtures with basalt fiber under various F-T cycles. The load level was determined by the ratio of applied load and failure load. As shown in Figure 6a, the entire loading process and the AE signal amplitude can be divided into three stages by combining the intensity of the AE signal amplitude and the load level. At the first stage, the lower AE signal amplitude values, ranging from 40 to 50 dB, were generated and recorded during compression loading, while the load level was below 0.1. The lower AE signal amplitude values in the first stage, were considered to be the signal due to the mechanical noise during loading. Then, several microcracks were preliminarily formed under compression loading during the first stage. After entering the second stage, a significant increase of the AE signal amplitude began to appear, ranging from 50 to 70 dB when the load level was between 0.1 and 0.9. The AE signal amplitude values increased with increasing load levels. The increasing AE signal amplitude implies that cracks were formed at this stage and the cracks also developed into stable crack growth. As the compression loading continued, the AE signal reached the third stage. During this stage, the highest value of the AE signal amplitude occurred, which means that the cracks in the asphalt mixture specimen developed rapidly. Meanwhile, the AE signal amplitude showed a trend of slow decline after reaching the maximum value as the compression loading continued. This is because macroscopic cracks occurred when the damage accumulated to a certain degree, and eventually the asphalt mixture specimen was destroyed.

Generally, the AE signal amplitude and load level have similar changes under various F-T cycles. However, by comparing the AE signal amplitudes of various repeated F-T cycles, it is clearly seen that the density of the AE signal amplitude gradually became slightly smaller. At the same time, the loading time is shortened to a certain degree with increasing F-T cycles. The first stage was gradually shortened, and the third stage was gradually increased. The occurrence of the second stage gradually moved forward. This change means that the asphalt mixtures processed with more F-T cycles began to have preliminary damage at lower load levels. Thus, it is evident that the F-T cycle has an obvious adverse influence on the compression strength of SBS-modified asphalt mixture with basalt fiber, which makes asphalt mixtures more likely to cause early failure under a compression load.

3.1.2. Signal Count

For the purpose of analyzing the effects of F-T cycles on the compression fracture damage, the evolutions between signal count and load level versus time during compression were obtained for the SBS-modified asphalt mixtures with basalt fiber under various F-T cycles. As shown in Figure 7a, the entire loading process and AE signal count can be divided into three stages by combining the intensity of the AE signal count and the load level. At the first stage, during the compression loading with load level below 0.1, there were almost no AE signal counts generated except several AE counts due to the mechanical noise while loading. After entering the second stage, the AE signal started to come alive. A significant increase in the AE signal count began to appear when the load level was between 0.1 and 0.9. The AE signal count values increased as the load level increased. The increasing AE signal count implies that cracks occurred gradually and preliminarily formed at this stage, then, cracks also developed into stable crack growth under continuous compression loading. As the compression loading continued, the AE signal reached the third stage. During this stage, the highest value of the AE signal count occurred, which means that the cracks in the asphalt mixture specimen developed rapidly. The AE signal count increased significantly, which means obvious cracks appeared inside the specimen, eventually losing resistance and causing damage.

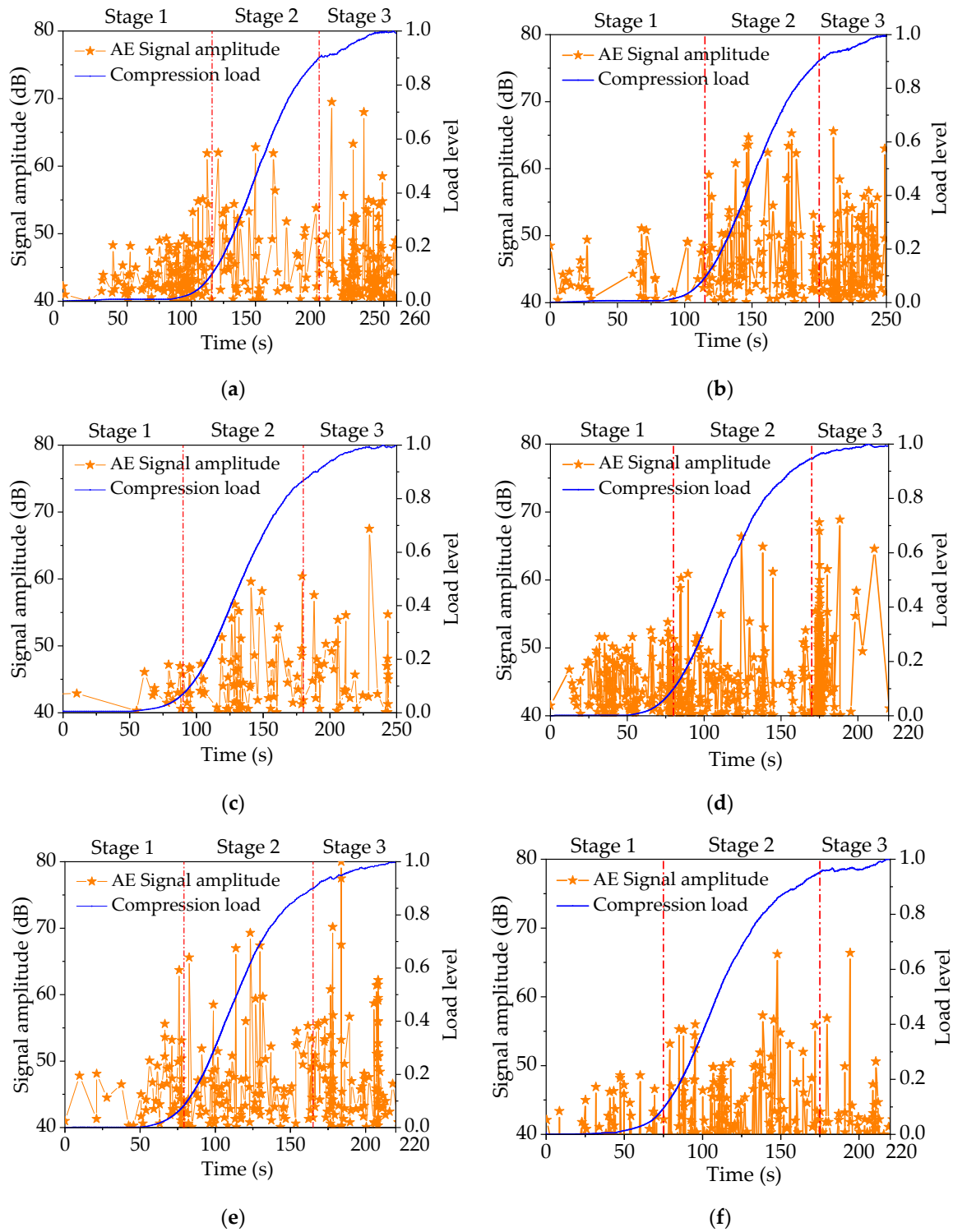


Figure 6. Cont.

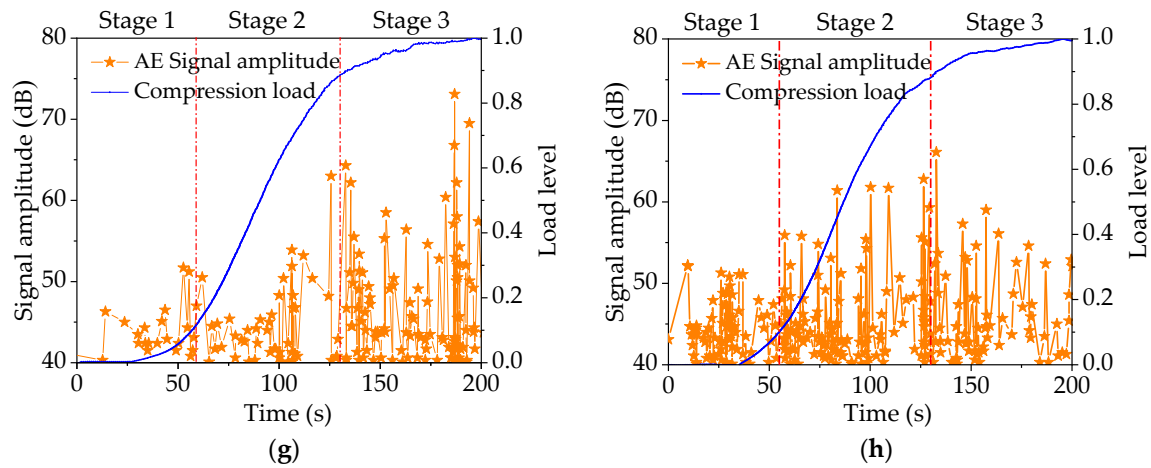


Figure 6. The AE amplitude and load level versus time during compression at 50 °C for SBS-modified asphalt mixture with basalt fiber under various freeze-thaw (F-T) cycles. (a) 0 F-T cycle; (b) 3 F-T cycles; (c) 6 F-T cycles; (d) 9 F-T cycles; (e) 12 F-T cycles; (f) 15 F-T cycles; (g) 18 F-T cycles; and (h) 21 F-T cycles.

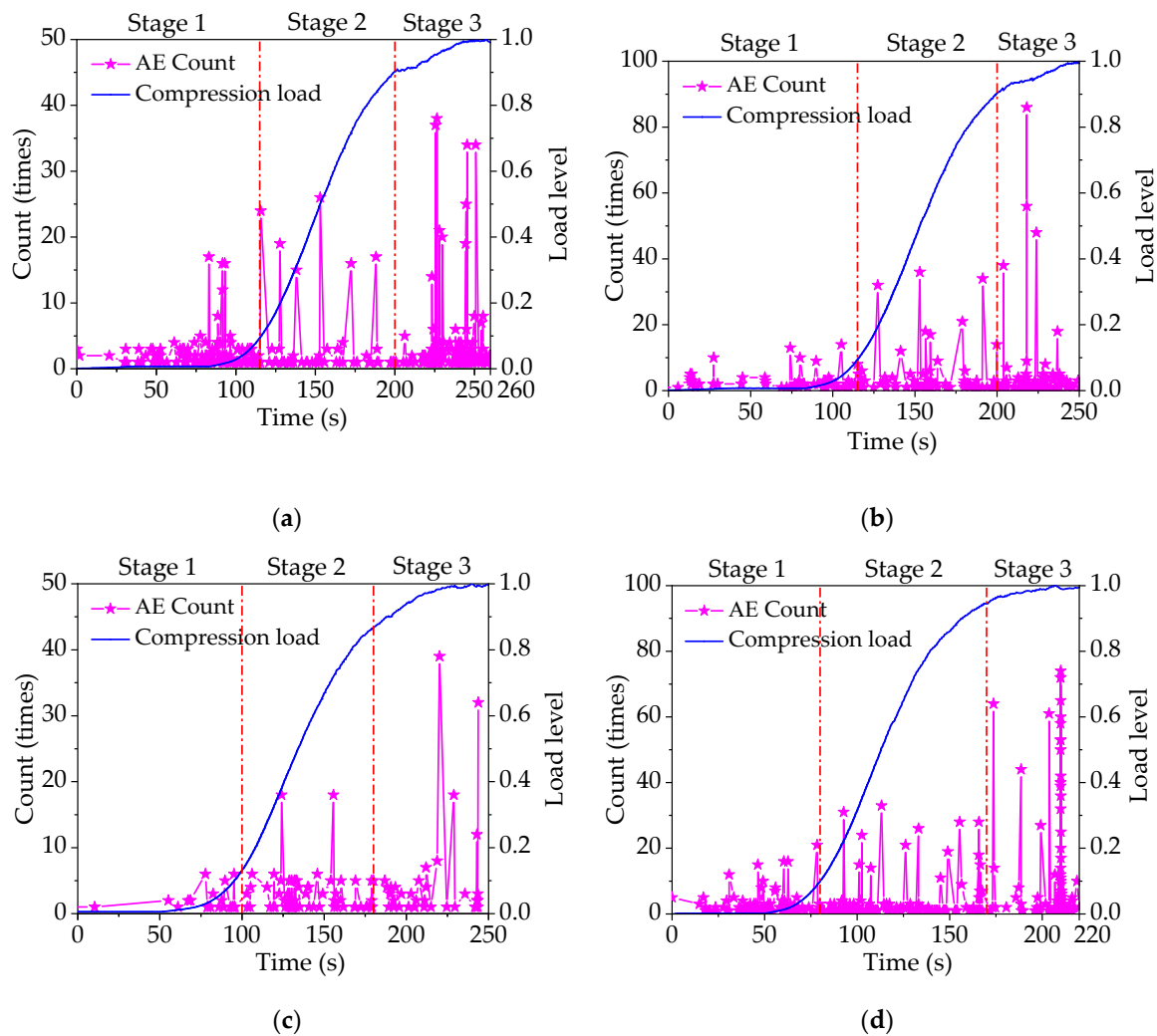


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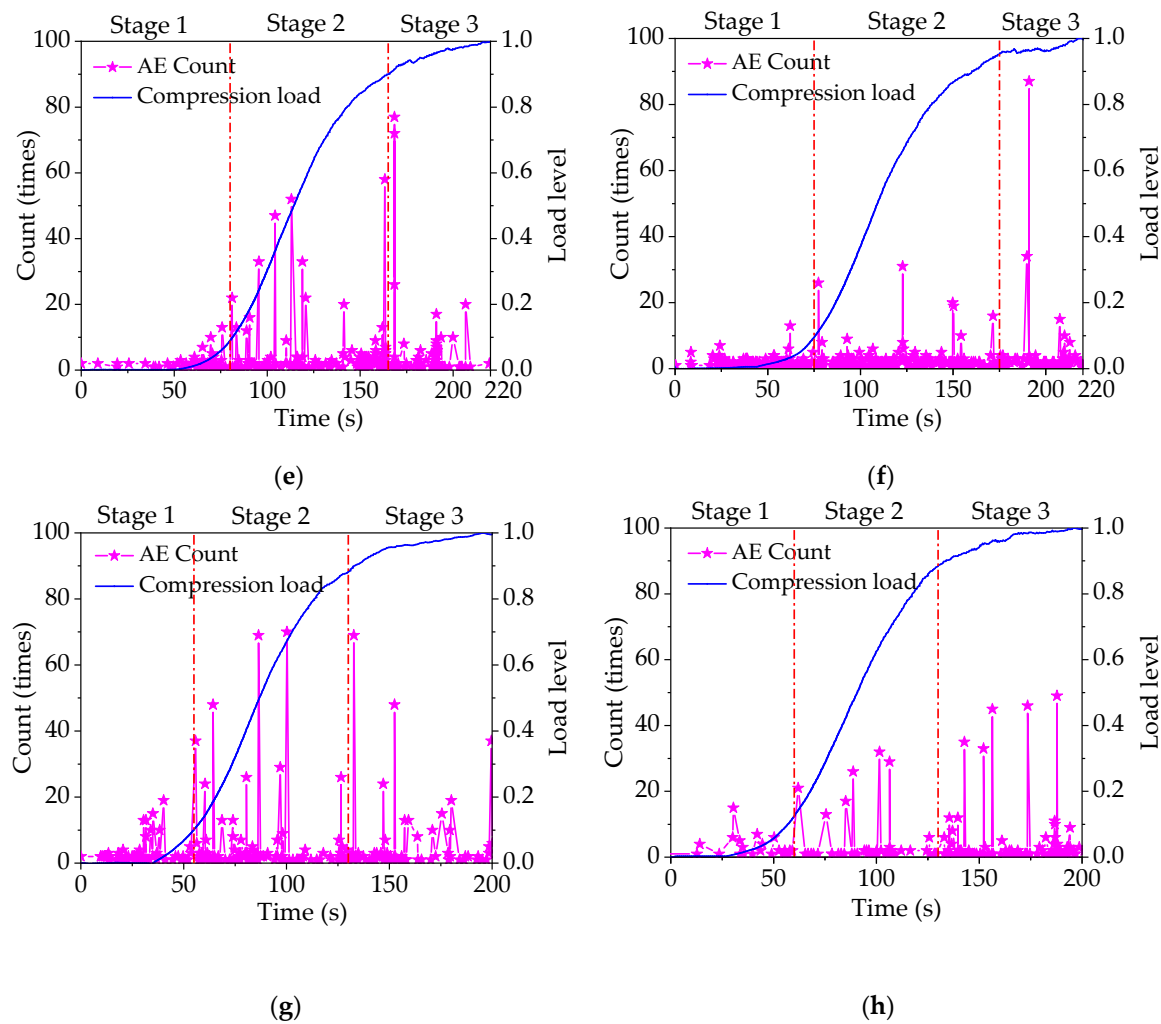


Figure 7. The AE count and load level versus time during compression at 50 °C for SBS-modified asphalt mixture with basalt fiber under various F-T cycles. (a) 0 F-T cycle; (b) 3 F-T cycles; (c) 6 F-T cycles; (d) 9 F-T cycles; (e) 12 F-T cycles; (f) 15 F-T cycles; (g) 18 F-T cycles; and (h) 21 F-T cycles.

As for the influences of F-T cycles on the AE signal count of the asphalt mixtures under splitting loading, the variations of the AE signal count and load level showed similar trends for different F-T cycles. However, by comparing the AE signal counts of different F-T cycles, it can be seen that the density of the AE signal count gradually became slightly smaller, and at the same time, the loading time was shortened to a certain degree with increasing F-T cycles. The first stage was gradually shortened, and the third stage was gradually increased. The occurrence of the second stage gradually moved forward. The F-T cycle processing accelerated the damage of the asphalt mixture specimen, i.e., the F-T cycle had a visible adverse influence on the compression strength of SBS-modified asphalt mixture with basalt fiber.

3.2. Splitting Fracture Characterization Analysis of SBS-Modified Asphalt Mixtures with Basalt Fiber under Various F-T Cycles

In order to characterize the low-temperature performance of asphalt mixture, the splitting test was adopted for the evaluation of the splitting strength of asphalt mixtures under various F-T cycles. A series of SGC asphalt mixture specimens were prepared and processed for 0–21 F-T cycles. At the same time, the AE technology, as a damage detection technology, was also applied to the fracture of asphalt mixtures.

3.2.1. Signal Amplitude

Similarly, for the purpose of analyzing the influences of F-T cycles on the splitting fracture damage, the variation between signal amplitude and load level versus time during splitting were obtained for the SBS-modified asphalt mixtures with basalt fiber under various F-T cycles. As shown in Figure 8a, the entire loading process and AE signal amplitude can be divided into three stages according to the combination of the intensity of the AE signal amplitude and the load level. During the first stage, the lower AE signal amplitude values distributed at about 40 dB with fewer signals were generated and recorded during the splitting loading, while the load level was below 0.2. During the initial stage under the splitting loading, several initial internal microcracks were preliminarily formed. During the second stage, the load level was between 0.2 and 0.8, a significant increase in the AE signal amplitude began to appear and the values were larger than those at the first stage. The abrupt changes of the AE signal amplitude indicates that the internal damage of the asphalt mixture formed rapidly, and the microcracks developed and expanded during this stage. As the splitting loading continued, the AE signal reached the third stage. The AE signal amplitude values gradually became gentle at the third stage. The AE signal amplitude values reached the maximum value and slowly declined. This is because macroscopic cracks occurred when the damage accumulated to a certain degree, and eventually the asphalt mixture specimen was destroyed.

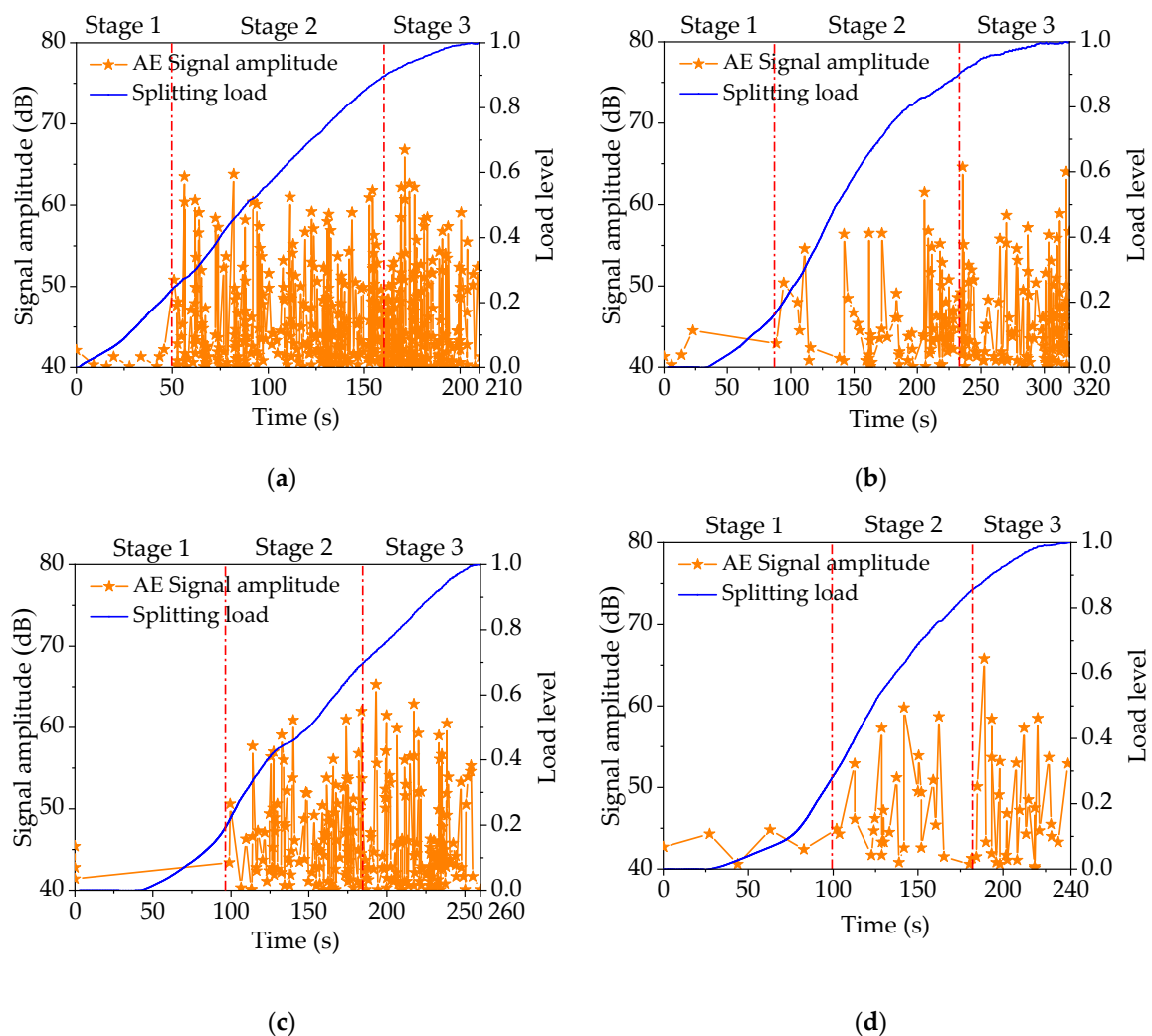


Figure 8. Cont.

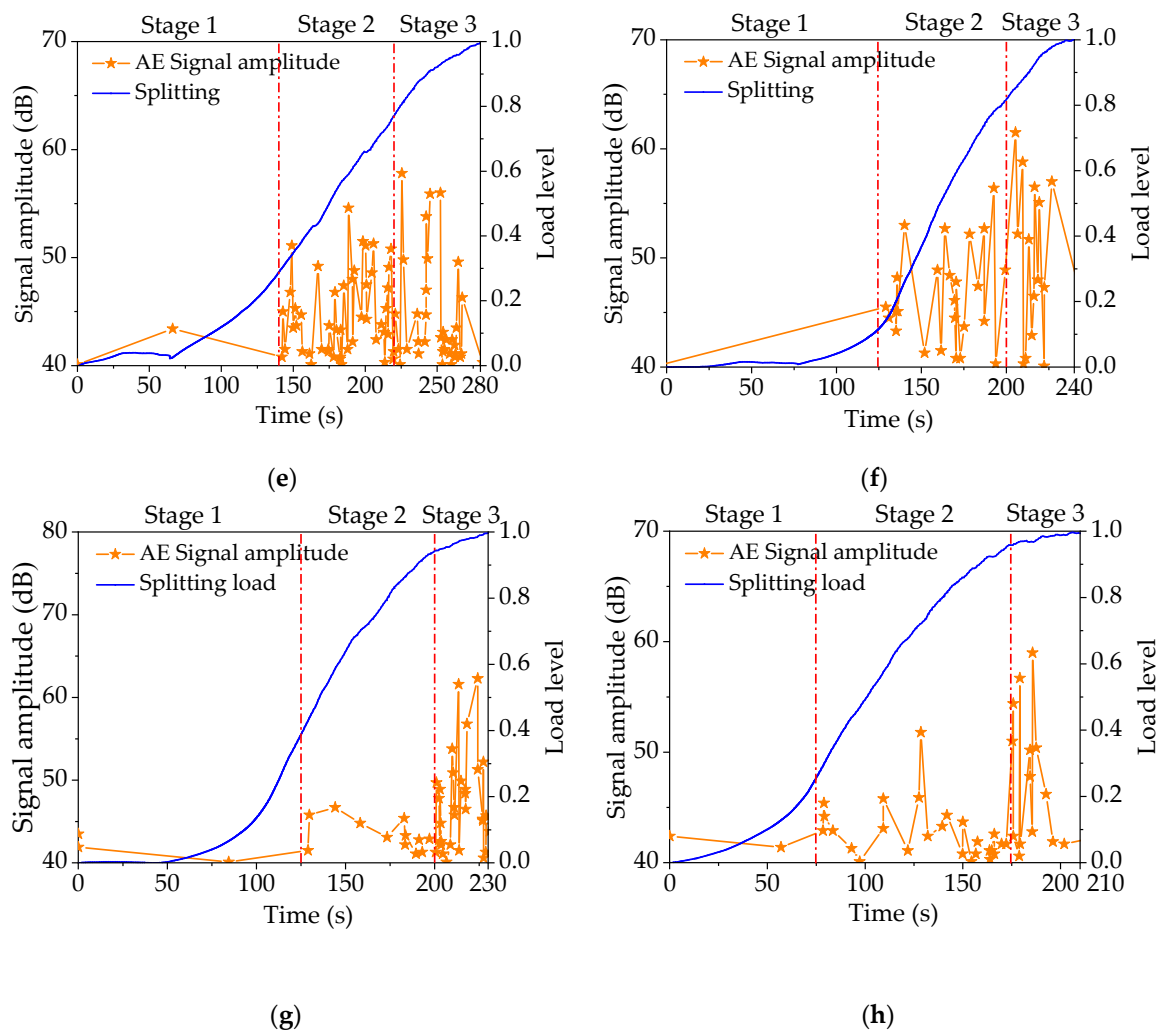


Figure 8. The AE amplitude and load level versus time during splitting at $-10\text{ }^{\circ}\text{C}$ for SBS-modified asphalt mixture with basalt fiber under various F-T cycles. (a) 0 F-T cycle; (b) 3 F-T cycles; (c) 6 F-T cycles; (d) 9 F-T cycles; (e) 12 F-T cycles; (f) 15 F-T cycles; (g) 18 F-T cycles; and (h) 21 F-T cycles.

In general, the AE signal amplitude and load level have similar changes under various repeated F-T cycles. A comparison of the AE signal amplitudes of various F-T cycles showed that the density of the AE signal amplitude gradually became slightly smaller with increasing F-T cycles. The first stage was gradually extended, and the third stage was gradually shortened. The loading time presented a gradual decreasing trend with F-T cycles. This variation trend means that asphalt mixtures processed with more F-T cycles began preliminary damage in a short load time. Thus, it is evident that the F-T cycle has a visible adverse influence on the splitting strength of SBS-modified asphalt mixture with basalt fiber, which makes asphalt mixtures more likely to cause early failure under the splitting load.

3.2.2. Signal Count

For the purpose of analyzing the influences of the F-T cycles on the splitting fracture damage, the variation curves between signal count and load level versus time during splitting were obtained for the SBS-modified asphalt mixtures with basalt fiber under various F-T cycles. As shown in Figure 9a, the entire loading process and AE signal count can be divided into three stages by combining the intensity of the AE signal count and the load level. During the first stage, when the splitting loading load level was below 0.2, there were almost no AE signal counts generated except several AE counts due to the mechanical noise while loading. After entering the second stage, the AE signal started to come alive. A significant increase in the AE signal count began to appear when the load level was

between 0.2 and 0.8. The AE signal count values increased with increasing load level. At the same time, the AE signal count values at the second stage increased overall and the signal was dense as compared with the first stage. The variation of the AE signal count implies that cracks occurred gradually and preliminarily formed at this stage, and then the cracks also developed into stable crack growth under continuous splitting loading. As the splitting loading continued, the AE signal reached the third stage. During this stage, the highest value of the AE signal count occurred, which means that the cracks in the asphalt mixture specimen developed rapidly. The AE signal count increased significantly, which means obvious cracks appeared inside the specimen, eventually losing resistance and causing damage.

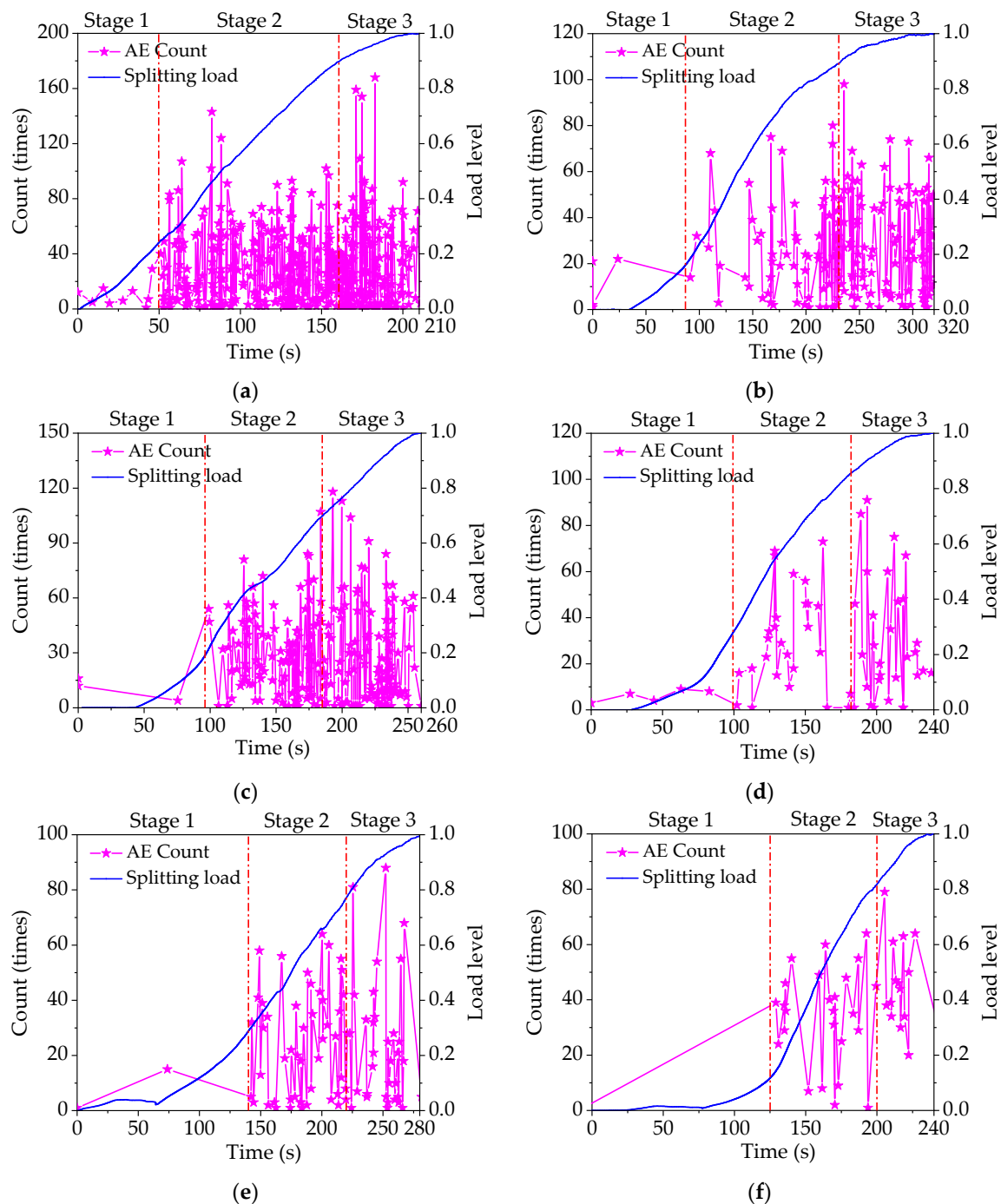


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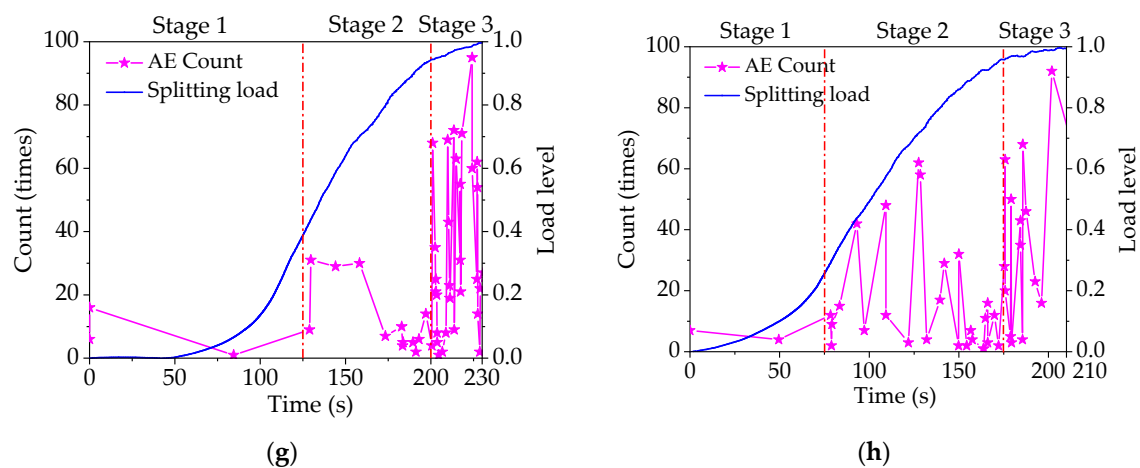


Figure 9. The AE count and load level versus time during splitting at $-10\text{ }^{\circ}\text{C}$ for SBS-modified asphalt mixture with basalt fiber under various F-T cycles. (a) 0 F-T cycle; (b) 3 F-T cycles; (c) 6 F-T cycles; (d) 9 F-T cycles; (e) 12 F-T cycles; (f) 15 F-T cycles; (g) 18 F-T cycles; and (h) 21 F-T cycles.

With respect to the influences of the F-T cycles on the AE signal count of the asphalt mixtures under splitting loading, it is obvious that the variations of AE signal count and load level have similar trends under various repeated F-T cycles. Compared with the AE signal counts of various F-T cycles, it is clear that the density of the AE signal count gradually became slightly smaller, at the same time, the loading time was shortened to a certain degree with increasing F-T cycles. The first stage was gradually shortened, and the third stage was gradually increased. The occurrence of the second stage gradually moved forward. The F-T cycle processing accelerated the damage of asphalt mixture specimen, i.e., the F-T cycle had a visible adverse influence on the splitting strength of SBS-modified asphalt mixture with basalt fiber.

4. Conclusions

This paper evaluated the influence of freeze-thaw cycles on the performance degradation and fracture damage of SBS-modified asphalt mixtures with basalt fiber using the high-temperature compression test, low-temperature splitting test, and acoustic emission technique. Conclusions can be achieved as follows:

- Acoustic emission parameters could well reflect the damage fracture characteristics of asphalt mixture specimen during the high-temperature compression and low-temperature splitting process. Meanwhile, the AE signal could be correlated with the fracture damage to study the influences of fracture damage.
- The fracture damage of the asphalt mixture specimens during compression or splitting can be classified into three stages by the variation of the AE signals, and the AE signal amplitude and count show clear correlations with the compression and splitting load level. Meanwhile, the AE signal clarifies the formation, development, and failure of internal damage for asphalt mixture specimens during the compression and splitting fracture.
- Damage gradually occurred inside asphalt mixture specimens under various F-T cycles. The intensity (value and density) of the AE signal parameters of asphalt mixture decreases with increasing F-T cycles. It is evident that the F-T cycle has a significant adverse effect on the mechanical strength of asphalt mixtures, which makes asphalt mixtures more likely to cause early failure.

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