

Article

Research on Fatigue Characteristics and Prediction of Large-Particle Asphalt Mixtures Based on Four-Point Bending Tests

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Abstract: Large aggregate asphalt mixtures can absorb noise, reduce water damage, effectively improve the service life of roads, and reduce environmental pressure. In this study, the fatigue characteristics of a large-sized asphalt mixture, LSAM-30, were investigated using four-point bending tests. The fatigue performance of LSAM-30 was compared to that of AC-13 and AC-20 asphalt mixtures across a range of temperatures, frequencies, and strains. The results indicated that the temperature, frequency, and strain significantly affect the fatigue performance of LSAM-30. As the temperature or frequency increased, the disparity in the fatigue performances of LSAM-30, AC-13, and AC-20 became more pronounced. Furthermore, the variations in the strain did not exhibit a clear pattern in the fatigue performance ratio among the three asphalt mixtures, with the ratio changes being minor (<5%). Additionally, an exponential-function-based predictive equation was proposed, showing how the fatigue characteristics of LSAM-30 vary with changes in frequency and temperature.

Keywords: large-sized asphalt mixture; four-point bending test; exponential function model; comparison of fatigue performance



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1. Introduction

Fatigue failure is the primary form of distress in asphalt pavements, and researchers have investigated the fatigue performance of asphalt mixtures extensively [1–4]. Strain sweep tests reveal that the maximum stress at an increased strain corresponds to the shear strength, and the principle of thermal equivalence also applies to the shear strength and shear rate [5]. The measured fatigue performances of asphalt mixtures under controlled conditions in accelerated loading facilities exhibit discrepancies from the actual fatigue performances of field materials [6,7]. Aging significantly affects the fatigue performance of asphalt mixtures, as evidenced by indirect tension and four-point bending tests [2]. Moreover, several different experimental methods describe fatigue damage, with some scholars conducting direct tensile fatigue tests under stress-controlled modes [8] or analyzing the fatigue performance of asphalt mixtures through fatigue tests based on energy methods [9,10]. Researchers have independently designed alternate bidirectional splitting fatigue tests to effectively simulate stress conditions in asphalt pavements [11]. Numerous experiments have investigated the fatigue performance of asphalt mixtures through three-point and semicircular bending tests [12–17]. In addition to the diversity of fatigue test methodologies, multiple evaluation indicators exist for the fatigue damage of asphalt mixtures. Researchers have suggested that the stiffness modulus can serve as an evaluation index for the fatigue performance of asphalt mixtures. For instance, when the modulus decreases to 50% of its initial value during asphalt material fatigue testing, the material is considered fatigued [18]. However, some scholars argue that reducing the stiffness modulus to 50% of the initial value may not entirely represent the fatigue failure criterion

for asphalt mixtures, proposing that a reduction of 65% or within the range of 15–25% of the initial value would be more appropriate [19,20].

Currently, researchers enhance the fatigue performance of asphalt mixtures primarily through the modification of component materials [21–25]. Investigations using fatigue performance tests have analyzed the fatigue resistances of conventional asphalt, rubber-powder-modified asphalt, and SBS-modified asphalt. The results demonstrated a significant enhancement in the fatigue performance of rubber powder- and SBS-modified asphalt compared to that of conventional asphalt, with SBS-modified asphalt exhibiting the best fatigue performance [24]. Furthermore, polyurethane-modified asphalt mixtures display a good high-temperature performance and resistance to water damage. Compared to conventional asphalt, polyurethane-modified asphalt mixtures have lower production costs, presenting a measurable cost advantage [26]. The addition of basalt fibers or diatomite to conventional asphalt also enhances the fatigue performance of asphalt mixtures. Basalt fibers improved the fatigue performance of the asphalt mixtures, whereas diatomite significantly enhanced their high-temperature stability. The simultaneous use of basalt fibers and diatomite resulted in an overall enhancement in the performance of asphalt mixtures [27]. The use of multiple materials for asphalt mixture modification is a common and effective method in experimental studies [22,28–30]. For instance, nano- CaCO_3 /SBR composite-modified asphalt mixtures exhibit superior high-temperature and fatigue performances compared to SBR-modified asphalt mixtures. Additionally, nano- ZnO/TiO_2 /SBS composite-modified asphalt mixtures display enhanced water stability, resistance to aging, and splitting strength compared with SBS-modified asphalt mixtures [31]. In addition to the improvement in asphalt mixture properties using different materials, some studies have approached modification through aggregates. For instance, the use of recycled aggregates derived from construction waste to prepare asphalt mixtures has been investigated [32–35]. Research indicates that when traffic volumes are low, recycled aggregates can replace 75% of natural aggregates to prepare asphalt mixtures, which are easier to compact, potentially saving resources during the construction compaction stages. However, indices such as the elastic and dynamic elastic moduli of asphalt mixtures decline with the increase in recycled aggregates [36]. Several studies have found that asphalt saturation, the elastic modulus, and the void content deteriorate in asphalt mixtures made with recycled aggregates compared to those made with pure natural aggregates. Nevertheless, they still meet technical requirements and can be used depending on actual engineering needs [37–41].

Gradation design is an important approach to achieve different fatigue performances in asphalt mixtures. Asphalt mixtures with different gradation curves exhibit notable differences in their sensitivity to test loading frequencies [42,43], and the gradation design also influences the void content of asphalt mixtures [44–46]. Asphalt mixtures designed using the Bailey method, which is a gradation design approach, demonstrated a commendable fatigue performance [47]. Moreover, a comparative study of two discontinuous graded rubberized asphalt mixtures revealed that when the 4.75 mm sieve passage rate was controlled to between 24% and 34%, rubber-modified asphalt displayed the optimal fatigue performance [48]. Beyond common gradations such as AC-13 and AC-20, researchers have introduced LSAM-30, a large-sized asphalt mixture (LSAM), as a gradation type [49]. In the design of LSAM-30, particular attention was paid to its drainage performance, ensuring smooth drainage of water from the pavement structure and thus effectively reducing the water damage and pavement deterioration issues caused by water accumulation [30]. Through an in-depth investigation and testing using three molds with improved thicknesses, the rutting resistance of LSAM-30 was proven to be excellent [50]. Additionally, an improved freeze–thaw splitting test further verified its good water damage resistance [51]. Another study found that different compaction methods and coarse-to-fine aggregate ratios significantly affected the performance of LSAM-30 [52]. When the asphalt content reached approximately 15%, LSAM-30 exhibited the most superior high-temperature rutting resistance [53,54]. Furthermore, through precise material proportioning optimization and reduced asphalt usage, LSAM-30 not only improves the production efficiency but also

effectively reduces carbon emissions and energy consumption during production [55]. These features endow LSAM-30 with significant advantages in terms of overall production costs and service life. Therefore, the widespread application of LSAM-30 will contribute to promoting the construction of a sustainable transportation infrastructure, reducing resource waste, and mitigating environmental pressures.

In conclusion, LSAM-30 demonstrates the capability to significantly enhance the longevity of roads, thereby having crucial implications for the sustainable advancement of road engineering. However, there are few studies specifically investigating the fatigue performance of LSAM-30. Moreover, there are no comparative studies on LSAM-30, AC-13, and AC-20 asphalt mixtures under identical test conditions. Therefore, this study uses four-point bending tests to investigate the fatigue characteristics of LSAM-30 by independently controlling the strain, frequency, and temperature. The aim was to establish fatigue equations based on different influencing factors and subsequently to conduct a comparative analysis of the fatigue performance of the three different gradations of asphalt mixtures. This analysis aimed to identify the disparities in fatigue performance among asphalt mixtures with different gradations and their underlying causes.

2. Materials and Methods

2.1. Materials

The base asphalt selected for this study was A-grade 70 road petroleum asphalt, with limestone as the aggregate and mineral powder as the filler. The different material performance indicators were tested in accordance with the specifications outlined in JTG E20-2011 “Test Methods of Bitumen and Bituminous Mixtures for Highway Engineering” [56]. The detailed indicator results are presented in Tables 1–3.

Table 1. Base asphalt test results.

Project	Unit	Standard	Actual
Penetration (100 g, 25 °C, 5 s)	0.1 mm	60–80	75.1
Penetration index	—	≥ -0.8	−0.2
Ductility (15 °C, 5 cm/min)	cm	≥ 100	170
Softening point (R and B)	°C	44–54	50
Rotation viscosity (135 °C)	Pa·s	≤ 3.0	1.205
Density (15 °C)	g/cm ³	—	1.031

Table 2. Aggregate test results.

Project	Unit	Coarse Aggregate		Fine Aggregate	
		Standard	Actual	Standard	Actual
Crushing value	%	≤ 28.0	15.3	—	—
Los Angeles wear value	%	≤ 28.0	10.3	—	—
Apparent relative density	—	≥ 2.60	2.64	≥ 2.50	2.697
Water absorption rate	%	≤ 2.0	0.31	—	—
Content of particles <0.075 mm	%	≤ 1.0	0.5	≤ 10.0	3
Content of needle-shaped particles	%	≤ 15.0	2.1	—	—

Table 3. Mineral powder test results.

Project	Unit	Standard	Actual
Density	g/m ³	≥ 2.50	2.675
Water content	%	≤ 1	0.3
Hydrophilicity coefficient	—	≤ 1	0.6
<0.075 mm content	%	75–100	95.8
Heating stability	—	No color change	No color change

2.2. Mix Gradation and Asphalt/Aggregate Ratio

The asphalt mixture gradations were LSAM-30, AC-13, and AC-20; the detailed gradations are presented in Table 4. Four asphalt/aggregate ratios were selected for this experiment with an interval of 0.3%. The preliminary asphalt/aggregate ratios for LSAM-30 were 3.2, 3.5, 3.8, and 4.1%. Table 5 presents the volume parameters and mechanical performance index results for LSAM-30. Based on indicators such as V_a , VMA, and VFA, the optimal asphalt/aggregate ratio for this experiment was identified as 3.6%. The preliminary asphalt/aggregate ratios for AC-20 were 4.2, 4.5, 4.8, and 5.1%, whereas those for AC-13 were 4.5, 4.8, 5.1, and 5.4%, respectively. Using the same testing method, the optimal asphalt/aggregate ratios were determined based on the Marshall mechanical performance indicators and volume indicators. Ultimately, the asphalt/aggregate ratio for AC-20 was selected as 4.5%, and that for AC-13 was 5.2%.

Table 4. Asphalt mixture grading table.

Mass Percentage (%) Passing through the Following Sieve Holes (mm)														
Mesh size	37.5	31.5	26.5	19	16	13.2	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075
LSAM-30	100	98.7	86.5	72.5	60.2	52.0	43.6	0.3	25.0	16.8	12.7	8	5.8	4.5
AC-20	--	--	100	95	90	76	53	34	26	19	10	8	6	4.5
AC-13	--	--	--	--	100	97	76	45	33	23	17	12	9	5.5

Table 5. Volume parameters and mechanical performance indexes of rotary compaction.

AC/%	%Gmm@Ni/%	%Gmm@Nd/%	V_a /%	VMA/%	VFA/%	DBR
3.2	85.6	93.2	5.5	13.8	54.3	1.36
3.5	87.1	94.9	4.3	13.6	61.6	1.25
3.8	87.9	95.7	3.4	13.2	67.2	1.08
4.1	88.6	96.8	2.8	13.7	72.5	0.92
4.4	89.2	97.5	2.5	14.2	76.4	0.81

2.3. Test Method

2.3.1. Sample Forming

The specimens were prepared using a gyratory compactor and subsequently cut into small-beam specimens with dimensions of 380 mm × 50 mm × 63 mm using an asphalt mixture cutting machine, as shown in Figure 1.

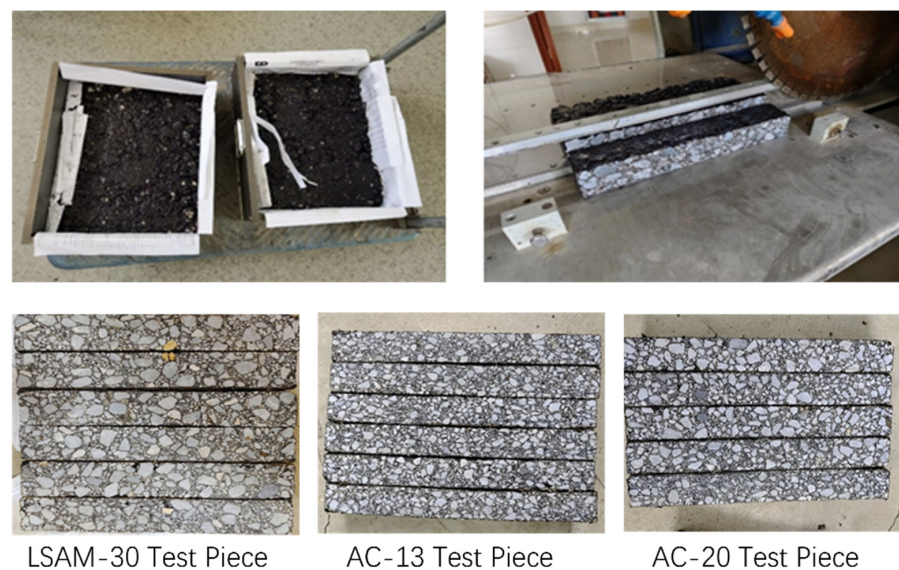


Figure 1. Preparation of test pieces.

2.3.2. Fatigue Test

The four-point bending fatigue test is a material mechanics method widely used to assess the fatigue performance of materials under repetitive loading conditions [57–62]. In this study, four-point bending fatigue life tests of asphalt mixtures were conducted in accordance with the specifications outlined in JTG E20-2011 “Test Methods of Bitumen and Bituminous Mixtures for Highway Engineering” [56]. The tests were conducted following the prescribed strain-controlled mode with a semi-sinusoidal waveform according to the specification requirements. The apparatus and procedure for the four-point bending test are shown in Figure 2. Typically, this type of test requires the use of a universal material-testing machine and four-point bending fixtures. The specimens were mounted onto fixtures and subjected to dynamic loading to simulate the fatigue stress experienced under actual working conditions.



Figure 2. Four-point bending testing machine.

2.3.3. Test Piece Failure Criteria

According to reference [63], in the strain-controlled mode, the fatigue failure criterion for asphalt mixtures is defined as the number of cycles when the stiffness modulus decreases to 50% or 40% of the initial modulus. Conversely, in the stress-controlled mode, the fatigue failure criterion was defined as the number of cycles required for the stiffness modulus to decrease to 10% of the initial modulus of the asphalt mixtures. In other fatigue studies, the peak phase angle can also be used as a criterion to determine the fatigue life within the relationship between the phase angle and cycle number. Given that this study adopted a strain-controlled mode, the fatigue failure criterion was set as a stiffness modulus reduction of 50% in the initial modulus for asphalt mixtures.

2.3.4. Selection of Experimental Conditions

In uninterrupted fatigue testing, frequency variations refer to the effects of loading frequencies on the frequent actions applied to asphalt mixtures. The rational design of the frequency gradient conditions ensured the stability of the experiment [3,43,64]. The range of frequency gradients typically spans from 0.1 Hz to 50 Hz, covering most frequency ranges encountered in practical applications. The selection of frequency gradients must align with experimental requirements and material characteristics. Generally, smaller frequency gradients yield more precise test results, albeit with a corresponding increase in test duration. For asphalt mixture fatigue tests, frequency gradients of 1, 2, 5, and 10 Hz are commonly used. The test temperature is an important factor that influences the fatigue performance of asphalt mixtures [43]. Typically, test temperatures should be controlled within the range of 0–20 °C, with temperature variations not exceeding ± 1 °C. High or low test temperatures can affect the fatigue performance parameters, subsequently affecting the service life of asphalt mixtures. Establishing the appropriate strain conditions is pivotal for controlling strain-based tests [65]. Excessive strain settings can lead to premature specimen failure before reaching the fatigue limit, whereas excessively low strain settings can significantly prolong fatigue testing [66,67].

To ensure the accuracy of the asphalt mixture fatigue performance tests, this study ultimately opted for a frequency gradient of 5 Hz. Three different frequencies, namely 5, 10, and 15 Hz, were selected, with test temperatures set at 5, 10, and 15 °C. The strain levels were set at 200, 400, 600, and 800 $\mu\epsilon$, respectively. The test parameters are listed in Table 6.

Table 6. Test parameters.

	Test Frequency (Hz)	Test Strain ($\mu\epsilon$)	Test Temperature (°C)
Test conditions	5, 10, 15	200, 400, 600, 800	5, 10, 15
Failure determination	The stiffness modulus is reduced to 50% of the initial value		

2.4. Fatigue Equation

SPSS 26.0 is one of the earliest statistical analysis software tools, allowing the establishment of correlations between different variables and unveiling patterns through the statistical analysis of data. This study investigated the impact of several different combinations of test conditions on the fatigue performance of LSAM-30 and analyzed and processed the experimental data using the SPSS data processing software [68,69].

The commonly used methods for describing the fatigue behavior of asphalt mixtures using fitting equation models are the double logarithm and exponential function models. For an extended fatigue duration, the fatigue equation for asphalt mixtures must exhibit a curve with a limit. Hence, compared with the double logarithm model, the exponential function model has better practical significance [70]. Consequently, in this study, the fatigue results of LSAM-30 under different experimental conditions were fitted using an exponential model to establish fatigue equations based on the temperature and frequency, as shown in Equation (1). Furthermore, owing to the relatively large values of strain and loading cycles, the logarithm of the fatigue test variables was specifically introduced into the exponential fatigue model for further processing to improve the accuracy of the prediction model. The final exponential fatigue model is presented in Equation (2).

$$y = ax^{-bx} \quad (1)$$

$$\log N = ae^{-b \log \epsilon} \quad (2)$$

In Equation (1), y corresponds to $\log N$ and x corresponds to $\log \epsilon$. Here, $\log N$ is the logarithm of the number of load cycles, a is a regression constant, $\log \epsilon$ is the logarithm of the tensile strain at the mid-span of the beam, and b is a regression constant.

3. Results and Discussion

3.1. Fatigue Performance of LSAM-30

3.1.1. Frequency Effect

The fatigue curves of LSAM-30 at different frequencies are illustrated in Figure 3, with $\log \epsilon$ as the x - and $\log N$ as the y -axis. For LSAM-30, the fatigue performance varied at different load frequencies, exhibiting a better fatigue performance at lower frequencies. This variation can be attributed to the internal material characteristics of LSAM-30. At lower frequencies, the internal components of LSAM-30 tended to maintain a more stable structure, alleviating displacements and friction among the material particles, thereby reducing the extent of fatigue damage. Furthermore, Meng [71] pointed out that low-frequency loading allows asphalt mixtures more time to relax stress, reducing the accumulation of internal stress and thus lowering the fatigue damage rate. Low-frequency loading also provides more time for cracks in asphalt mixtures to heal, further enhancing their fatigue performance. This aligns with the fatigue characteristics of LSAM-30 observed in the present study under low-frequency conditions.

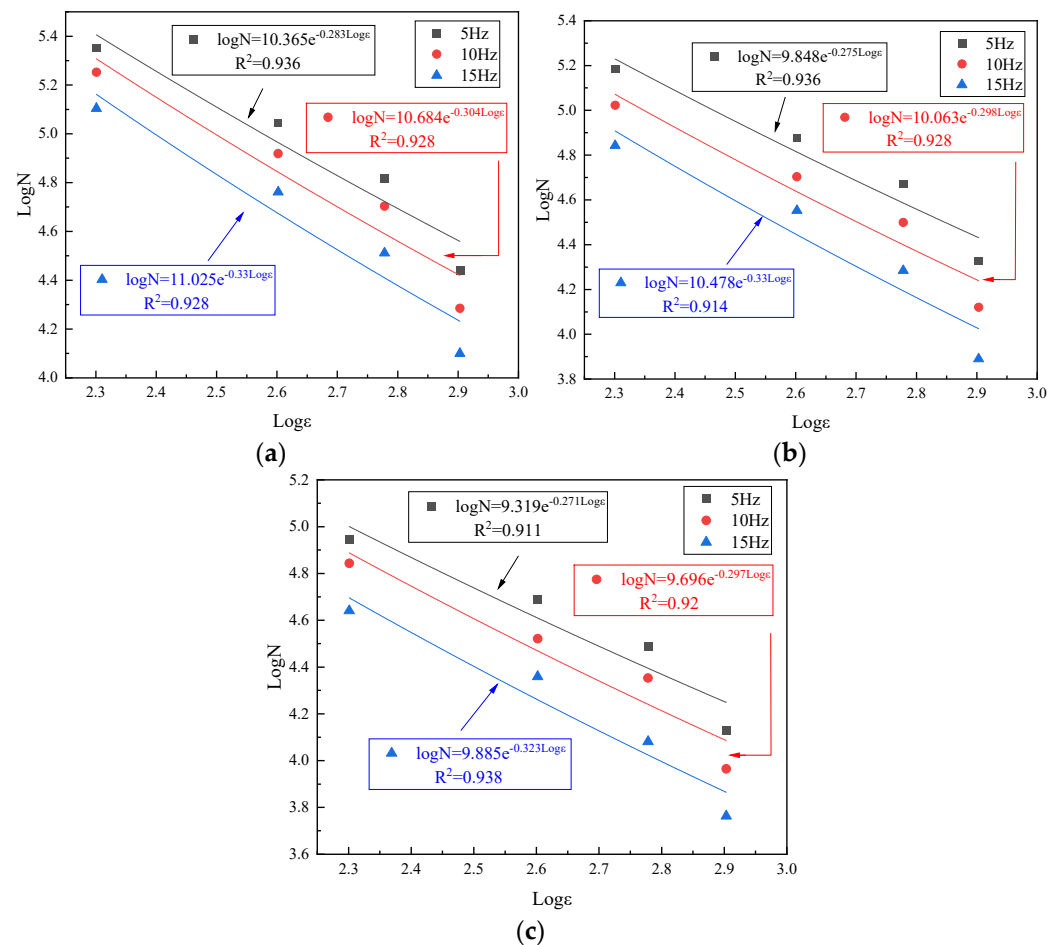


Figure 3. Effect of frequency on fatigue curves of LSAM-30 at different temperatures: (a) 5 °C, (b) 10 °C, (c) 15 °C.

3.1.2. Temperature Effect

The fatigue curves of LSAM-30 at different temperatures are depicted in Figure 4, with $\log \epsilon$ as the x - and $\log N$ as the y -axis. LSAM-30 exhibited varied fatigue outcomes at different temperatures. Under a consistent strain and frequency, the fatigue performance gradually diminished with an increasing temperature. This decline might be attributed to the gradual softening of the asphalt responsible for the binding within LSAM-30 at high temperatures. As the asphalt softens, the bonding effect between the asphalt and aggregates diminishes, reducing the shear strength and resulting in softening and decreased cohesion. As indicated in another study [72], at high temperatures, the viscosity of asphalt decreases, and its fluidity increases, making asphalt mixtures more prone to deformation and flow when subjected to repeated loads. This deformation and flow accelerate the damage to the internal structure of the asphalt mixtures, thus reducing their fatigue life. The changes in the fatigue performances of LSAM-30 at high temperatures were similar.

3.1.3. Strain Effect

The fatigue curves of LSAM-30 under different strains are shown in Figure 5, where f is the x - and $\log N$ is the y -axis. LSAM-30 under conditions of 200 $\mu\epsilon$ of strain exhibits the optimal fatigue performance. Previous studies indicated that a higher strain level leads to a shorter fatigue life of asphalt mixtures. This is because a greater strain can cause more microcracks and damage within the asphalt mixture, accelerating the fatigue failure [73–75]. Similar results were observed for LSAM-30. When the strain is higher, the greater load borne by LSAM-30 can lead to the emergence of microcracks within the material, which

triggers fatigue damage. In contrast, when the strain was low, the probability of occurrence of microcracks within LSAM-30 decreased, resulting in an increase in the fatigue life.

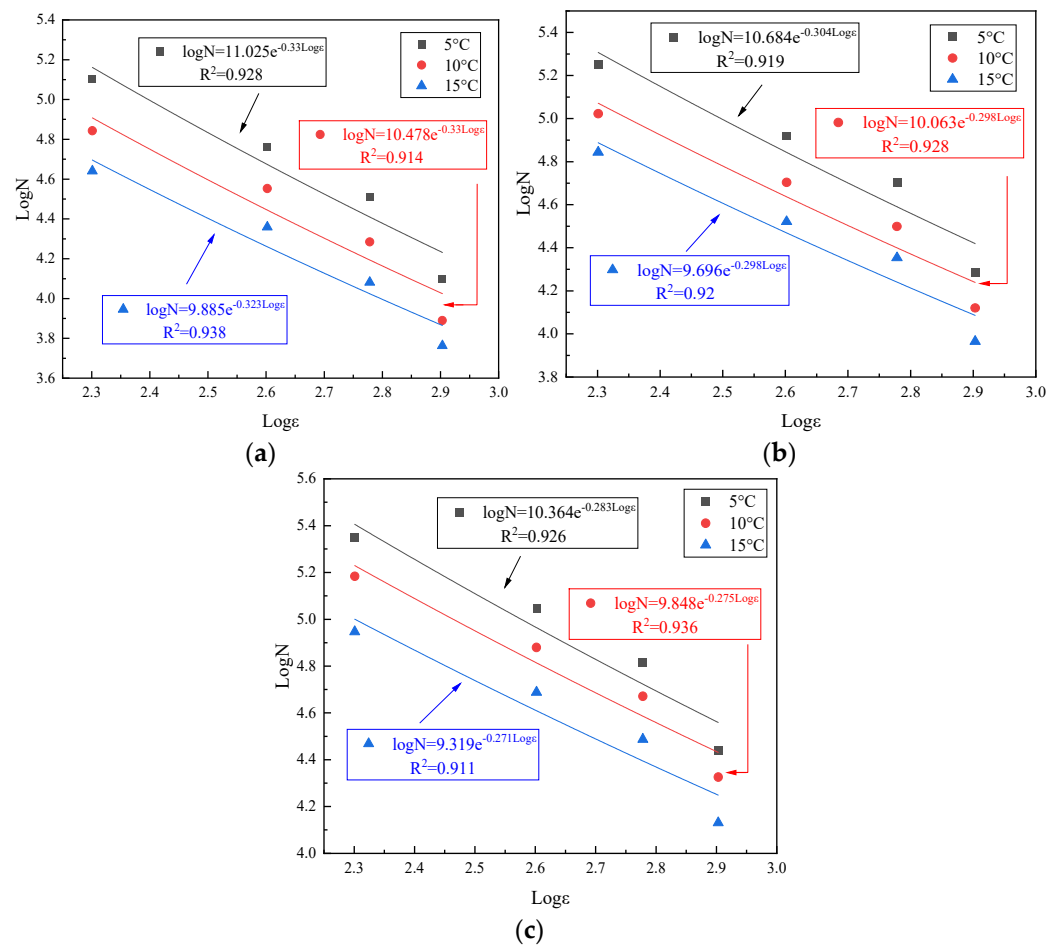


Figure 4. Effect of temperature on the fatigue curves of LSAM-30 at different frequencies: (a) 5 Hz, (b) 10 Hz, (c) 15 Hz.

3.2. LSAM-30 Fatigue Equation

3.2.1. Frequency Factor

The exponential function parameters a and b from Equation (2) are summarized in Table 7 and plotted in Figure 6, with $\log f$ on the x -axis and the parameters a and b on the y -axis.

Table 7. Summary of exponential function parameters a and b at different frequencies.

Frequency	Temperature	a	b
5	15	9.319	−0.271
10	15	9.696	−0.297
15	15	9.885	−0.323
5	10	9.848	−0.275
10	10	10.063	−0.298
15	10	10.477	−0.33
5	5	10.364	−0.283
10	5	10.684	−0.304
15	5	11.025	−0.333

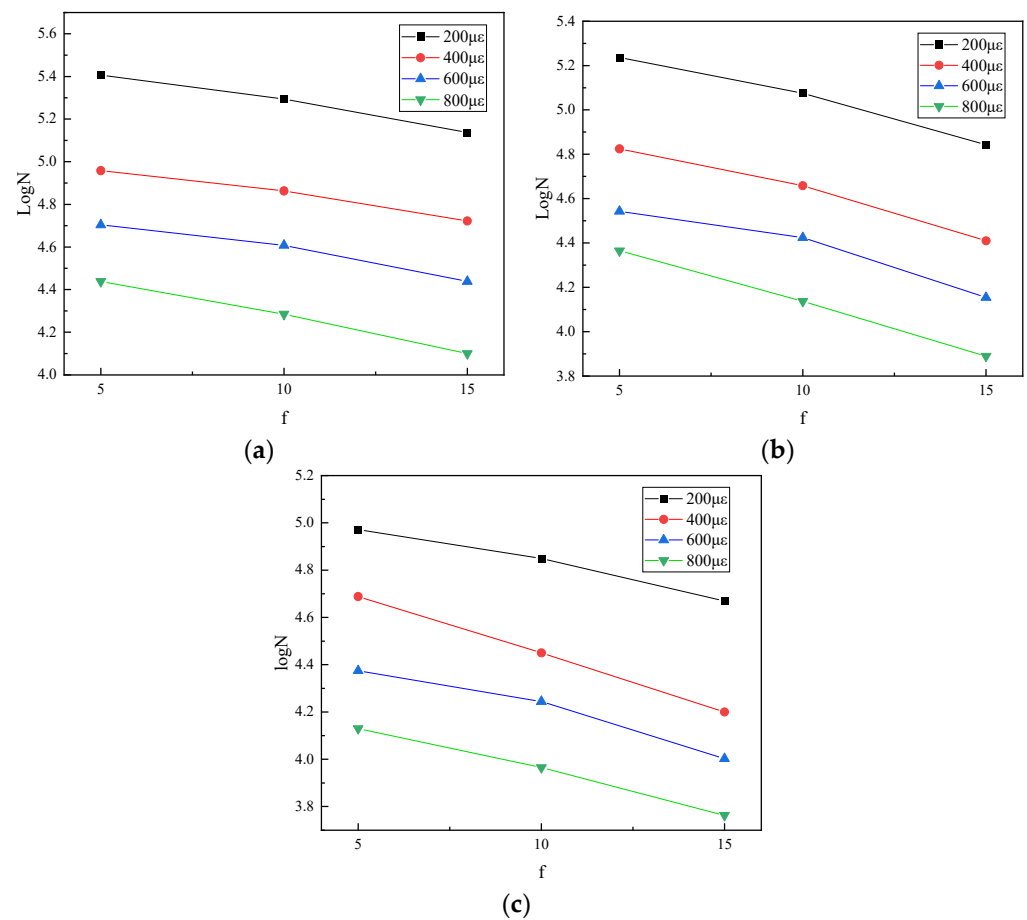


Figure 5. Effect of strain on fatigue curves of LSAM-30 at different temperatures: (a) 5 °C, (b) 10 °C, (c) 15 °C.

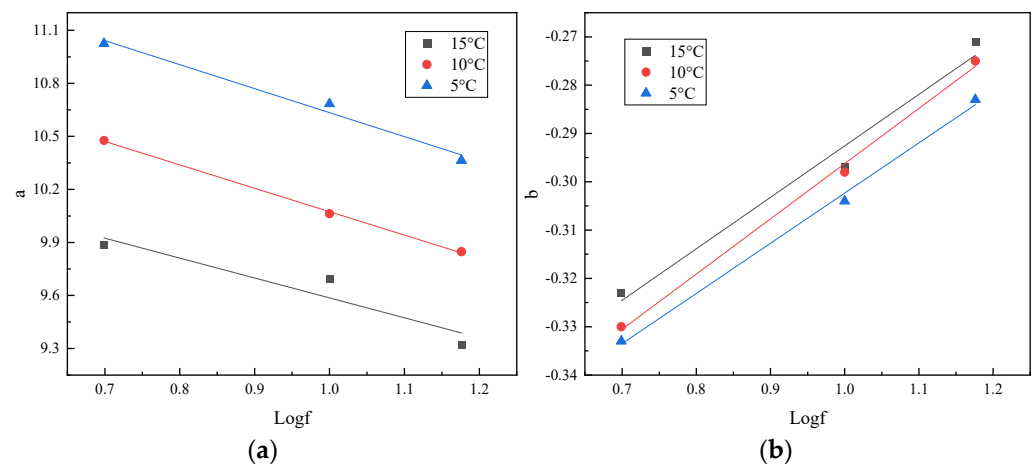


Figure 6. Effect of frequency on parameters: (a) parameter a , (b) parameter b .

Figure 6 shows that there is a strong linear relationship between the exponential fatigue model parameters a and b and LSAM-30 and $\text{Log}f$. By using the linear relationship represented by Equation (3) to fit the corresponding data, the fitted parameter values and fitting accuracies were determined and are summarized in Table 8.

$$a(b) = m_i \log f + n_i \quad (3)$$

where m_i and n_i represent the parameters after fitting a and b against $\log f$; f is the frequency.

Table 8. Summary of parameter fitting results.

Temperature/°C	a			b		
	m_1	n_1	R^2	m_1	n_1	R^2
15	1.126	10.713	0.889	−0.107	−0.339	0.978
10	1.324	11.399	0.999	−0.114	−0.411	0.997
5	1.358	11.993	0.983	−0.104	−0.406	0.997

By substituting the fitted parameters m_i and n_i from Table 8 into Equation (3) and the LSAM-30 exponential fatigue equation, different fatigue equations based on the frequency factor of LSAM-30 at different test temperatures were obtained, as listed in Table 9.

Table 9. Fatigue equations of LSAM-30 depending on the frequency factor.

Temperature	Fatigue Equation Based on a Frequency Factor
15	$\log N = (1.126 \log f + 10.713)e^{-(0.107 \log f - 0.339) \log \varepsilon}$
10	$\log N = (1.324 \log f + 11.399)e^{-(0.1 \log f + 0.299) \log \varepsilon}$
5	$\log N = (1.358 \log f + 11.993)e^{-(0.104 \log f - 0.406) \log \varepsilon}$

The fatigue equation based on the temperature factor for LSAM-30 is determined as Equation (4):

$$\log N = (a \log f + b)e^{-(c \log f + d) \log \varepsilon} \quad (4)$$

where N is the number of load cycles; a , b , c , and d are constants corresponding to specific conditions; f is the frequency; and ε is the strain.

3.2.2. Temperature Factor

The exponential function parameters a and b from Equation (2) are summarized in Table 10 and plotted with $\log T$ on the x -axis and the respective exponential function parameters a and b on the y -axis, generating Figure 7.

Table 10. Summary of exponential function parameters a and b at different temperatures.

Temperature	Frequency	a	b
15	15	11.025	10.684
10	15	10.477	10.063
5	15	9.885	9.696
15	10	11.025	10.684
10	10	10.477	10.063
5	10	9.885	9.696
15	5	11.025	10.684
10	5	10.477	10.063
5	5	9.885	9.696

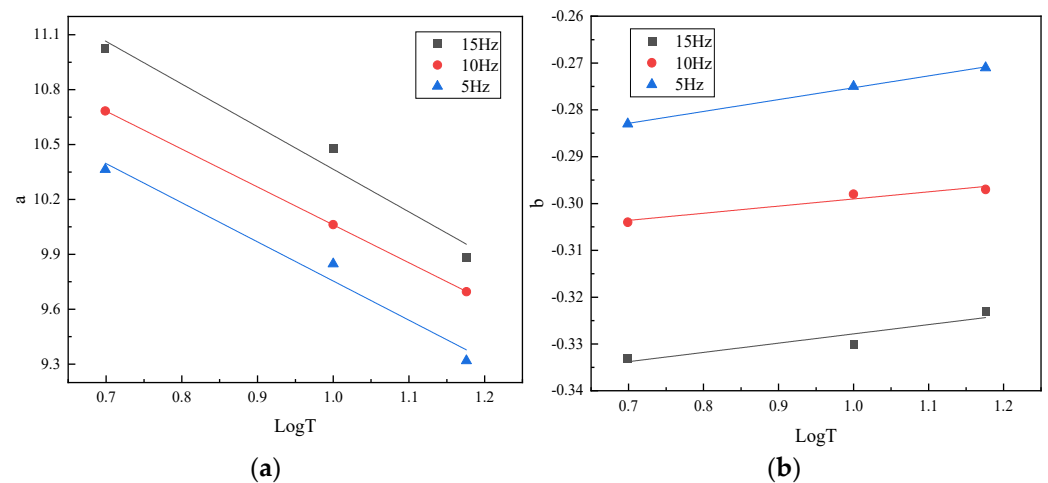


Figure 7. Effect of temperature on parameters: (a) parameter a , (b) parameter b .

The analysis in Figure 7 reveals a strong linear correlation between the temperature parameters a and b and $\log T$. The linear relationship depicted by Equation (5) was used to fit the relevant data, and the resulting parameter values along with the fitting accuracy are summarized in Table 11:

$$a(b) = m_i \log T + n_i \quad (5)$$

M_i and n_i are the parameters derived from the fitting of a and b with $\log T$ and T is the temperature.

Table 11. Summary of fitting results.

Frequency/Hz	a			b		
	m_1	n_1	R^2	m_1	n_1	R^2
15	−2.328	12.639	0.971	0.019	−0.348	0.864
10	−2.07	12.131	0.999	0.015	−0.314	0.943
5	−2.139	11.894	0.975	0.025	−0.3	0.998

By substituting the obtained fitted parameters into the exponential fatigue equation of LSAM-30, the fatigue equation for LSAM-30 was derived based on the temperature factor, as presented in Table 12.

Table 12. Fatigue equation of LSAM-30 based on the temperature factor.

Frequency/Hz	Temperature-Based Fatigue Equation
15	$\log N = (-2.328 \log T + 12.639)e^{-(0.019 \log T - 0.348) \log \varepsilon}$
10	$\log N = (-2.07 \log T + 12.131)e^{-(0.015 \log T - 0.314) \log \varepsilon}$
5	$\log N = (-2.139 \log T + 11.894)e^{-(0.025 \log T + 0.3) \log \varepsilon}$

The fatigue equation for LSAM-30 based on the temperature factor is expressed in Equation (6).

$$\log N = (a \log T + b)e^{-(c \log T + d) \log \varepsilon} \quad (6)$$

In this equation, N is the number of load cycles; a , b , c , and d are constants depending on the conditions; T is the temperature; and ε is the strain.

3.3. Comparative Fatigue Study

The fatigue performances of the three asphalt mixtures under different test conditions are shown in Figure 8a–i. Here, $\log N$ is the logarithmic value of the number of load cycles, while $\log \epsilon$ is the logarithmic value of strain, for instance, $\log 200$ is 2.3. As depicted in Figure 9, under the same frequency, temperature, and strain conditions, AC-13 exhibited a notably better fatigue performance than AC-20 and LSAM-30, with the fatigue performance ranking of AC-13 > AC-20 > LSAM-30. This performance difference arises from the variation in the particle size and density among the three asphalt mixtures. AC-13, which had the smallest particle size, had fewer voids than AC-20 and LSAM-30, resulting in stronger interparticle forces and a higher compressive strength. Additionally, AC-13 had a higher asphalt content than the other two mixtures. Consequently, under repeated strains, it exhibited better elastic recovery without inducing crack propagation, enabling it to withstand cyclic loading more effectively and thereby demonstrating a superior fatigue performance.

3.3.1. Frequency Effect

To explore the impact of gradation on the fatigue performance at different frequencies, a graph was plotted with 5 Hz, 10 Hz, and 15 Hz on the x-axis and the fatigue performance ratios of the three asphalt mixtures on the y-axis, as illustrated in Figure 9. Taking Figure 9a as an example, at a frequency of 5 Hz, the value for LSAM-30 represents the average fatigue performance at 5 °C and 5 Hz across four strain levels, at 4.91. The value for AC-20 corresponds to the average fatigue performance at 5 °C and 5 Hz across four strain levels, at 5.23. The value of AC-13 under the same conditions was 5.43. Consequently, the ratio of their respective values is 1:1.065:1.106. Similar calculations were applied to the fatigue performance ratios under other conditions.

The results from Figure 9a indicate that at 5 °C and 5 Hz, AC-13 exhibits a 3.9% higher fatigue performance compared to AC-20 and a 10.6% higher performance compared to LSAM-30. Moreover, AC-20 displayed a 6.5% higher fatigue performance than LSAM-30 under the same conditions. At 5 °C and 10 Hz, AC-13 showcases a 4.4% higher fatigue performance than AC-20 and an 11.4% higher performance than LSAM-30, while AC-20 surpasses LSAM-30 by 6.7%. Finally, at 5 °C and 15 Hz, AC-13 demonstrates a 4.13% higher fatigue performance than AC-20 and a 13.4% higher performance than LSAM-30, while AC-20 outperforms LSAM-30 by 8.9%.

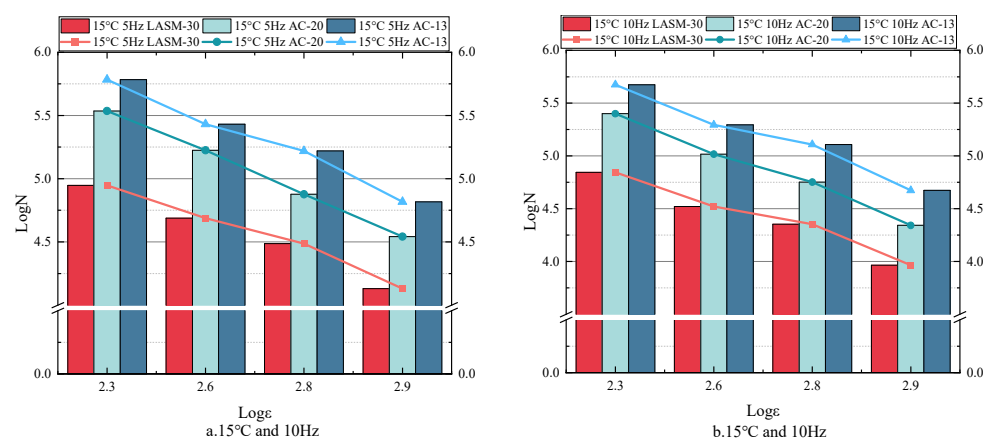


Figure 8. Cont.

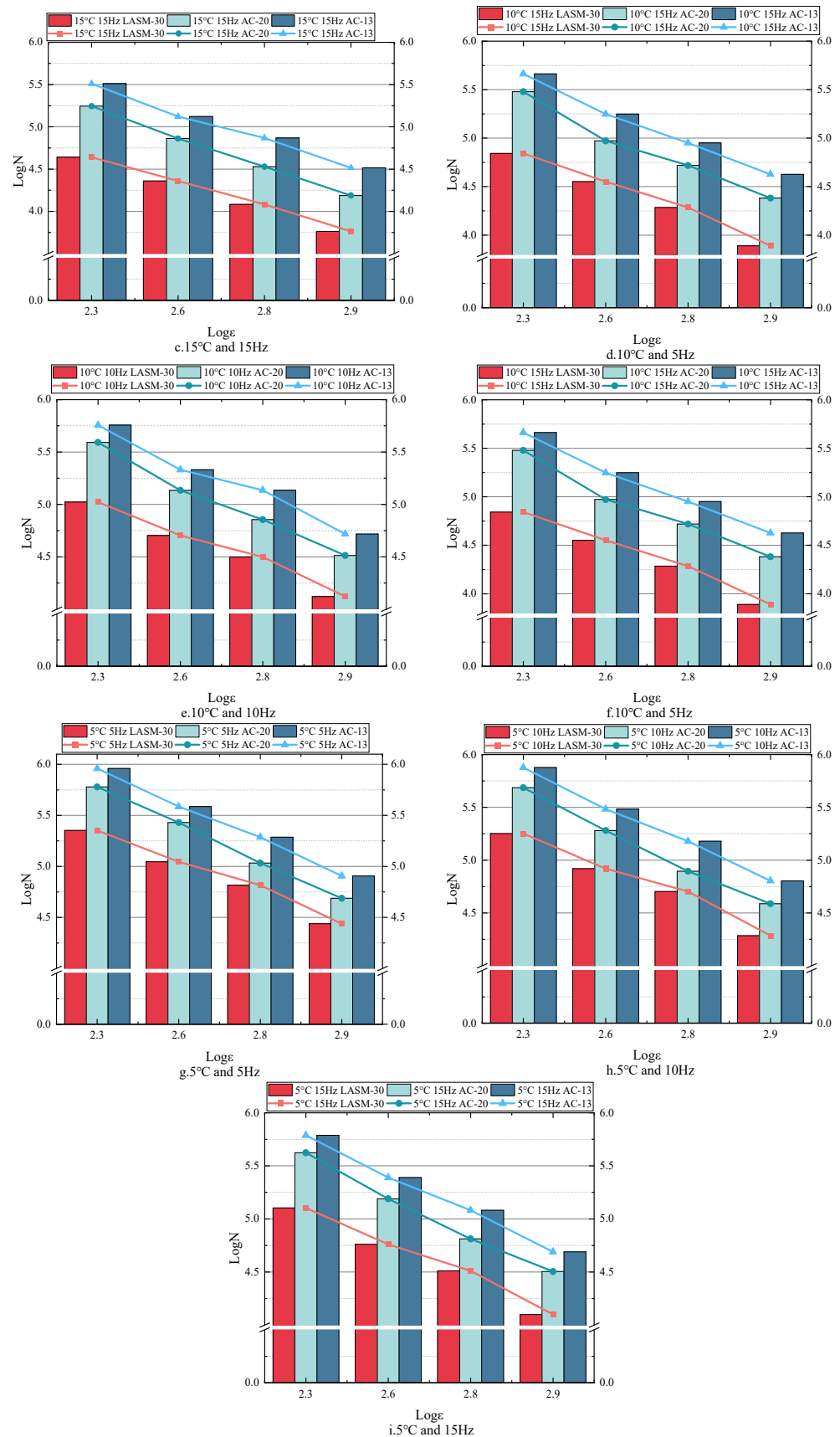


Figure 8. Comparison of the fatigue performance of three types of asphalt mixtures under different test conditions.

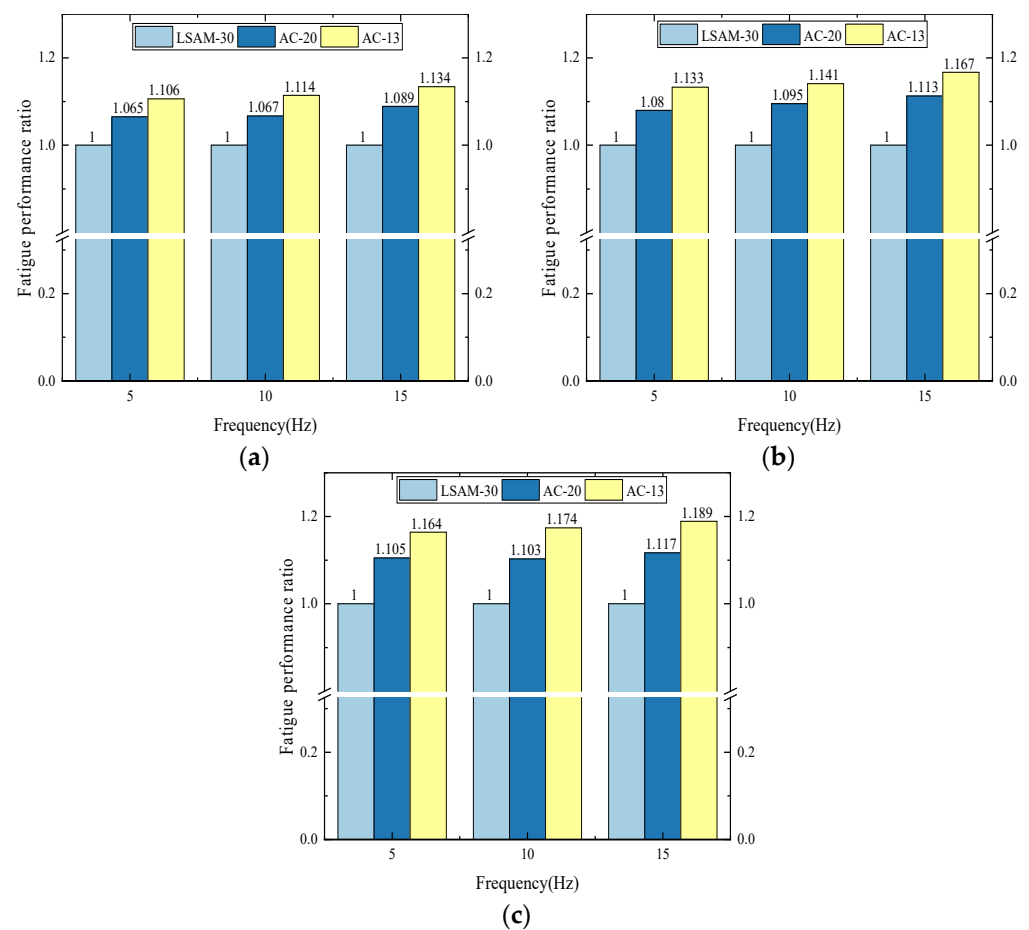


Figure 9. Fatigue performance ratio at different frequencies: (a) 5 °C, (b) 10 °C, (c) 15 °C.

This observation suggests that compared to low frequencies, AC-13 and AC-20 exhibit significantly higher fatigue performances than LSAM-30 under high-frequency loading. This indicates an escalating influence of aggregate gradation on the fatigue performance at higher frequencies, specifically from 5 to 15 Hz, widening the performance gap among the different graded asphalt mixes. Similar outcomes are observed at 10 °C and 15 °C. The likely cause of this phenomenon may be the relatively smaller surface area of LSAM-30, which could induce a greater stress concentration, a reduced displacement capacity, structural contraction, and deflection, thereby exacerbating fatigue damage and leading to failure. Furthermore, characteristics such as the aggregate density, strength, and shape can affect fatigue performance. Under high-frequency loading, LSAM-30 aggregates are more prone to forming deposits and structural non-uniformities, affecting the reliability and performance of the entire LSAM-30 sample.

Compared with the results at high frequencies, the fatigue performances of the three asphalt mixtures at low frequencies were more similar, and as the frequency decreased, the impact of aggregate gradation on the fatigue performance gradually diminished. This may be attributed to the fact that at lower frequencies, the voids between the aggregates in LSAM-30 were relatively large, allowing the asphalt to fill and wet these voids, forming a strongly compacted aggregate–asphalt mixture. This mixture exhibited a greater frictional resistance, resulting in a more compact structure that could better resist external stresses. However, under low-frequency loading conditions, the asphalt in the mixture has more time to relax and reduce the accumulation of internal stress [76]. Additionally, low-frequency loading allows more time for cracks in the asphalt mixture to heal, further enhancing its fatigue performance [77]. Both factors contribute to improving the fatigue performance of asphalt mixtures. Therefore, the fatigue performance of LSAM-30 was more susceptible to changes

in frequency, and the structural reinforcement effect at low frequencies was more significant, reducing the difference in fatigue performance compared with the other two asphalt mixtures.

3.3.2. Temperature Effect

From Figure 10a, at 5 Hz and 5 °C, the fatigue performance of AC-13 is 3.9% higher than that of AC-20 and 10.6% higher than that of LSAM-30. AC-20 exhibited a 6.4% higher fatigue performance than LSAM-30. At 5 Hz and 10 °C, AC-13's fatigue performance surpasses AC-20 by 4.9% and LSAM-30 by 13.3%, while AC-20 outperforms LSAM-30 by 8%. Under 5 Hz and 15 °C conditions, AC-13's fatigue performance exceeds AC-20 by 5.3% and LSAM-30 by 16.4%, while AC-20 shows a 10.5% superiority over LSAM-30 in terms of the fatigue performance.

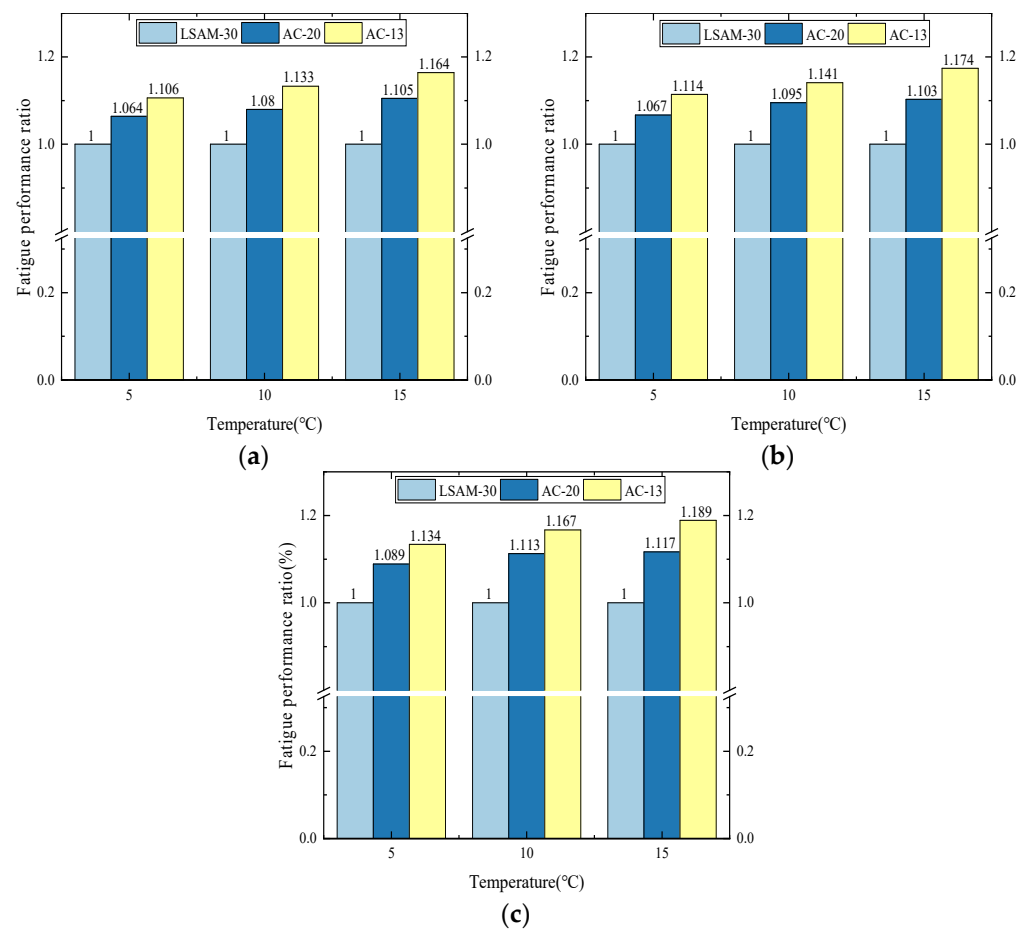


Figure 10. Fatigue performance ratio at different temperatures: (a) 5 Hz, (b) 10 Hz, (c) 15 Hz.

From this observation, it is evident that under high-temperature conditions, AC-13 and AC-20 exhibit significantly superior fatigue performances compared to LSAM-30. This indicates that under fixed-frequency conditions, with an increasing temperature, the disparity in the fatigue performance of asphalt mixtures with different gradations gradually increases. The impact of the gradation on the fatigue performance of LSAM-30 increased with increasing temperature. Similar outcomes were observed at 10 and 15 Hz.

This outcome might partly stem from the softening of asphalt at high temperatures, particularly under bending and shearing stresses, which might limit the surface contact area of LSAM-30 aggregates. This reduction could diminish the ability of the asphalt to bond to the aggregate surface, subsequently reducing the strength and adhesion of the mixture and resulting in fatigue failure. Additionally, the reduction in the elastic modulus of the three asphalt mixtures at elevated temperatures led to increased material deformation capabilities, thereby enhancing the fatigue life loss. Moreover, LSAM-30 aggregates tended

to develop interaggregate voids and more microcracks and defects at high temperatures, further diminishing the fatigue life. In summary, the inferior fatigue performance of LSAM-30 under high-temperature conditions may result from a combination of factors such as reduced asphalt adhesion and aggregate surface contact area, increased inter-aggregate voids, and the formation of microcracks and defects.

At low temperatures, the fatigue performances of LSAM-30 were like those of the other two mixtures, potentially due to LSAM-30's enhanced resistance to crack propagation in cold environments. This resilience could be attributed to the additional support and restraint provided by the LSAM-30 aggregates, which mitigated the asphalt stress concentration and reduced fatigue crack initiation and propagation. Moreover, at lower temperatures, less deformation and displacement occurred in the mixtures, resulting in reduced contact areas between the aggregates and limiting the possibility of relative movement. Consequently, this situation aids in diminishing the effects of fatigue shear stress and the separation between the asphalt and aggregates.

3.3.3. Strain Effect

Figure 11a shows that at 15 °C and 15 Hz, under a strain of 200 $\mu\epsilon$, AC-13 exhibits a 16.9% higher fatigue performance compared to LSAM-30, while AC-20 surpasses LSAM-30 by 11.9%. At 400 $\mu\epsilon$, AC-13 demonstrates a 15.9% better fatigue performance than LSAM-30, with AC-20 exceeding LSAM-30 by 11.4%. Similarly, at 600 $\mu\epsilon$, AC-13's fatigue performance outperforms LSAM-30 by 16.3%, while AC-20 surpasses LSAM-30 by 8.7%. Finally, at 800 $\mu\epsilon$, AC-13 displays a 16.6% higher fatigue performance than LSAM-30, and AC-20 outperforms LSAM-30 by 10%.

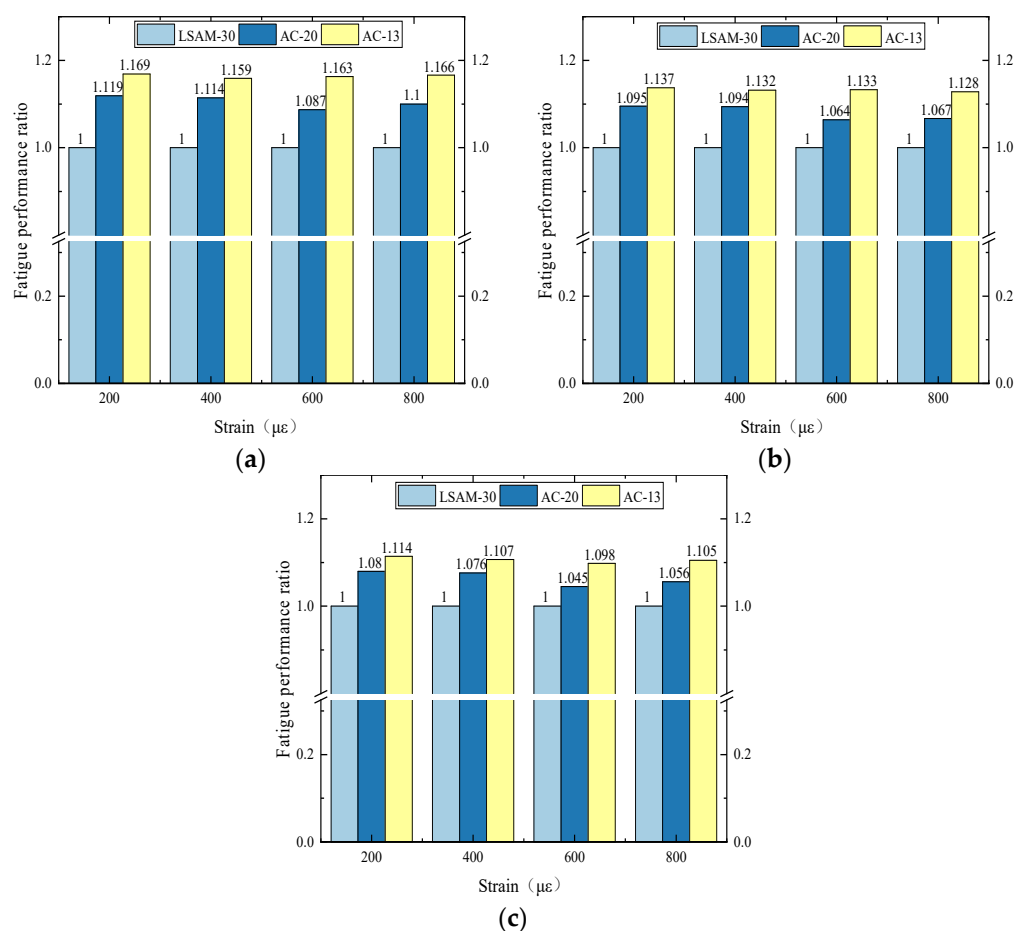


Figure 11. Fatigue performance ratio at different strains: (a) 15 °C and 15 Hz, (b) 10 °C and 15 Hz, (c) 5 °C and 15 Hz.

Comparing the variations in fatigue life ratios among the three asphalt mixtures at fixed temperatures and frequencies with changing strains, it was observed that there is no discernible pattern in the fatigue life ratio with varying strains. Moreover, different strains had a minimal impact (<5%) on the variation in the fatigue performance of asphalt mixtures with different gradations. This can be attributed to the good ductility of the asphalt in the mixtures and the effective friction between the frameworks, allowing them to effectively absorb and dissipate external loads and thereby maintaining a stable fatigue resistance across different strain conditions. However, considerable variations in the four strain gradients may lead to fluctuating fatigue performance ratios among different gradations, obscuring any discernible pattern in the fatigue performance ratio.

A comparison of the fatigue performance ratios across all conditions revealed that the fatigue performance ratios of the three asphalt mixtures did not exhibit significant changes with varying strains but demonstrated considerable variations with alterations in temperature and frequency. With an increasing temperature or frequency, the fatigue performance ratios of the three asphalt mixtures consistently increased. This indicates that the LSAM-30 asphalt mixture exhibited a stable resistance to crack propagation in low-temperature environments. The LSAM-30 aggregate provides enhanced support and confinement, mitigates stress concentrations in the asphalt, and reduces the initiation and extension of fatigue cracks. Moreover, under low-frequency conditions, the internal structure of LSAM-30 tends to stabilize, forming a denser structure that can withstand external stresses better.

4. Conclusions and Outlook

4.1. Conclusions

In this study, four-point bending tests were conducted to compare and analyze the fatigue performances of LSAM-30, AC-20, and AC-13 under different frequencies (5, 10, and 15 Hz), temperatures (5, 10, and 15 °C), and strains (200, 400, 600, and 800 $\mu\epsilon$). This investigation aimed to establish the fatigue characteristics of LSAM-30 and subsequently develop fatigue prediction equations based on the frequency and temperature factors for LSAM-30. The major conclusions drawn from this study are as follows:

- (1) The fatigue performance of LSAM-30 varied under different loading frequencies. At lower frequencies, the internal material of LSAM-30 tends to maintain a stable structure, and the asphalt in LSAM-30 has more time to relax, which can help alleviate the displacement and friction between material particles, thereby reducing the impact of fatigue damage.
- (2) A comparison of the fatigue results of LSAM-30, AC-20, and AC-13 under all conditions revealed that the fatigue performance ratio of the three asphalt mixtures did not vary significantly with strain but exhibited significant changes with variations in temperature and frequency.
- (3) With an increase in temperature or frequency, the fatigue performance ratio of the three asphalt mixtures increased, indicating that the increase in temperature and frequency weakened the supporting effect of large-sized aggregates in LSAM-30 asphalt mixtures. In comparison to AC-13 and AC-20, the temperature or frequency is more likely to affect the fatigue performance of LSAM-30.

4.2. Outlook

In summary, under low-frequency conditions, LSAM-30 can effectively leverage the supportive role of its large aggregate particles. However, its fatigue performance tends to deteriorate under high-temperature or high-frequency conditions. Therefore, in practical engineering scenarios characterized by lower temperatures and lower load frequencies, prioritizing the selection of LSAM-30 is advisable. This approach will aid in enhancing the longevity of roads in low-temperature or low-frequency environments, consequently reducing the consumption of maintenance resources and funds while bolstering the sustainability of the road infrastructure.

This study determined the fatigue characteristics of LSAM-30 by selecting specific experimental parameters and established an exponential fatigue prediction equation for LSAM-30 based on temperature and frequency factors. However, the applicability of this equation requires further investigation. In addition, the limited number of experimental variables selected in this study for LSAM-30 suggests the potential for considering additional influencing factors. This could involve experimenting with suitable combinations of factors such as particle sizes, temperatures, frequencies, strains, asphalt types, and asphalt concentrations. These extended experiments significantly enhance the accuracy of the exponential prediction model. However, the predictive equations obtained in this study have not yet been widely applied or validated. In future work, they can be applied to predict the fatigue performance of other types of asphalt mixtures and will be continuously revised to enable their extensive application in fatigue performance studies of different asphalt mixtures.

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