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Research Article

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Experimental studies on the dynamic viscoelastic properties of basalt fiber-reinforced asphalt mixtures

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Abstract: To study the influence of basalt fibers on the viscoelastic mechanical properties of asphalt concrete (AC) mixtures, unconfined compressive dynamic modulus tests were performed on styrene–butadiene–styrene (SBS)-modified AC mixtures reinforced with various contents of basalt fibers ranging from 0.2 to 0.5% by weight at five temperatures and six load frequencies, and the dynamic moduli and phase angles of the mixtures were measured. Compared with the test results of the control mixture (with no basalt fibers), the data show that the high-temperature dynamic modulus of the mixtures initially increases and subsequently decreases with increasing fiber content and reaches its maximum value when the basalt fiber content is 0.3%, while the low-temperature dynamic modulus decreases monotonically with increasing fiber content. Furthermore, the phase angle of the mixtures initially decreases and later increases with increasing fiber content and reaches its minimum value when the basalt fiber content is 0.3%. These behaviors indicate that the addition of basalt fiber improves the high-temperature rutting resistance and low-temperature cracking resistance of the SBS-modified AC mixtures. In addition, the results of the wheel rut test exhibit a good correlation with the results of the dynamic modulus test, revealing the reliability of the dynamic modulus test for evaluating the high-temperature rutting resistance of basalt-fiber-reinforced AC mixtures.

Keywords: basalt-fiber-reinforced asphalt mixture, dynamic modulus, phase angle

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1 Introduction

High-temperature rutting and low-temperature cracking are the two most predominant types of distress in road pavement, shortening the service life of the pavement and increasing the maintenance cost. Various studies have demonstrated that adding different types of fibers and polymers to asphalt concrete (AC) could be an effective method for postponing the deterioration of AC pavement and increasing the service life [1–3]. Basalt fiber is a type of natural mineral fiber with the advantages of good asphalt adsorption, high strength, high-temperature resistance, and environmental friendliness. It has been reported that adding short basalt fibers into AC can enhance the low-temperature crack resistance, high-temperature rutting resistance, and water stability of AC mixtures [4–6].

It is well recognized that the mechanical behavior of AC mixtures strongly depends on time, temperature, and frequency, which can be characterized by dynamic modulus tests or static viscoelasticity tests (e.g., stress relaxation or creep). The dynamic modulus test is an AASHTO standard test for characterizing the stiffness of AC mixtures [7]. The report of the National Cooperative Highway Research Program (NCHRP) of the United States suggests that the dynamic modulus ($|E^*|$) and rutting indicator ($|E^*|/\sin\delta$) can evaluate the high-temperature rutting resistance and fatigue resistance of AC mixtures well [8].

Ye et al. [9,10] investigated the influence of three types of fibers, including cellulose fibers, polyester fibers, and mineral fibers, on the dynamic and fatigue properties of fiber-reinforced AC mixtures and demonstrated that the dynamic modulus and phase angle of fiber-reinforced AC mixtures at 15°C were lower than those of the control mixture. The decrease in the dynamic modulus indicates that the addition of fibers reduces the stiffness of the AC mixture and improves its flexibility. The decrease in the phase angle also indicates the enhancement of the elastic property and the improvement of the fatigue damage resistance of the fiber-reinforced AC mixture. Apeagyei [11] conducted dynamic modulus tests at 38°C and flow number (FN) tests at 54°C on 16 AC mixtures, and the results showed that the FN was significantly correlated with $|E^*|$, and that $|E^*|$ could be a potential rutting specification parameter. In addition to the improvements in high-temperature performance, Zheng et al. [4] investigated the low-temperature cracking resistance of fiber-reinforced AC mixtures, and the improvement effect of basalt fiber was better than that of polyester fiber and xylogen fiber. Based on the response surface methodology, Wang et al. [5] proposed a design optimization of SBS-modified AC mixtures with basalt fibers: fiber content of 0.34%, fiber length of 6 mm, and asphalt–aggregate ratio of 6.57%. Morova [12] demonstrated that basalt fiber had a positive effect on the high-temperature stability of AC mixtures. Qin et al. [13] found that basalt fiber could substantially improve the high-temperature rheological properties and crack resistance of asphalt mastics. These studies show that the addition of basalt fibers can improve the road performance of AC mixtures through parameters such as the dynamic modulus and phase angle, but a few studies are available on the effect of basalt fiber content on the dynamic modulus, phase angle, and high/low-temperature road performance of SBS-modified AC mixtures. When the fiber content is small, the enhancement effect on the AC mixture is not obvious. When the fiber content is too high, the fiber easily produces negative effects, such as agglomeration. Hence, only with appropriate fiber content can the AC mixture achieve the best road performance.

In addition to experimental research, numerical simulation is increasingly used to analyze the multiscale mechanical properties of fiber-reinforced asphalt mixtures [14,15]. Cao et al. [16] predicted the dynamic moduli of the AC material using a finite element method coupled with random aggregate generation technique and considering the linear viscoelasticity of the porous matrix of bituminous mastics. Peng et al. [17] applied the modified two-phase micromechanics model and the generalized self-consistent model to predict the dynamic modulus of asphalt concrete. Zhang et al. [18] employed a new algorithm for generating a 3D numerical model in MATLAB software to reflect the random distribution and orientation of the round and straight basalt fibers dispersed in the asphalt-like matrix, and study the compressive and shear creep behavior and reinforcement effect of different fiber contents under constant loading with ABAQUS finite element software. Sun et al. [19] used a mesoscopic damage constitutive model in accordance with the Mori–Tanaka homogenization algorithm and progressive damage theory to predict the composited material properties of the basalt-fiber-reinforced concrete, and investigated the effects of basalt fiber on the macroscopic compressive, splitting tensile, and bending performances of the concrete by finite element simulation. The multiscale simulation of AC mixtures needs to be verified by standard tests. An appropriate multiscale simulation strategy can provide a promising and powerful tool for gradation design and rapid performance prediction of the AC mixtures.

The aim of this paper is to study the influence of basalt fiber content on the viscoelastic mechanical properties of SBS-modified AC mixtures and determine the optimal fiber content. We conduct unconfined dynamic modulus tests recommended by AASHTO T342 [7] to measure the frequency sweep dynamic mechanical properties of the mixtures reinforced with various basalt fibers at low and high temperatures to evaluate the influence of the basalt fiber content on the dynamic modulus, phase angle and rutting factor of the mixtures. Finally, the test outcomes of dynamic modulus are discussed and compared with the results of wheel rut tests, and the correlation between the dynamic modulus, the rutting factor, and the dynamic stability is established.

2 Materials and testing

2.1 Raw materials

To prepare the AC-13C mixture specimens for dynamic modulus tests, artificially crushed basalt was used as the coarse aggregate, artificial sand was used as the fine aggregate; and limestone powder with a particle size of 0–0.075 mm was used as the mineral filler. The SBS-modified asphalt binder used in this paper was produced by Maoming Petrochemical Co., Ltd. in China. Table 1 lists the physical properties of the asphalt binder tested according to the specification JTG E20-2011 [20]. Basalt fibers with a length of 6 mm were used as reinforcement additives in this study, and the physical and mechanical properties are listed in Table 2. Figure 1 shows the morphology of the basalt fibers.

Table 1: Physical properties of the SBS-modified asphalt binder

Test item	Unit	Test value	Required value	Standard method
Penetration (25°C, 5 s, 100 g)	0.1 mm	55	40–60	JTGE20-T0604
Elongation (5°C, 5 cm min^{-1})	cm	26	≥20	JTGE20-T0605
Softening point	°C	68	≥60	JTGE20-T0606
Solubility (trichloroethylene)	%	99.6	≥99	JTGE20-T0607
Density (25°C)	g cm^{-3}	1.039	—	JTGE20-T0603
Kinetic viscosity (135°C)	Pa s	1.79	≤3	JTGE20-T0620
Flash point	°C	290	≥230	JTGE20-T0611
Recovery of elasticity (25°C)	%	83	≥75	JTGE20-T0662
Mass loss after RTFOT	%	0.5	≤1.0	JTGE20-T0609
Penetration ratio after RTFOT (25°C)	%	71	≥65	JTGE20-T0604
Elongation after RTFOT (5°C, 5 cm min^{-1})	cm	16	≥15	JTGE20-T0605

Table 2: Physical and mechanical properties of the basalt fiber

Project	Unit	Value
Density	g cm^{-3}	2.65
Average length	mm	6
Fiber diameter	μm	14
Tensile strength	MPa	3,060
Elastic modulus	GPa	99
Elongation at break	%	3
Thermal conductivity	W m^{-1} K	0.03–0.038
Melt temperature	°C	1,050

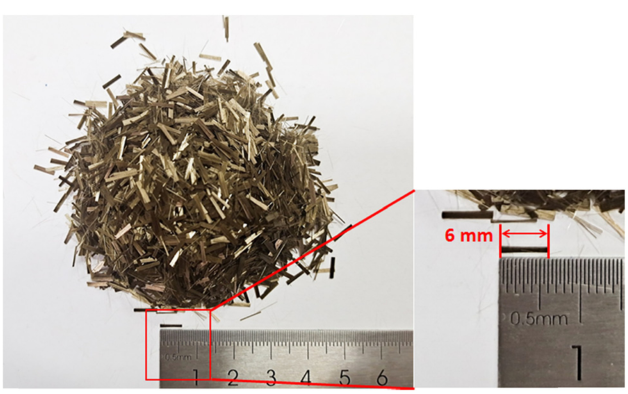

Figure 1: Morphology of 6 mm long basalt fibers.

2.2 Aggregate gradation and specimen preparation

AC-13C asphalt mixture gradation is designed according to the Standard Test Methods of Bitumen and Bituminous Mixtures for Highway Engineering [20], as listed in Table 3, which is widely used in the surface layer of asphalt pavements in China. The asphalt–aggregate mass ratios are determined to be 4.84, 4.9, 4.96, 5.03, and 5.10% for the AC mixtures with 0.0, 0.2, 0.3, 0.4, and 0.5% basalt fibers by weight, respectively. Cylinders with a diameter of 150 mm and height of 170 mm are first fabricated with a 76-PV2522 Superpave gyratory compactor (Controls Corporation, Liscate, Italy) and then cored and cut into specimens with a diameter of 100 mm and height of 150 mm for dynamic modulus tests.

2.3 Experimental procedure

In this paper, a DTS-30 servo-hydraulic dynamic testing machine with a temperature chamber (IPC Global Pty Ltd. Boronia, Australia) is used for the dynamic modulus measurements, as shown in Figure 2. To reduce the friction between the clamps and the specimen, double-layer polytetrafluoroethylene (PTFE) films are placed on both ends of the specimen. Two LVDT deformation sensors with a measurement range of ±1 mm and a gauge length of 100 mm are used to record the deformation data. Haversine compressive stress is applied according to AASHTO T342 [7] on the specimen at five specified temperatures (−10, 4.4, 21.1, 37.8, and 54.4°C) and six load frequencies (0.1, 0.5, 1.0, 5, 10, and 25 Hz). The stress amplitudes are appropriately selected to meet the linear viscoelasticity, ensuring that the strain of each load cycle does not exceed 50–150 microstrains and that the total permanent strain does not exceed 1,500 microstrains. Before the tests at each temperature, the specimens are conditioned in heat preservation for at least 4 h so that the temperature is uniform throughout the mass of the specimen.

Table 3: Aggregate gradation of the AC-13C asphalt mixture

	Passing rate (%)									
Sieve size (mm)	**16**	**13.2**	**9.5**	**4.75**	**2.36**	**1.18**	**0.6**	**0.3**	**0.15**	**0.075**
Upper limit	100	100.0	85.0	68.0	50.0	38.0	28.0	20.0	15.0	8.0
Lower limit	100	90.0	68.0	38.0	24.0	15.0	10.0	7.0	5.0	4.0
Composite gradation	100	95.6	77.1	53.3	35.4	24.0	17.2	12.0	9.1	6.2

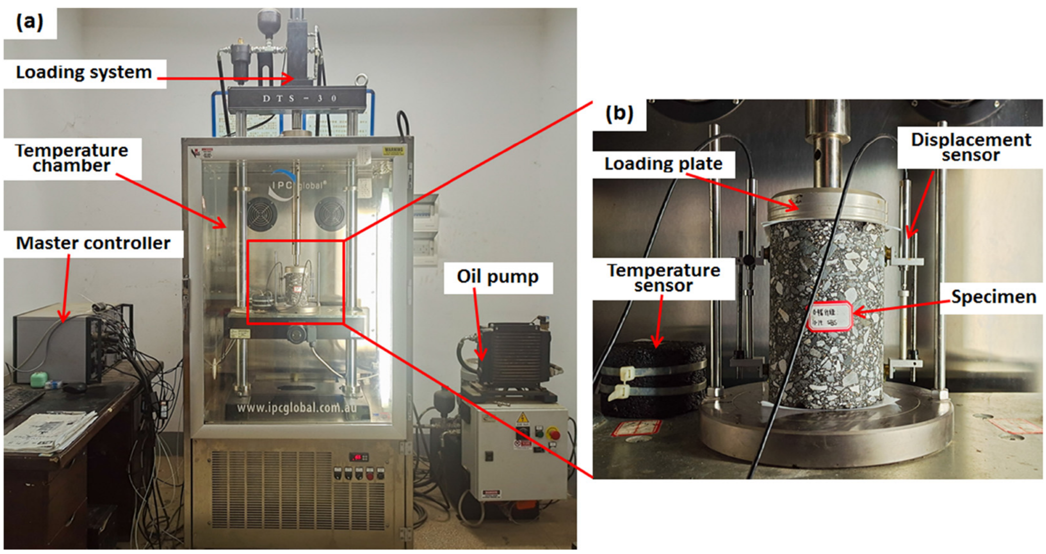

Figure 2: (a) DTS-30 dynamic testing machine and (b) specimen and measurement sensors.

For a linearly viscoelastic material, such as the AC mixtures investigated in this study, subjected to harmonic oscillatory stress $\sigma_0 \exp(i\omega t)$ of frequency ω, the resultant strain is $\varepsilon_0 \exp(i\omega t - \delta)$, in which σ_0 and ε_0 are the applied stress amplitude and the measured strain amplitude, respectively, and δ is the phase lag between the strain and stress due to the viscoelasticity of the material. At each temperature and frequency, the complex modulus (E^*), storage modulus (E'), loss modulus (E'') and phase angle (δ) can be correlated by the following equations [21]:

$$E^* = |E^*|\exp(i\delta) = \frac{\sigma_0}{\varepsilon_0}[\cos(\delta) + i\ \sin(\delta)] = E' + iE'', \quad (1)$$

$$\delta = \tan^{-1}\left(\frac{E''}{E'}\right) = t_i/t_p, \quad (2)$$

where $|E^*|$ is the dynamic modulus, t_i is the time lag between the peak sinusoidal stress and strain, and t_p is the time for a complete stress cycle.

3 Results and discussion

3.1 Relationship between the dynamic modulus and fiber content

Because $|E^*|$ is expressed as the ratio of the stress and the amplitudes, it reflects the stiffness of the asphalt mixtures. Figure 3 shows the $|E^*|$ measurement results for SBS-modified AC mixtures with various basalt fibers. It reveals that for all AC mixtures, $|E^*|$ increases with increasing frequency at all temperatures and decreases with increasing temperature at any given frequency.

Figure 4 shows the variation of $|E^*|$ with the fiber content at the lowest temperature (−10°C) and the highest temperature (54.4°C). Figure 4(a) indicates a remarkable reduction of the low-temperature $|E^*|$ of fiber-reinforced AC mixtures in comparison with that of the control mixture, e.g., $|E^*|$ values of AC mixtures with fiber contents of

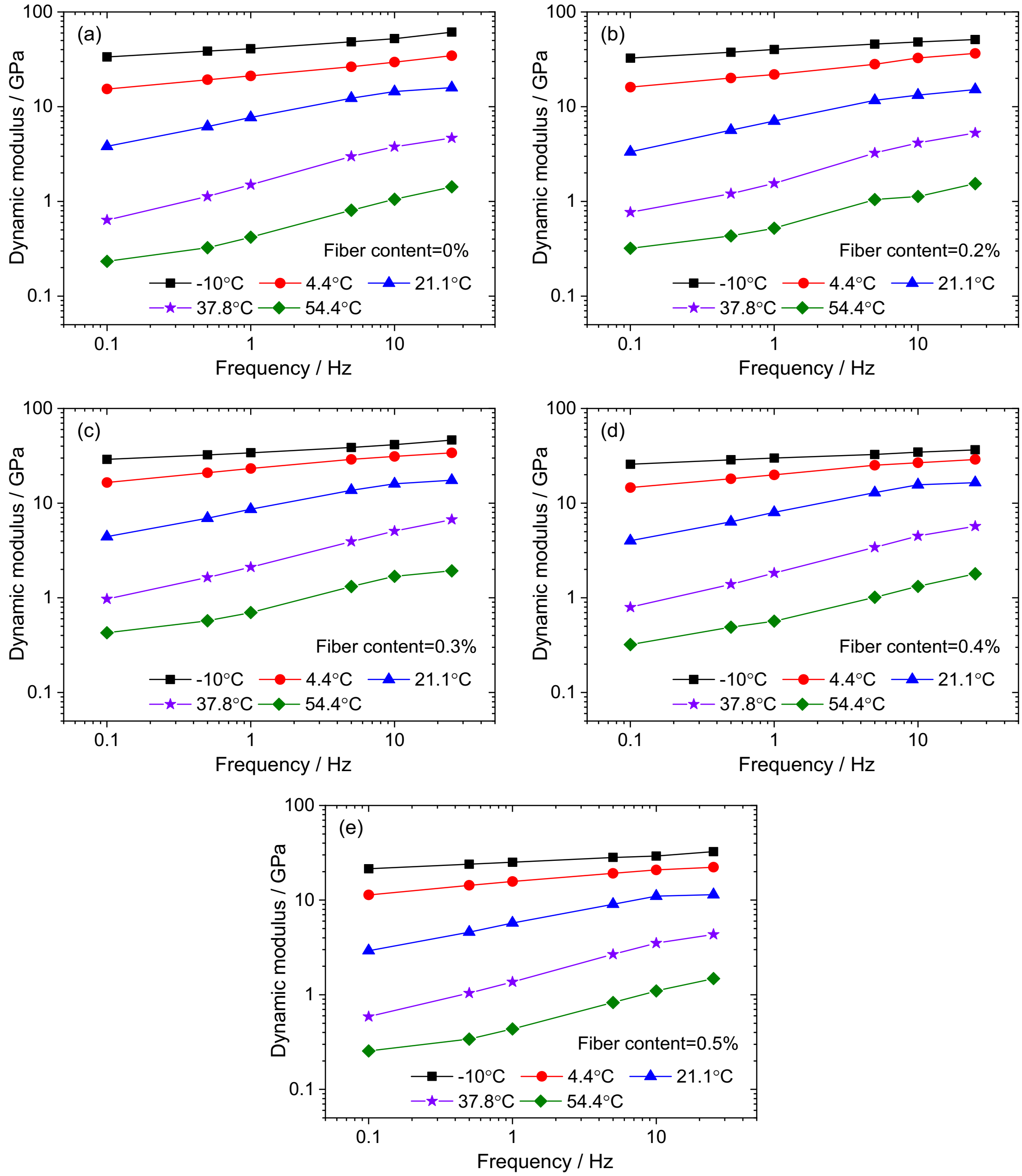

Figure 3: Variation of $|E^*|$ with frequency at various temperatures for SBS-modified AC mixtures with basalt fibers: (a) 0% fiber, (b) 0.2% fiber, (c) 0.3% fiber, (d) 0.4% fiber, and (e) 0.5% fiber.

0.5 and 0.3% are reduced by 13.5–24.3 and 36.1–47.0%, respectively, for the given test frequencies compared with that of the control mixture. This reduction reveals an enhancement of the flexibility and cracking resistance of the fiber-reinforced AC mixtures at low temperatures. This result may be attributed to basalt fiber network formation in the mixture, which plays a positive role in reinforcement [12]. Figure 4(b) shows that the high-temperature $|E^*|$ initially increases and then decreases with increasing fiber content and reaches its maximum value when the fiber content is 0.3%. Moreover, the high-temperature $|E^*|$ of all fiber-reinforced AC mixtures is greater than that of the control mixture, indicating an improvement in the stiffness and rutting resistance at high temperatures. Quantitatively, the $|E^*|$ values of AC mixtures with 0.3% fibers at 54.4°C increase by 35.46, 59.96, 63.04, 67.06, 76.31, and 83.69%, depending on the load frequency, compared with that of the control mixture.

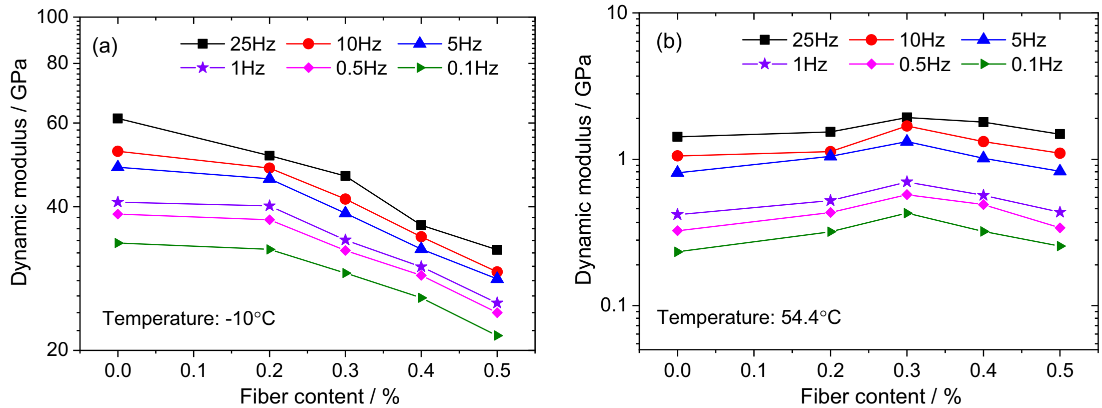

Figure 4: Variation of $|E^*|$ basalt fiber content at (a) −10°C and (b) 54.4°C.

3.2 Relationship between the phase angle and fiber content

The phase angle is the parameter characterizing the phase lag between the strain response and applied stress in viscoelastic materials, which becomes 0° and 90° for ideal elastic materials and ideal viscous materials, respectively. A larger phase angle manifests more viscous and less elastic behavior. Figure 5(a)–(e) show the frequency sweep data of the phase angle in the dynamic modulus tests of AC mixtures with various basalt fibers, and the same trend can be seen for mixtures with different amounts of fibers. It is obvious from Figure 6 that the phase angles of the fiber-reinforced AC mixtures are smaller than that of the control mixture in the test frequency range, regardless of the test temperature. The reduction in the phase angle reveals that the fiber-reinforced mixtures behave more elastically and less viscously than the control mixture, which produces less permanent deformation and improves the rutting resistance. Moreover, at the lowest temperature (−10°C), the phase angle of the fiber-reinforced AC mixture decreases with increasing frequency, as shown in Figure 6(a), while the opposite trend is found at the highest temperature (54.4°C) as shown in Figure 6(b). This behavior is also apparent in Figure 7; in addition, we can evaluate the influence of the fiber content on the phase angle. The phase angles initially decrease and then increase with increasing fiber content, and the mixtures with 0.3% fibers by weight have the minimum phase angles. This result again indicates that the addition of basalt fiber improves the rutting resistance of the mixtures.

3.3 Relationship between the rutting factor and fiber content

In the previous two sections, the dynamic modulus and phase angle were separately used to evaluate the high-temperature rutting performance of the basalt-fiber-reinforced AC mixtures. The rutting factor ($|E^*|/\sin\delta$) is a comprehensive consideration of these two indicators [8,10]. A high dynamic modulus and low phase angle benefit the high-temperature performance of asphalt mixtures, which reduces the high-temperature flow deformation and increases the permanent deformation resistance. The higher the rutting factor, the smaller the flow deformation and the greater the resistance to rutting. Table 4 shows the calculated rutting factors of AC mixtures with various basalt fibers at 54.4°C for six load frequencies from the measured dynamic moduli and phase angles. Obviously, all the basalt-fiber-reinforced AC mixtures have higher rutting factors than the control mixture, and the mixtures with 0.3% basalt fibers have the highest rutting factor and consequently the best rutting resistance at each test frequency. According to the values of the rutting factor, the rutting resistance of basalt-fiber-reinforced AC mixtures is in the order of 0.3% > 0.4% > 0.2% > 0.5% > 0.0%.

3.4 Discussions and further verification

The test results of the dynamic modulus and phase angle show that the addition of basalt fiber enhances the low-temperature cracking resistance and high-temperature

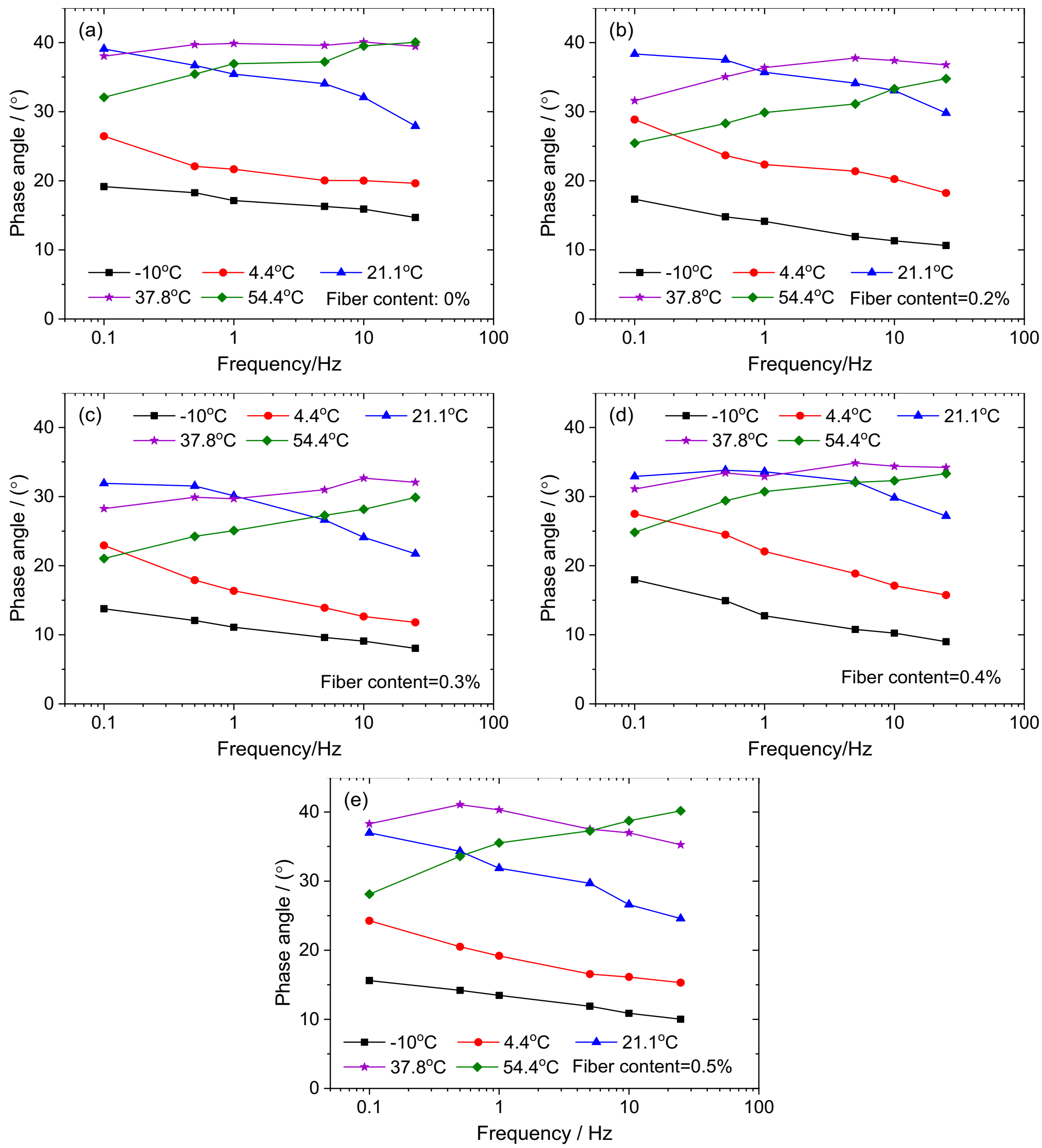

Figure 5: Variation of phase angles with frequencies at various temperatures for SBS-modified AC mixtures with basalt fibers: (a) 0% fiber, (b) 0.2% fiber, (c) 0.3% fiber, (d) 0.4% fiber, and (e) 0.5% fiber.

rutting resistance of the AC mixtures, and the mixtures with 0.3% basalt fiber content have the best rutting resistance. To explain these phenomena, the temperature sensitivity of AC mixtures should be considered. The material properties and failure mechanism of AC mixtures depend on the temperature. At low temperatures, the unreinforced AC mixture is hard and brittle and is prone to cracking. When basalt fibers are added to an AC mixture, the fibers can bear part of the internal stress of the mixture, and the "bridging" and "reinforcing" effects can reduce the stress concentration, making the mixture more uniform and enhancing the low-temperature load capacity [2,12,13]. Moreover, the basalt fiber has good flexibility and its bridging action can closely connect the two broken parts at the microcrack [13], which enhances the low-temperature flexibility and enables the mixture to withstand the greater tensile strain. Moreover, the degree of strain enhancement of basalt fibers in the AC mixture is greater than that of stress enhancement so the dynamic modulus decreases [3]. At high temperatures, the adhesion of asphalt decreases greatly so the pavement is prone to rutting. The basalt fibers can absorb the oil in the asphalt and increase the adhesion of the asphalt; moreover, the fibers can absorb free asphalt and increase the amount of

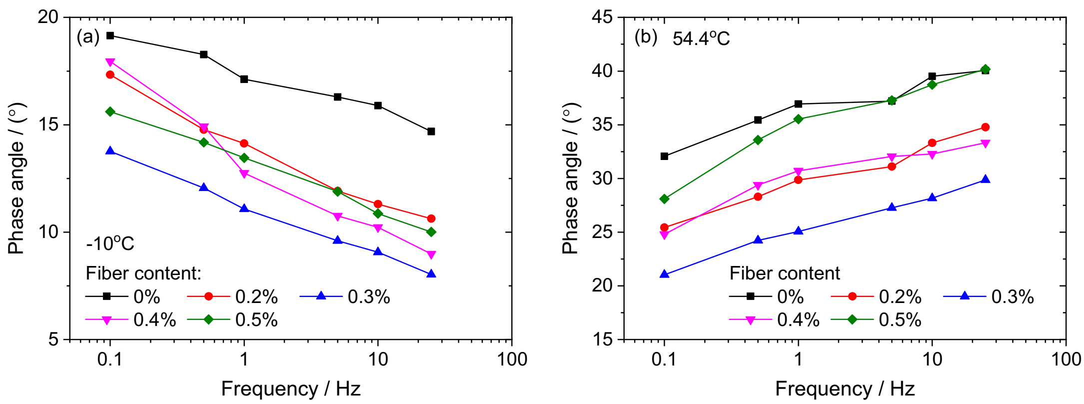

Figure 6: Phase angles of AC mixtures with various basalt fibers from frequency sweep measurements at (a) −10°C and (b) 54.4°C.

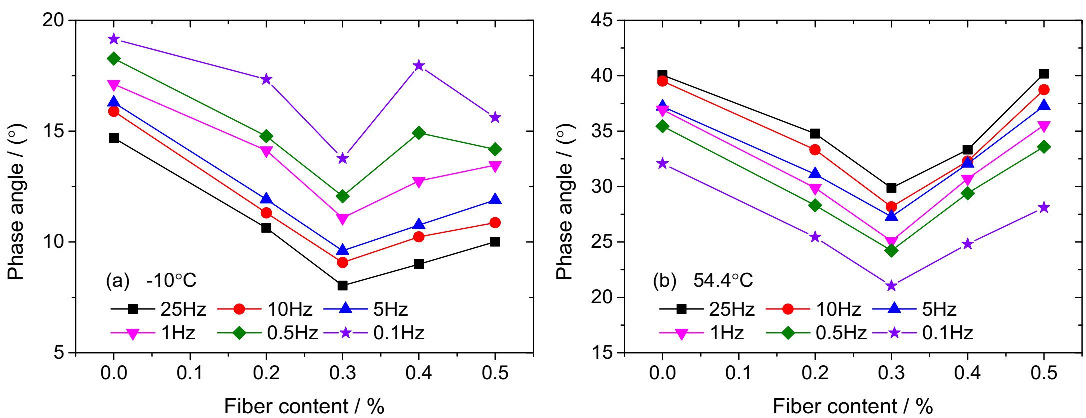

Figure 7: Variation of phase angles of AC mixtures with basalt fiber contents at (a) −10°C and (b) 54.4°C.

Table 4: Rutting factor, $|E^*|/\sin\delta$, of AC mixtures at 54.4°C

Fiber content (%)	$|E^*|/\sin\delta$ (GPa)					
	25 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz
0.0	2.21	1.66	1.34	0.70	0.56	0.44
0.2	2.70	2.05	2.03	1.05	0.91	0.74
0.3	4.13	3.69	3.21	1.59	1.30	1.06
0.4	3.27	2.47	1.91	1.11	1.00	0.76
0.5	2.30	1.76	1.37	0.75	0.61	0.54

structural asphalts [3]. Therefore, after adding fibers, the strain of the AC mixture is smaller than that of the control mixture under the same stress; thus, the addition of fibers can improve the dynamic modulus and high-temperature deformation resistance of the AC mixture. However, if the content of fibers is too high (>0.3%), the excess fibers will cause defects, such as fiber agglomeration, which leads to a decrease in the dynamic modulus of the mixture.

The phase angle characterizes the viscosity of the material, while the viscosity at different temperatures is primarily determined by the asphalt binder. When the content of basalt fiber is appropriate, the fibers that are uniformly distributed in the mixture can form a three-dimensional network structure [12], which can absorb free asphalt and increase the amount of structural asphalt [3], which causes reinforced mixtures to behave more elastically and less viscously and so the phase angle decreases. When the fiber content is greater than the optimal value (0.3%), it easily causes internal defects, such as fiber agglomeration, which increases the viscous deformation of AC mixtures under loading and so the phase angle increases.

To verify the influence of the dynamic modulus on the high-temperature performance of basalt-fiber-reinforced AC mixtures, we performed wheel rut tests according to the specification JTG E20-2011 [20] and compared the results with the dynamic modulus and rutting factor.

Table 5: Results of wheel rut tests

Fiber content (%)	Specimen ID	DS/ (times per mm)	Mean value/ (times per mm)	Coefficient of variation (%)
0.0	#1	7,470	6,497	18.76
	#2	5,130		
	#3	6,890		
0.2	#1	13,029	12,906	14.17
	#2	10,996		
	#3	14,693		
0.3	#1	24,896	25,391	3.24
	#2	26,340		
	#3	24,936		
0.4	#1	19,020	19,090	5.59
	#2	20,190		
	#3	18,061		
0.5	#1	14,739	13,659	7.87
	#2	13,650		
	#3	12,588		

The wheel rut samples are compacted by an LDCX-1 wheel rut specimen sampling machine (Shanghai Luda Experiment Instrument Co., Ltd. Shanghai, China), and the specimen size is 300 mm × 300 mm × 50 mm. The wheel rut tests are performed on an LDCZ-1 automatic wheel rut tester (Shanghai Luda Experiment Instrument Co., Ltd. Shanghai, China). The test temperature is 60°C, the wheel pressure is 0.7 MPa, and the rutting resistance performance parameter obtained from the test is the dynamic stability (DS). The equation for DS is as follows [20]:

$$\mathrm{DS} = \frac{(t_2 - t_1) \times N}{d_2 - d_1} \times C_1 \times C_2, \quad (3)$$

where d_1 and d_2 are the deformations in mm at times t_1 and t_2, respectively. In this test, t_1 and t_2 are set to 45 and 60 min, respectively; C_1 is the coefficient of the test instrument type, which is 1.0 for the test in this article; $C_2 = 1.0$ is the time coefficient for the specimen with a length and width of 300 mm; and N is the rolling speed of the rubber wheel of the wheel rut tester, which is taken 42 times min^{-1} according to the specification.

Table 5 shows the DS obtained in wheel rut tests on AC mixtures with various basalt fiber contents of 0.2, 0.3, 0.4, and 0.5% and without basalt fibers.

The test results in Table 5 show that the value of the DS more than doubles because of the addition of basalt fibers, which indicates that the rutting resistance of basalt-fiber-reinforced AC mixtures is substantially improved. The DS reaches a maximum when the basalt fiber content is 0.3%, and according to the DS values, the rutting resistance of basalt-fiber-reinforced AC mixtures is of the order of 0.3% > 0.4% > 0.5% ≈ 0.2% > 0%, which is basically consistent with the rutting factor results. To facilitate the comparison and analysis of the results, Figure 8(a) and (b) show the correlation of the dynamic modulus $|E^*|$ and rutting factor $|E^*|/\sin\delta$, respectively, with the DS at 54.4°C. Figure 8 shows that, at 54.4°C, a good correlation holds between the dynamic modulus $|E^*|$ and DS and the rutting factor and DS, which verifies that the dynamic modulus at high temperature (54.4°C) can be used to characterize the high-temperature stability of AC mixtures. In addition, Figure 8 shows that a strong correlation ($R^2 > 0.85$) holds between the dynamic modulus/rutting factor and DS at 54.4°C and 25 Hz, indicating that the dynamic modulus/rutting factor at 54.4°C and 25 Hz is more suitable for describing the high-temperature performance of basalt-fiber-reinforced AC mixtures.

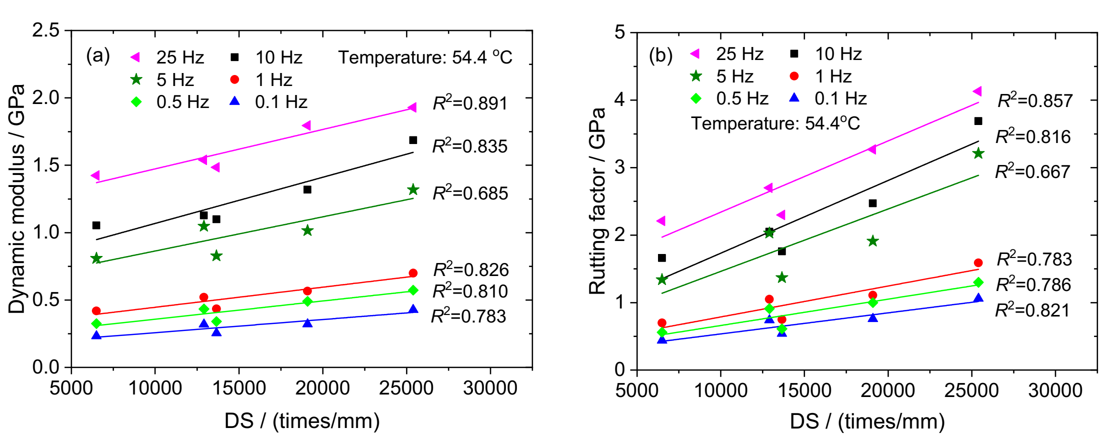

Figure 8: (a) Correlations between the dynamic modulus and DS and (b) correlations between the rutting factor and DS.

4 Conclusions

In this paper, the dynamic modulus tests of SBS-modified AC mixtures at different temperatures and frequencies were performed, and the influence of basalt fiber content on the dynamic viscoelastic properties of AC mixtures was investigated. The following conclusions can be drawn:

(1) Regardless of whether basalt fibers are added, the dynamic modulus of AC mixtures increases with increasing load frequency and decreases with increasing temperature; the phase angle varies with frequency in two ways that depend on temperature: it decreases with increasing frequency at low temperatures and increases with increasing frequency at high temperatures.

(2) The phase angle of basalt-fiber-reinforced AC mixtures is smaller than that of the control mixture, and it initially decreases and then increases with increasing fiber content; however, the variation of dynamic modulus with the fiber content is temperature-dependent and the addition of basalt fibers increases the high-temperature dynamic modulus and decreases the low-temperature dynamic modulus of AC mixtures, which improves the high-temperature stability and rutting resistance and enhances the low-temperature flexibility and cracking resistance. When the basalt fiber content is 0.3%, the fiber-reinforced AC mixture has the highest high-temperature dynamic modulus and the lowest phase angle and so it has the best high-temperature rutting resistance.

(3) The DS obtained from the wheel rut tests has a good correlation with the high-temperature dynamic modulus/rutting factor, which verifies that the dynamic modulus at high temperatures can be used to characterize the high-temperature stability of asphalt mixtures.

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Conflict of interest: Authors state no conflict of interest.

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