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Enhancing the Performance of Asphalt Mastic with Natural Fiber Reinforcement: Basalt and Bamboo Fibers

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Abstract: Incorporating fibers into asphalt mixtures as additives and stabilizers can significantly enhance the performance of asphalt pavements. This study aimed to analyze the impact of using basalt and bamboo fibers as modifiers on the properties of asphalt mastics. The effects of different types of fibers on rutting resistance, fatigue resistance, elastic recovery, and low-temperature cracking performance were tested using frequency scanning, linear amplitude scanning (LAS), multiple stress creep and recovery (MSCR), elastic recovery, and bending beam rheometer (BBR) experiments. The study results suggest that adding fibers into asphalt mastics can effectively improve their stiffness, and the higher the fiber content, the better the stiffness enhancement. Moreover, the characteristic flow index of asphalt mastics grows gradually with the rise in temperature, indicating that these materials exhibit near-Newtonian fluid behavior at elevated temperatures. Furthermore, incorporating fibers significantly enhances the high-temperature rutting resistance of asphalt mastics. However, the addition of fibers did not demonstrate any appreciable benefits in terms of fatigue resistance. The elasticity of asphalt mastics cannot be significantly changed by fiber content without compromising their elastic recovery. Surprisingly, the study's findings showed that adding basalt fibers to asphalt mastics did not improve their resistance to low-temperature cracks. On the other hand, it was discovered that the ability of asphalt mastics to resist cracking at low temperatures could be made up for by the use of bamboo fibers as a modifier together with a raised temperature. Overall, it was discovered that bamboo fibers performed better than basalt fibers at improving the performance of modified asphalt mastics.

Keywords: asphalt mastic; basalt fiber; bamboo fiber; rutting; fatigue

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1. Introduction

Asphalt mastic is a micro-dispersion system found in asphalt mixtures, where the filler acts as the dispersed phase in a high-consistency asphalt medium. The composition and microstructure of the mastic as well as its rheological characteristics, have a significant impact on the asphalt mixes' high-temperature stability and low-temperature deformation resistance. Recently, fibers have become a common additive or modifier to enhance the adhesion characteristics of asphalt mastic, increase the shear resistance of the mixture, and extend the pavement's service life [1,2]. The fibers disperse uniformly throughout the asphalt mixture and form a network structure that produces reinforcing and bridging effects, significantly enhancing the stability of both asphalt and asphalt mixtures.

Fibers are widely used to improve the performance of asphalt pavements, but the research on fiber-modified asphalt mastic is limited and focused on a single type of fiber.

Different fibers exhibit different modification effects on asphalt mixtures in various performance areas. For instance, the stiffness and rutting resistance of asphalt mixtures can be improved by the inclusion of polyester fiber and basalt fiber. On the other hand, it has been discovered that bamboo fiber increases the fatigue life of asphalt mixtures. Straw fiber works better at low temperatures despite being less effective at high temperatures. The addition of fibers to asphalt mixtures can improve the resistance to crack extension and raise the damage temperature. It should be emphasized, though, that the addition of fibers has a limit on how much low-temperature strength in asphalt mixtures may be improved. Asphalt mixtures' moisture sensitivity can be increased by aramid fibers, while their mechanical qualities can be enhanced by ceramic fibers [3–5]. The low-temperature performance of asphalt mixtures can be enhanced by mixing polyester fiber with an anhydrous calcium sulfate whisker. Combining various fibers and rubber powder has the potential to increase the asphalt mixtures' resistance to freeze–thaw damage and moisture stability. The impact of freeze–thaw cycles on fiber-modified asphalt mixtures; however, continues to be a problem that requires attention. Overall, using natural fibers has the benefit of being environmentally benign and renewable, which promotes sustainable development. Future technical applications and research in the realm of fibers in asphalt mixtures look promising.

The types of fibers currently used in roadways are diverse, and the modification effect of different fiber types on asphalt mixtures is shown in different performance areas. Chen et al. found that adding polyester and straw fibers improved the performance of asphalt because they were compatible with asphalt and that straw fibers were not as effective as polyester fibers in modifying asphalt at high temperatures, while straw fibers were more effective at low temperatures [6]. Yang et al. used three different fibers (i.e., carbon fibers, steel fibers, and steel wool) as microwave-absorbing materials to create self-healing asphalt mixtures that improved the mechanical properties and healing ability of the mixtures [7]. Liu et al. used ceramic fibers to develop ceramic fiber modified asphalt mixtures, showing that there is variability in the degree of influence of different fiber types on the mechanical properties of asphalt mixtures, and good wettability and dispersion of fibers and asphalt in the mixtures were found by scanning electron microscopy (SEM) experiments [8]. Fan et al. prepared a polyester fiber composite reinforced asphalt mixture (ACPRA) to meet the low temperature performance requirements by optimizing the anhydrous calcium sulfate whisker (ACSW) and polyester fiber content, where the asphalt aggregate ratio was 4.0%, the ACSW content was 10.8%, and the polyester fiber content was 0.4% [9].

The addition of basalt fibers to asphalt mixtures can strengthen the mixture and effectively improve its high and low-temperature performance. Many studies have been conducted to investigate the reinforcing properties of basalt fibers on asphalt mixtures, including mechanical behavior, low and high-temperature performance, and water sensitivity [10–13]. Qin X et al. suggested that compared with lignin fiber and polyester fiber, basalt fiber had a more significant impact on improving the performance of asphalt mortar [14]. Gao C et al. observed that basalt fibers were randomly distributed in the asphalt mixture matrix and had a strong wrapping force and connection with the matrix asphalt [15]. Nihat Morova [16] found that the incorporation of basalt fibers could substantially improve the high-temperature stability of asphalt mixtures. Wu et al. [17] stated that the addition of fibers enhanced the deformation tolerance of the asphalt mixture, although the specific influence of fiber type on the material's low-temperature performance varied. Xie et al. explored the rheological characteristics of basalt fiber-reinforced asphalt mastics and concluded that the incorporation of basalt fibers improved the stiffness, rutting resistance, and cracking resistance of the asphalt binder, but reduced its fatigue performance [18]. The use of bamboo fiber in asphalt mixtures not only reduces the environmental impact but also offers economic advantages. Bamboo forests are abundant and have relatively fast growth characteristics, reaching full maturity within 3 to 5 years, which solves the problem of intermittent scarcity of reinforcement material resources in terms of supply sources [19].

Furthermore, bamboo fiber is an eco-friendly fiber that is degradable, recyclable, low cost and renewable [20,21]. Jia et al. noticed that including bamboo fibers to asphalt mixtures strengthened their stiffness and durability to cracking at medium temperatures but had no meaningful effect on their high-temperature qualities [22]. Sheng et al. [23] observed that the inclusion of bamboo fibers in asphalt mixtures improved their resistance to water damage, rutting, and low-temperature cracking. Similarly, Jia et al. [24] found that the addition of bamboo fibers enhanced the dynamic modulus of asphalt mixtures. While the fatigue life of the modified mixtures was still better than that of traditional hot mix asphalt (HMA) after aging, these findings highlight the potential of renewable fibers as a viable alternative for enhancing the fatigue life of asphalt mixtures in support of sustainable development. Furthermore, Li et al. recovered bamboo fibers from bamboo residues to enhance asphalt mixture performance, which not only achieved waste utilization, but also delivered considerable environmental benefits and great promotion value [25].

In summary, while fibers are currently being used to enhance the road performance of asphalt pavements, research on fiber-modified asphalt mastic is limited, with a focus on a single type of fiber, and lacking comparison between different types of fibers. Natural fibers have the advantages of being renewable and green, and can improve the overall performance of asphalt mixtures and extend the service life of roads. Their application has good socio-economic benefits and development prospects, making them significant for sustainable development. Therefore, this study selected two natural fibers, basalt fiber and bamboo fiber, to modify the asphalt mastic, providing valuable insights for future research and engineering applications of these fibers in modified asphalt.

2. Materials and Methods

2.1. Materials

2.1.1. Asphalt Binder

The base asphalt used in this study was provided by Beijing Changping Asphalt Plant, with a penetration grade of pen-70. Table 1 shows the basic asphalt's primary physical features.

Table 1. Base asphalt's physical features.

Properties	Testing Standards	Results
Penetration (0.1 mm) at 25 °C	JTG E20-2011/T0604	75.2
Softening point (°C)	JTG E20-2011/T0606	49.2
Ductility (cm) at 5 °C	JTG E20-2011/T0605	35.5
Viscosity (Pa·s) at 135 °C	JTG E20-2011/T0625	0.35

2.1.2. Filler

In this study, plain asphalt mastics were made by mixing the base asphalt binder and filler in a 1:1 ratio, and Table 2 lists the physical properties of the filler.

Table 2. Properties of the filler material.

Apparent Density g/cm^3	Water Content (%)	Hydrophilic Coefficient	Appearance	Screening Test (%)		
				100	90–100	75–100
2.792	0.33	1.0	No agglomeration	100	95.8	83.1

2.1.3. Fibers

Basalt fibers are a type of high-performance fiber material that is inorganic, environmentally friendly, and considered to be a green material. They are composed of various oxides, including silica, alumina, calcium oxide, magnesium oxide, iron oxide, and titanium dioxide. Basalt fibers possess several exceptional properties, such as high strength, excellent electrical insulation, corrosion resistance, and high-temperature resistance. The main physical characteristics of the basalt fibers selected for this study are shown in Table 3. The bamboo powder used in this study was made from 5–6-year-old moso bamboo processed by mechanical crushing, and the physical properties are demonstrated in Table 4.

Table 3. Properties of the basalt fiber.

Density g/cm^3	Elongation (%)	Ash (%)	Moisture Content (%)	Length (mm)	Modulus (GPa)	Intensity (MPa)
1.78	1.45	0.29	0.35	6	238	4950

Table 4. Properties of the bamboo fiber.

Appearance	Odor	Ash Content	Density	Moisture	Purity	Water Solubility
light yellow	slight bamboo fragrance	≤0.5%	0.26 ± 0.03 g/mL	5–7%	100%	insoluble

To prevent fiber agglomeration in high-content asphalt mastics, the rheological performance of asphalt mastics was investigated at lower fiber content in this study. Two kinds of fibers, 6 mm basalt fibers and 200-mesh bamboo fibers, were utilized to create modified asphalt mastics with fiber concentrations of 3%, 6%, and 9%. The average length of 200-mesh bamboo fiber is around 1 mm, and the diameter of 6 mm basalt fiber should be around 6 µm. These contents were chosen to ensure sufficient asphalt adsorption while preventing fiber agglomeration. Figure 1 illustrates the macroscopic looks of basalt and bamboo fibers.

Figure 1. Basalt and bamboo fiber morphology.

2.2. Methods

Since there are currently no established methods for evaluating the behavior of asphalt mastic materials, this study evaluated its performance using test criteria of asphalt.

The rheological performance of this study is mainly based on DSR equipment and BBR equipment, and the schematic diagram of a series of tests is shown in Figures 2 and 3.

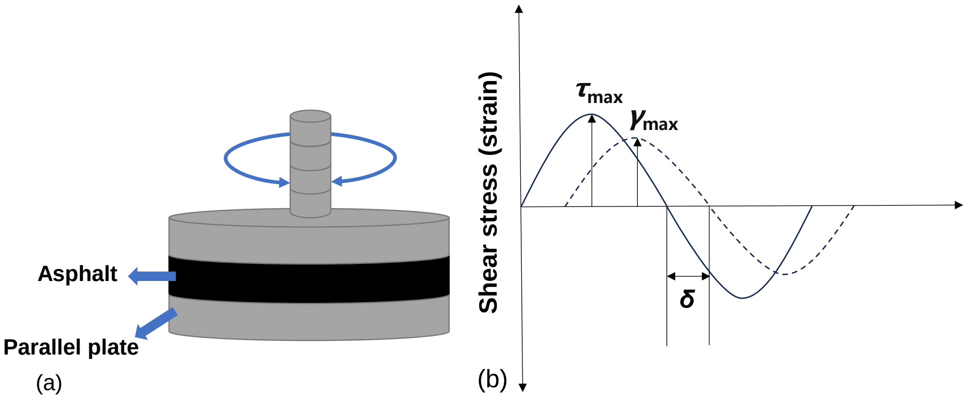

Figure 2. Schematic diagram of the tests: (**a**) operational principle of DSR; (**b**) wave pattern of stress and strain.

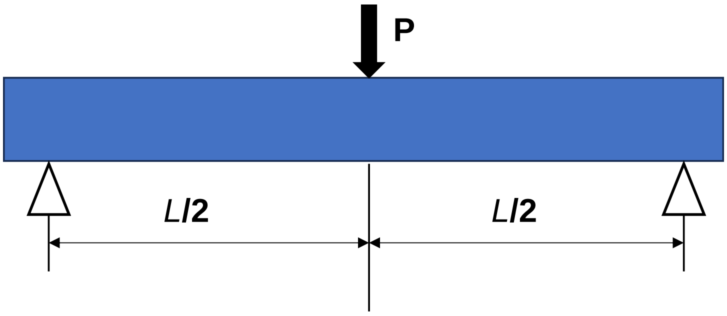

Figure 3. Schematic diagram of BBR test.

2.2.1. Preparation Procedure of Modified Asphalt Mastic

The procedure of preparing fiber asphalt mastic involves four steps. First, the fibers are dried at 105 °C for 24 h to remove any surface moisture. Second, 600 g of solid asphalt is liquefied by heating it at 135 °C for 2 h, before combining it with the filler and fiber. The filler and fiber are added gradually to the asphalt while stirring at 2000 revolutions per minute to prevent fiber clumping. Finally, continuous stirring at 135 °C for around 30 min with heated filler and fibers produces a homogeneous material. Table 5 lists the test material composition.

Table 5. A list of the asphalt mastics tested.

NO.	Percentage of Basalt Fiber in Weight (%)	Percentage of Bamboo Fiber in Weight (%)
1	0	0
2	3	0
3	6	0
4	9	0
5	0	3
6	0	6
7	0	9

2.2.2. Frequency Sweep Test

The rheological tests were carried out utilizing an Anton Par MCR 102 dynamic shear rheometer (DSR). The testing was executed utilizing two different plate geometries. A parallel plate geometry with a diameter of 25 mm and a 1 mm gap was utilized for temperatures over 40 °C, whereas an 8 mm parallel-plate geometry with a 2 mm gap was employed for temperatures under 40 °C. Frequency sweep experiments were conducted at seven different temperatures ranging from 10 °C to 70 °C, which encompassed a range of 0.1 rad/s to 100 rad/s. Subsequently, the results of the experiment were evaluated using the Christenson–Anderson–Marasteanu (CAM) model, and the master curve was fitted accordingly [26–28].

2.2.3. Linear Amplitude Sweep (LAS) Test

The AASHTO TP 101 LAS test protocol was used to assess the asphalt mastic's performance [29]. In addition, the LAS test was also employed to analyze the fatigue performance of asphalt mastic in this study. Specifically, the LAS test was conducted using a linear strain sweep with amplitudes ranging from 0.1% to 30% over a 5 min period (referred to as LAS-5), at an intermediate temperature of 20 °C, which is typical of the Beijing region. The LAS test data in Figure 4 were analyzed using the simplified viscoelastic continuum damage (S-VECD) model, which was specifically designed for fatigue modeling of asphalt concrete [30,31]. An artificial failure criterion of a 35% reduction in $|G^*|\sin\delta$ was utilized to assess the fatigue life of the binder [32].

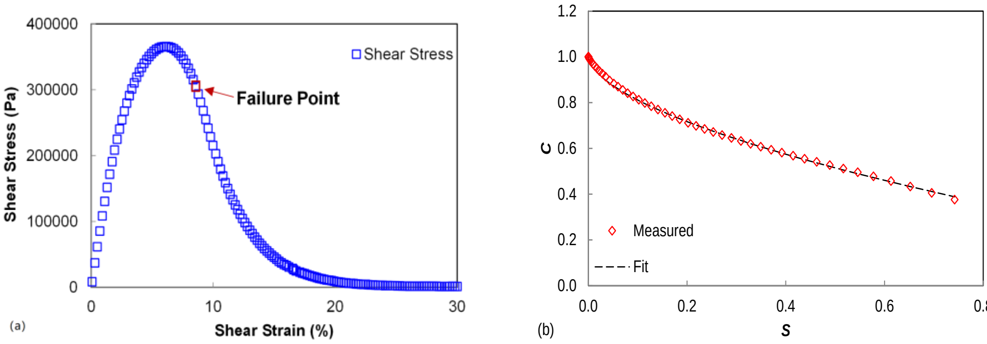

Figure 4. Modification of the fatigue model of the base asphalt binder at 20 °C by incorporating LAS data: (**a**) stress–strain curve; (**b**) damage characteristic curve.

2.2.4. Multiple Stress Creep Recovery (MSCR) Test

The capacity of asphalt binder to resist permanent deformation under high-temperature conditions was determined using the Multiple Stress Creep Recovery (MSCR) test based on the AASHTO TO 70 [33] protocol. The DSR applies a low stress level of 0.1 kPa for ten cycles, followed by a recovery period of 90 s, and then another ten cycles at a stress level of 3.2 kPa. The MSCR test performance parameters include recovery rate (R) and non-recoverable compliance ($J_{\rm nr}$), which are calculated using Equations (1) and (2). The parameters are determined for each of the ten creep-recovery cycles, with the average values of R and Jnr at each stress level (0.1 kPa and 3.2 kPa) being reported as $R_{0.1}$, $J_{\rm nr0.1}$, $R_{3.2}$, and $J_{\rm nr3.2}$.

$$R = (\gamma_p - \gamma_{nr})/(\gamma_p - \gamma_0) \tag{1}$$

$$J_{nr} = (\gamma_{nr} - \gamma_0)/\tau \tag{2}$$

2.2.5. Elastic Recovery (ER) Test

The Elastic Recovery (ER) test is an evaluation conducted on asphalt materials at medium temperatures to assess their ability to recover from deformation after undergoing elastic deformation. Specifically, the test is performed at a temperature of 20 °C and a shear rate of 2.315%s^{-1}. The ER (Elastic Recovery) test consists of two stages. In the first stage, the asphalt material is subjected to a constant loading rate until the shear strain reaches 277.78%, denoted as γ_1, within a loading time of 2 min. In the second stage, the asphalt material is unloaded and allowed to undergo recovery for 30 min. The strain at the end of the test is referred to as γ_2. The difference between γ_1 and γ_2 represents the elastic recovery strain of the asphalt material during the unloading recovery stage. The elastic recovery rate, defined as $(\gamma_1 - \gamma_2)/\gamma_1$, indicates the material's ability to recover at medium temperature. This reflects the percentage of strain that is recovered after unloading. A graphical representation of typical time–strain test results can be observed in Figure 5.

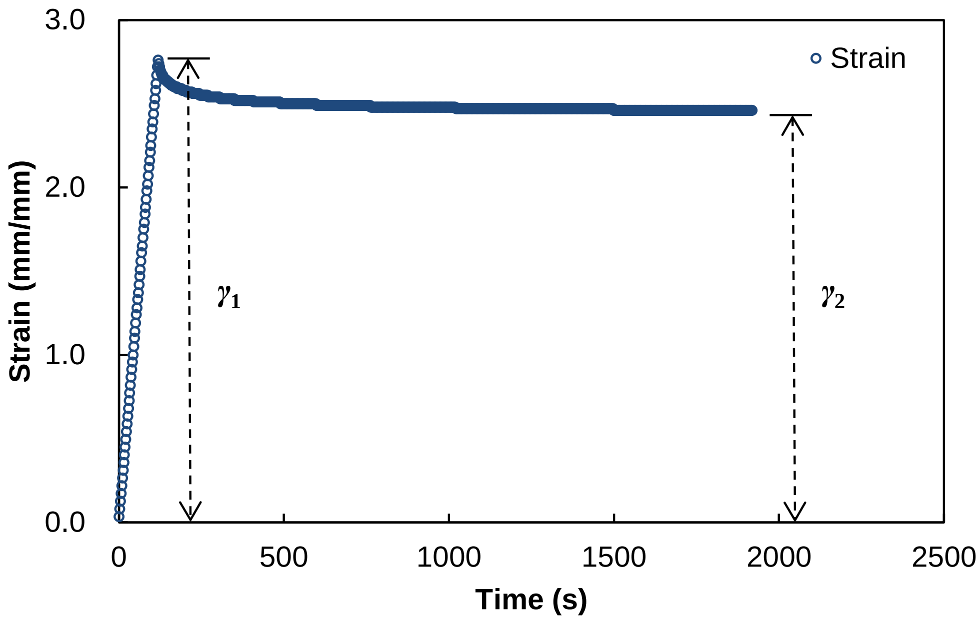

Figure 5. Time–strain results model based on ER test.

2.2.6. Bending Beam Rheometer (BBR) Test

To assess the low-temperature performance of the asphalt mastic, a bending beam rheometer (BBR) was utilized to determine its creep resistance. The BBR samples, which had dimensions of 125 mm × 12.5 mm × 6.25 mm, were chilled in an ethanol bath for 60 min at −6 °C, −12 °C, and −18 °C. The beam was supported by two stainless steel supports, and a load of 100 g was applied to the beam. The creep stiffness (*S*) and creep rate (*m*) of the asphalt mastics were measured after a loading time of 60 s. The stiffness of the beam was continuously monitored to determine its deflection over time. These parameters were utilized to assess the performance of the asphalt mastics under low-temperature conditions.

3. Results and Discussion

3.1. Modulus and Phase Angle Are Affected by Frequency

The dynamic shear modulus $|G^*|$ of the fiber-modified asphalt mastic was found to exhibit a positive correlation with the loading frequency, as shown in Figure 3. The logarithmic value of $|G^*|$ and the loading frequency were discovered to be in a logarithmic relationship. This is explained by the reduced contact time between the applied stress and the asphalt material at higher frequencies. Additionally, asphalt materials are viscoelastic by nature and can deform in three ways: elastic, viscoelastic, and vicious. As a consequence, the modulus of asphalt material rises as load action frequency rises. This is because at higher frequencies, the load action time is shorter, resulting in smaller deformation of the asphalt material and thus an increase in modulus. Conversely, at lower frequencies, the longer load action time leads to increased deformation and a decrease in modulus. Figure 6 shows that the dynamic modulus of the modified asphalt mixture steadily increased with the addition of basalt and bamboo fibers, a finding that is consistent with the reinforcing effect of fibers mentioned by Qin et al. in their paper, a phenomenon that can be explained by the fact that natural fibers can increase the modulus of asphalt mastic by acting as reinforcement and adhesion [14]. The chemical adsorption and attachment of the fibers to the asphalt simultaneously reduces the amount of free asphalt and increases the amount of structural asphalt, increasing the stability of the asphalt mastic.

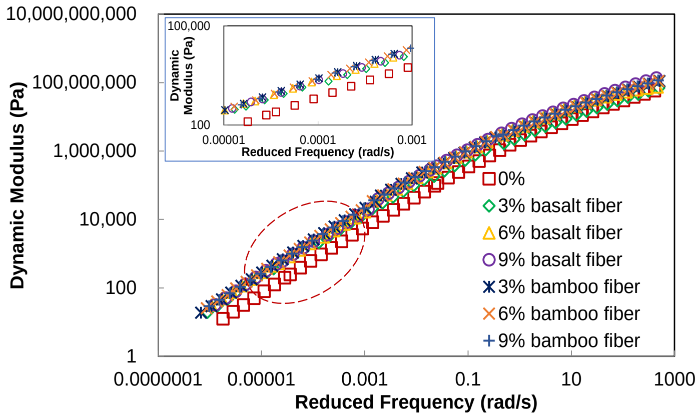

Figure 6. Master curves displaying the dynamic modulus for various types of fiber-modified asphalt mastic.

The phase angle is an important parameter for characterizing the viscoelastic behavior of a material. It represents the time difference between the stress and strain waveforms when a material is subjected to a load. The tangent of the phase angle reflects the relative contributions of the elastic and viscous components in the material during stress application. A phase angle of 0° indicates purely elastic behavior, while an angle of 90° indicates purely viscous behavior. If the phase angle falls between these values, the material is considered viscoelastic. Increasing the load frequency leads to a smaller phase angle in the asphalt mastic, as shown in Figure 7. The fiber-modified asphalt mastics exhibit lower phase angles compared to the matrix asphalt. Figure 8 illustrates the state of the fibers in the asphalt mastic. Increasing the content of basalt fibers and bamboo fibers effectively enhances the strength of asphalt mastic. The mechanisms and effects of basalt fibers and bamboo fibers in enhancing asphalt mastic differ slightly. Basalt fibers are inorganic fibers with high strength and rigidity. They possess excellent mechanical properties and can provide high tensile and flexural strength. The interface interactions between basalt fibers and asphalt are mainly physical adsorption and surface adhesion, and due to their inorganic nature, they exhibit strong binding ability with asphalt. Bamboo fibers, on the other hand, are natural organic fibers with a certain degree of flexibility and plasticity. The interface interactions of bamboo fibers in asphalt mastic are primarily attributed to the natural hydrophilicity of fiber surfaces and the compatibility with the asphalt's colloidal substances, resulting in good adhesion.

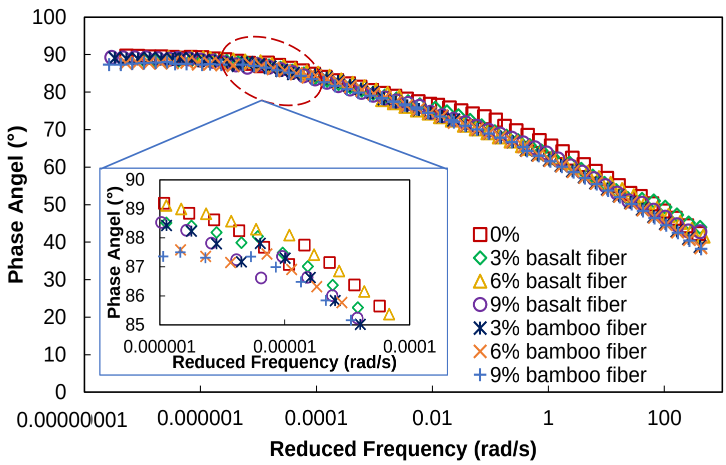

Figure 7. Master curves of phase angle for various types of fiber-modified asphalt mastic.

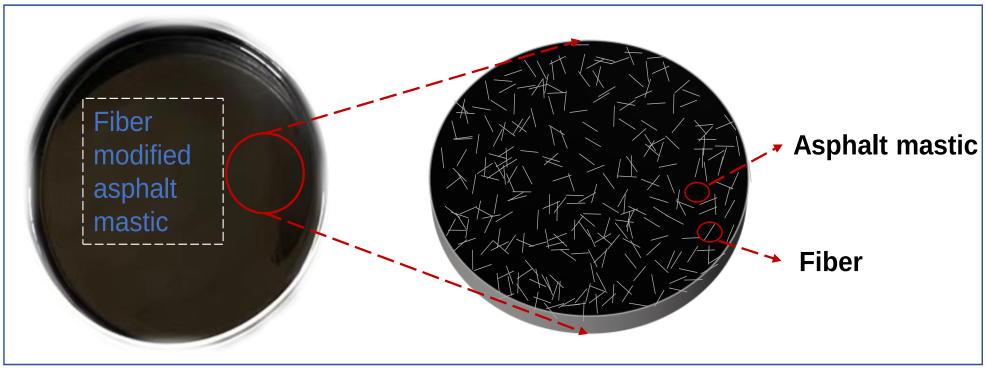

Figure 8. Illustration of asphalt mastic sample.

3.2. Modulus and Phase Angle Are Affected by Temperature

The dynamic shear modulus and phase angle of asphalt mastics were investigated in this work under frequencies of 10 rad/s and various temperatures. Figure 9 depicts the correlation between temperature and the dynamic shear modulus of asphalt mastics. The graph shows that the modulus keeps decreasing when the testing temperature rises. This implies that regular asphalt mastics and fiber asphalt mastics are temperature-sensitive materials.

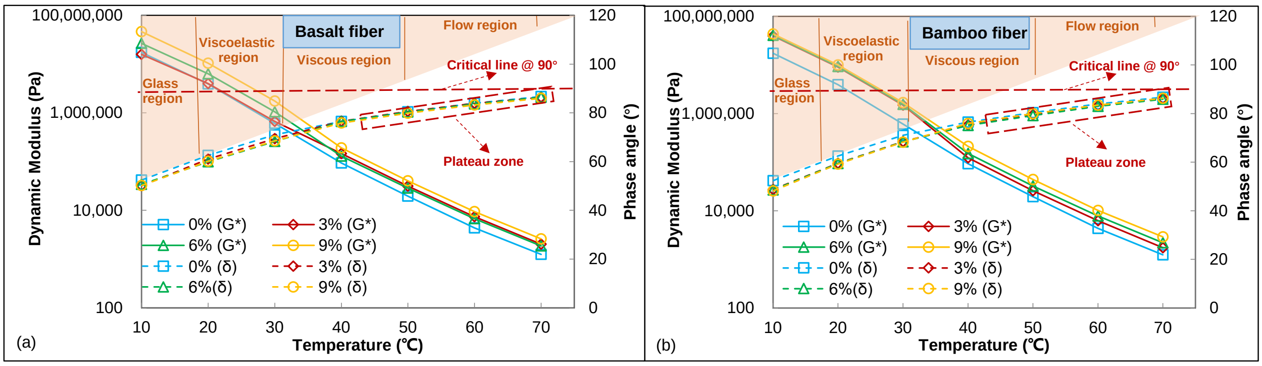

Figure 9. Temperature's effect on fiber-modified asphalt mastics' modulus and phase angle: (**a**) basalt fiber; (**b**) bamboo fiber.

The phase angle of asphalt mastics is affected by temperature, as seen in Figure 9. The phase angle increases rapidly with increasing experimental temperature before stabilizing as the temperature increases further. This suggests that natural asphalt mastics and mastics treated with fibers are temperature sensitive. Moreover, adding fibers to asphalt mastics can dramatically raise the dynamic shear modulus, improving compressive strength and creating a reinforcement effect. The phase angle of various asphalt mastics grows progressively as the testing temperature rises. Plain asphalt mastics have a more noticeable phase angle than fiber asphalt mastics. With increasing temperature, the viscous component of asphalt mastics becomes more prominent, making them susceptible to high-temperature permanent deformation. As the trial temperature rises, the properties of various asphalt mastics transition from elastic to viscous behavior, with conventional asphalt mastics exhibiting the most pronounced viscous condition and being highly susceptible to high-temperature permanent deformation. However, the addition of fibers can significantly enhance the resistance of asphalt mastics to deformation at high temperatures. Figure 9 illustrates that all the samples' phase angles fall within the range of 60 to 80°, indicating significant viscoelastic characteristics for the chosen matrix asphalt and the basalt and bamboo fiber asphalt mastic materials used in the experiment.

3.3. Initial Temperature of Self Healing

The flow characteristic index (n) was determined by Equation (3) [34]:

$$\eta* = m|w|^{n-1} \quad (3)$$

The equation used in this study includes several variables, including the frequency (w), composite viscosity (η*), and fitting parameters (m and n). The flow characteristic index is determined by the fitted parameter n, which is used to analyze the fiber asphalt mastic's initial self-healing temperature and evaluate its capacity for self healing.

The viscosity values of asphalt mastic modified with different fibers are shown in Figure 10. It can be observed that the viscosity gradually decreases between 10 °C and 40 °C as the loading frequency increases. However, as the temperature continues to rise from 50 °C to 70 °C, the viscosity remains at a similar level, regardless of the loading frequency. From the perspective of frequency, this is mainly due to the fact that at lower frequencies, the time scale of viscous dissipation is longer, and the asphalt molecules have sufficient time to complete their viscous dissipation through various modes of movement, resulting in a higher viscosity. As the frequency increases, the time scale of viscous dissipation decreases, and the asphalt molecules cannot move quickly enough to complete the viscous dissipation, leading to a decrease in viscosity. The interactions between asphalt molecules are stronger at low temperatures from a thermal standpoint. As a result, the viscosity of the asphalt gradually decreases as the loading frequency rises, because the asphalt molecules need more time to complete their viscous dissipation. The time scale for viscous dissipation; however, shortens as the temperature rises due to weaker connections between asphalt molecules. The asphalt molecules can move swiftly enough to complete the viscous dissipation even as the loading frequency rises, resulting in a rather steady viscosity. The viscosity of the asphalt mastic can also be increased by adding fibers. This is due to the fact that fibers can adsorb asphalt molecules, boosting their interactions and raising the viscosity, and that they have a high surface energy [35].

Table 6 presents the n values for the fiber asphalt mastic. The information shows that asphalt mastic treated with fibers showed a rise in flow characteristics index as the temperature rose, revealing that at higher temperatures, the asphalt mastic presented characteristics resembling those of a virtually Newtonian fluid.

Plain asphalt mastic's flow characteristic index rose from 0.571 to 0.98 in the temperature range of 10 °C to 70 °C. Meanwhile, the index for the asphalt mastic treated with basalt fibers flow properties decreased marginally. The n rose from 0.493 to 0.965, 0.532 to 0.972, and 0.609 to 0.974, respectively, for asphalt mastics treated with basalt fiber at 3%, 6%, and 9%. Additionally, the flowability of the 3%, 6%, and 9% bamboo-fiber-modified asphalt mastics increased from 0.532 to 0.967, 0.528 to 0.953, and 0.525 to 0.961, respectively. These results demonstrate that both basalt and bamboo-fiber-modified asphalt mastics exhibit favorable flowability within the temperature range of 10 °C to 70 °C.

Table 6. The values of n for asphalt mastics modified with fibers.

T (°C)	0%	Basalt Fiber Content (%)			Bamboo Fiber Content (%)		
		3%	6%	9%	3%	6%	9%
10	0.571	0.493	0.530	0.532	0.532	0.528	0.525
20	0.740	0.696	0.701	0.697	0.692	0.690	0.687
30	0.828	0.797	0.795	0.797	0.793	0.792	0.791
40	0.874	0.870	0.870	0.867	0.859	0.855	0.863
50	0.920	0.923	0.918	0.914	0.910	0.904	0.915
60	0.956	0.949	0.950	0.947	0.945	0.932	0.941
70	0.924	0.965	0.974	0.972	0.967	0.953	0.961

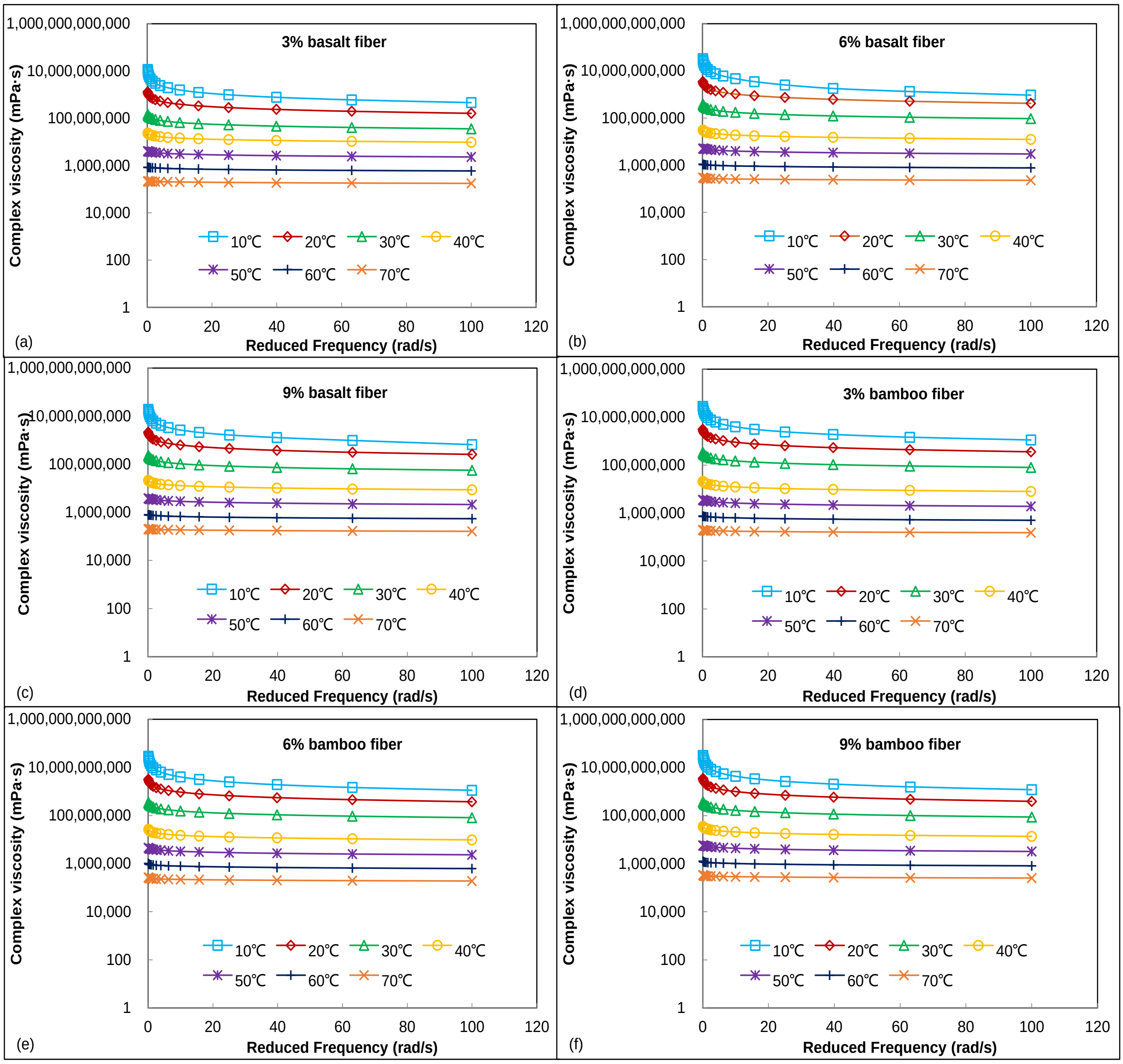

Figure 10. Viscosity results of modified asphalt mastic: (**a**) 3% basalt fiber; (**b**) 6% basalt fiber; (**c**) 9% basalt fiber; (**d**) 3% bamboo fiber; (**e**) 6% bamboo fiber; (**f**) 9% bamboo fiber.

The temperature dependence of the *n* for many fiber asphalt mastics is shown in Figure 11. The addition of more fibers to the asphalt mastic results in an increase in the initial self-healing temperature. This indicates that the flowability of the asphalt mastic decreases as a result of the addition of fibers, and higher temperatures are needed to reach the same flow condition.

The plain asphalt mastic's initial self-healing temperature was discovered to be 46 °C at the 0.9 level. When basalt fibers were added to the asphalt mastic at 3%, 6%, and 9% fiber contents, the initial self-healing temperatures were found to be 46 °C, 46 °C, and 47 °C, respectively. In contrast, the bamboo-fiber-modified asphalt mastics with the same fiber contents displayed initial self-healing temperatures of 48 °C, 49 °C, and 47 °C, respectively. The findings imply an ideal fiber content for equally distributed fibers in asphalt mastic, and that increasing the fiber concentration reduces the asphalt's flowability. Maintaining the same flow state requires raising the temperature. When the fiber content exceeds the optimum value, clustering of fibers is likely to occur. This phenomenon may lead to an increase in the self-healing capacity and flowability of the asphalt [36,37]. Additionally, it reduces the temperature required to maintain the desired flow state. Consequently, it is crucial to establish an appropriate crack self-healing temperature based on the type and quantity of fibers incorporated into the asphalt mastic. This approach ensures the achievement of the desired self-healing effect and minimizes material consumption during actual construction.

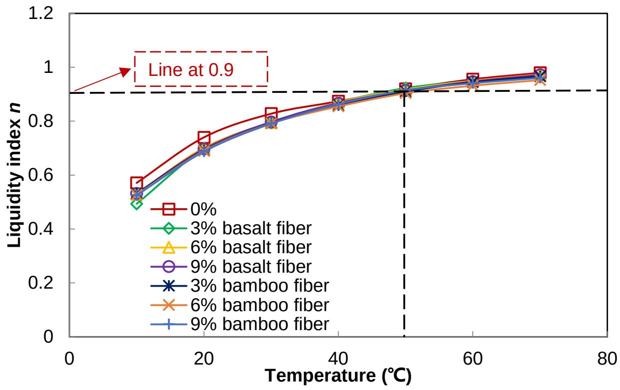

Figure 11. Evaluation of flow characteristics index in fiber-modified asphalt mastics.

The research findings indicate that an increase in fiber concentration leads to a rise in the initial self-healing temperature of the asphalt mastic, which suggests that fiber–fiber interaction is the main factor influencing the flowability of asphalt mastic with high fiber content. Consequently, in practical applications, the crack self-healing temperature should be adjusted according to the type and quantity of fibers used to achieve the desired self-healing effect while minimizing material consumption.

3.4. Fatigue Performance

This research takes for granted the homogeneity of asphalt mastic and uses the S-VECD model developed for asphalt to predict the behavior of asphalt mastic [38,39]. The stress–strain results acquired from the LAS test are presented in Figure 12, along with data points before and after the discovered viscous damage locations. Compared to the stress–strain curve of plain asphalt mastic, the curve of fiber-modified asphalt mastic exhibits a higher breaking stress and a lower strain. This indicates that the addition of fibers increases the material's strength while reducing its deformation. The enhanced elastic properties of the asphalt material are associated with its higher yield strain. However, it should be noted that the inclusion of fiber additives can potentially diminish the material's elasticity.

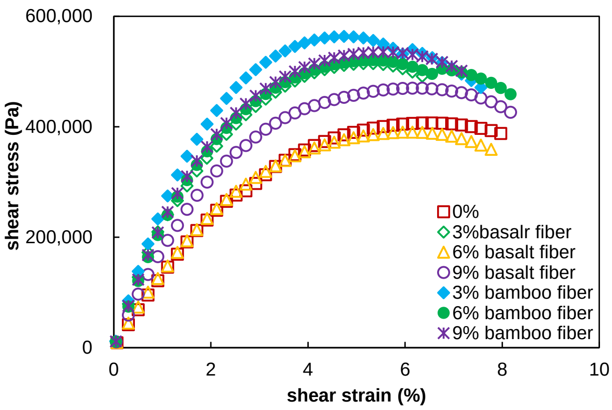

Figure 12. Curves illustrating the relationship between strain and stress in fiber-modified asphalt mastics.

It is important to recognize that the value of failure strain alone provides an indication of the asphalt mastic's performance under repetitive loads and does not necessarily reflect its fatigue resistance. For a more accurate assessment of fatigue behavior, additional evaluations of fatigue damage and failure characteristics need to be conducted.

According to the S-VECD model's calculations, Figure 13 shows the damage characteristic curves (DCC) for plain and fiber asphalt mastic. Incorporating natural fibers into the asphalt mastic was found to have a significant impact on the fatigue damage evolution. The various damage qualities of different asphalt mastics are represented by the relevant results of each DCC using the correlation between C and S as an input to predict fatigue resistance. Significantly, the material's stiffness, which rises with fiber content, mainly determines where the $C(S)$ curve is located. Usually, a lower stiffness corresponds to a lower position for the curve.

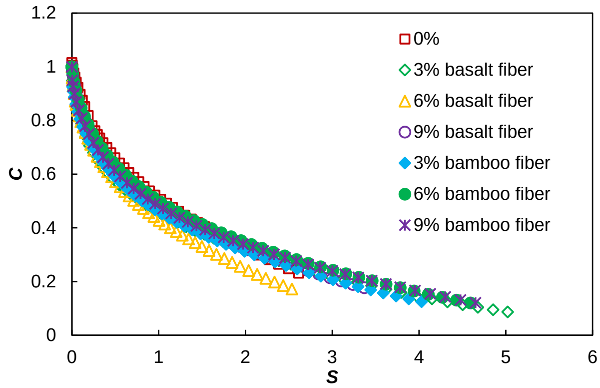

Figure 13. Effects of fiber incorporation on the C vs. S curves of asphalt mastics.

The present research employs a criterion for asphalt mastic failure estimation based on a 35% decrease in $|G^*|$*sin δ [32]. Figure 14 shows the results of a simulation under cyclic fatigue loading with strain control that used the measured material parameters to calculate the fatigue life after fiber modification. The results indicate that the fiber-modified asphalt mastic has a lower fatigue life than common asphalt mastic. Furthermore, the fatigue life decreases as the fiber content continues to increase, indicating uneven dispersion of fibers in the asphalt mastic can occur. Bamboo fibers negatively affect the asphalt mastic's fatigue life, likely due to their short particle size, which causes stress concentration and surface damage, resulting in reduced load-carrying capacity and diminished fatigue performance of the asphalt material.

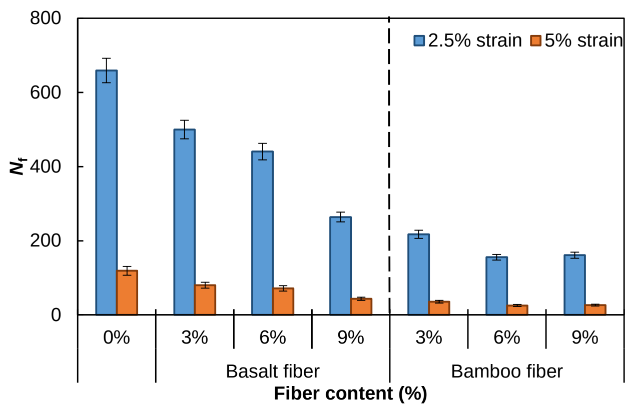

Figure 14. Fatigue life evaluation of asphalt mastics modified with fibers.

3.5. Crack Growth Characteristics

Figure 15 displays the fundamental geometry and characteristics of DSR parallel plates. The crack length and extension rate calculation methods have been described in detail by

Wang et al. [32]. Figure 16 summarizes the fracture criteria for all asphalt mastics evaluated in the LAS-5 test. It is evident from the LAS test that all the asphalt mastics exhibit the same patterns of fracture development. Initially, the cracking rate (*da/dN*) increases rapidly, then slowly, eventually becoming unstable until it breaks.

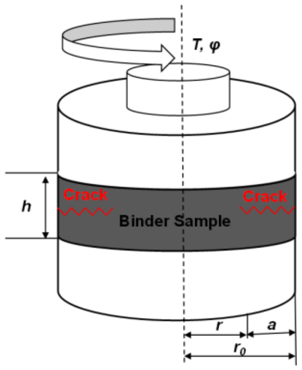

Figure 15. A diagrammatic representation for the calculation of asphalt binder crack length [32].

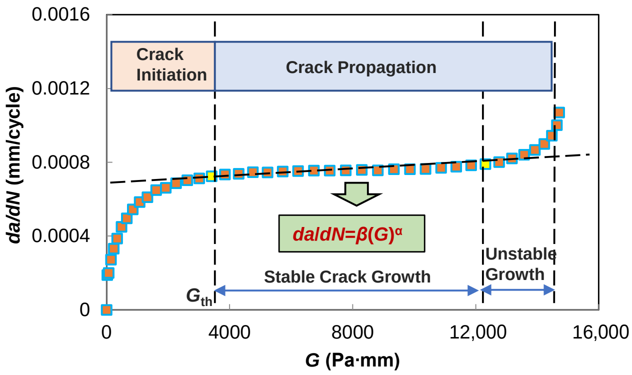

Figure 16. This pertains to the correlation between the rate of cracking (*da/dN*) and the energy release rate (*G*).

Figures 17 and 18 illustrate that all the asphalt mastics examined exhibit identical crack initiation phases and different crack propagation characteristics. Under load, cracks initiate within the asphalt material due to internal defects and generate stress concentration at the initial crack location. The micro-cracks propagate rapidly under repeated loading until they reach a critical size, causing structural damage. However, the presence of fibers in the asphalt mastic can create a restraining effect around the cracks, which can prevent further crack propagation. The enhanced performance of bamboo powder fibers in asphalt mastics can be attributed to the mechanical interlocking effect between the rough and uneven surface of the fibers and the asphalt mastic, resulting in a strong bond. This interlocking effect creates a tight connection, and when the material is subjected to external forces, the fibers act as a skeleton within the hybrid system, effectively transferring stress and improving the overall strength of the material. The bending strength of bamboo powder fibers plays a critical role in this mechanism, as their specific length-to-diameter ratio allows them to act as bridges for stress transfer [17]. As a result, the resistance to crack propagation becomes the primary factor influencing the fatigue properties of the asphalt mastic. Furthermore, fiber-modified asphalt mastic exhibited lower *da/dN* levels as *G* increased and longer crack lengths as loading cycles increased, indicating better crack resistance.

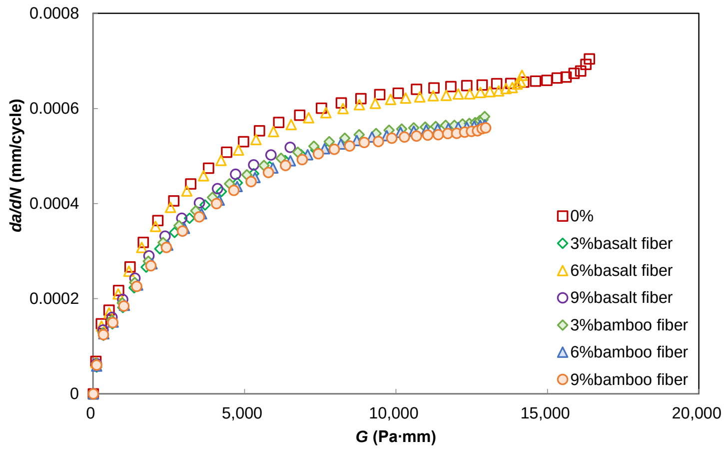

Figure 17. Diagram showing two-phase crack growth in an LAS test.

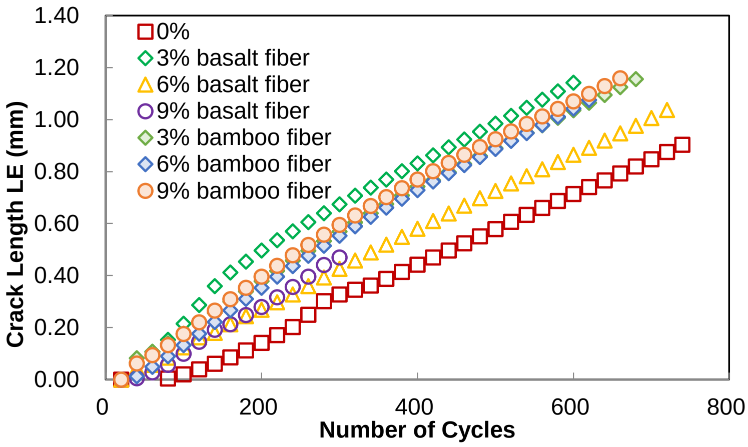

Figure 18. Crack length summary of fiber modified asphalt mastic.

The fracture length of fiber-modified asphalt mastic is also considerably longer than that of regular asphalt mastic under the same number of cyclic loadings, as illustrated in Figure 17. This suggests that fiber integration has a detrimental effect on the asphalt mastic's fatigue performance. The observed effect can be explained by the strong mechanical properties of bamboo fibers, which tend to cause stress concentration when exposed to outside forces, making asphalt mastic samples more likely to crack at room temperature.

3.6. Rutting Resistance

Due to the fact that the rutting factor is influenced by many factors, such as tire pressure, tire size, vehicle speed, road surface temperature, etc., which cannot be completely consistent in actual road use, in order to accurately evaluate the performance of asphalt pavement at high temperatures, it is more appropriate to use the non-recoverable creep J_{nr}, because it can provide more objective and stable evaluation results. In addition, the measurement method of J_{nr} is relatively simple and easy to operate, and it is currently widely used to evaluate the high-temperature performance of asphalt pavement.

Figure 19 illustrates that adding fibers to asphalt mastics improves the material's stability at higher temperatures by comparing the time–strain curves derived from the MSCR test. It has been discovered that bamboo fibers have a better modification effect than basalt fibers, and the high-temperature stability of fiber-modified asphalt mastics steadily increases with increasing fiber percentage. When assessing the ability of asphalt materials to resist rutting at high temperatures, a lower J_{nr} value is indicative of superior performance. J_{nr} is a widely used standard index that quantifies the extent of irreversible deformation or creep in a material subjected to a sustained load over a period of time.

According to Figure 20, the J_{nr} value falls as the fiber content rises, suggesting that fibers can improve asphalt mastic's resistance to rutting at high temperatures. The main reason is likely due to the formation of a network structure by fibers in the asphalt mastic, which increases its cohesion and shear strength. Under high-temperature conditions, the fibers effectively disperse and bear the stress of the asphalt, preventing deformation and damage of the mastic, thereby improving its structural stability. Additionally, the addition of fibers can enhance the shear resistance of the asphalt mastic, reducing deformation and flow under high temperature conditions. Fibers can absorb and disperse shear forces, increasing the viscoelasticity of the mastic and preventing shear failure.

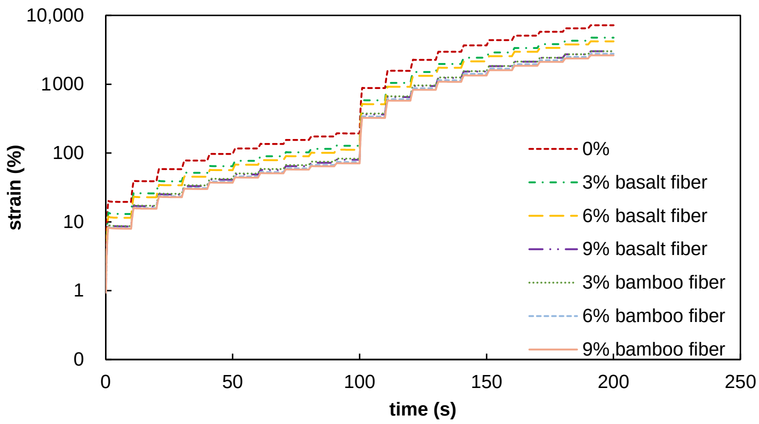

Figure 19. Time–strain curves of different types of fiber-modified asphalt mastics.

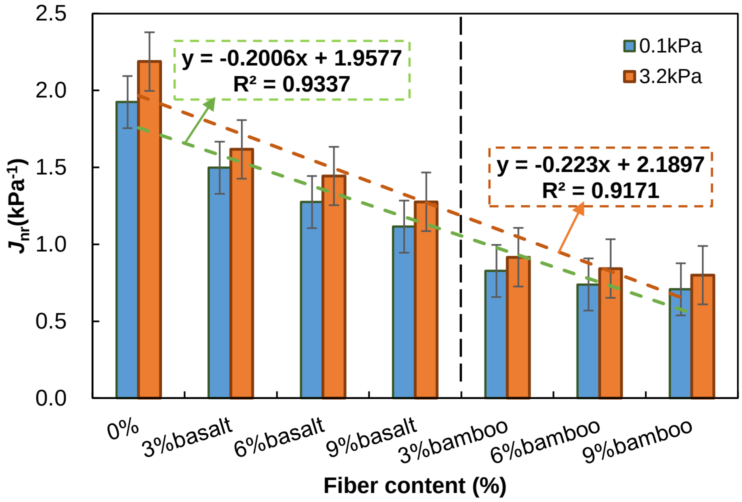

Figure 20. Effect of fiber modification on asphalt mastic J_{nr} values.

The results of the $J_{nr\text{-}diff}$-index-based sensitivity analysis of asphalt mastics to high-temperature creep stress are shown in Figure 21. The investigation demonstrates that the modified asphalt mastics' stress sensitivity rises when basalt fiber content rises. Bamboo-fiber-modified asphalt mixtures exhibit irregular changes in stress sensitivity, unlike basalt-fiber-modified asphalt mastics, which show a monotonic increase with increasing fiber content. According to AASHTO MP 19 [40], the $J_{nr\text{-}diff}$ index has a threshold value of 75%. Both the asphalt mastics modified with basalt fibers and those modified with bamboo fibers satisfy this technical standard, indicating that the modified asphalt mastics are resistant to stress sensitivity.

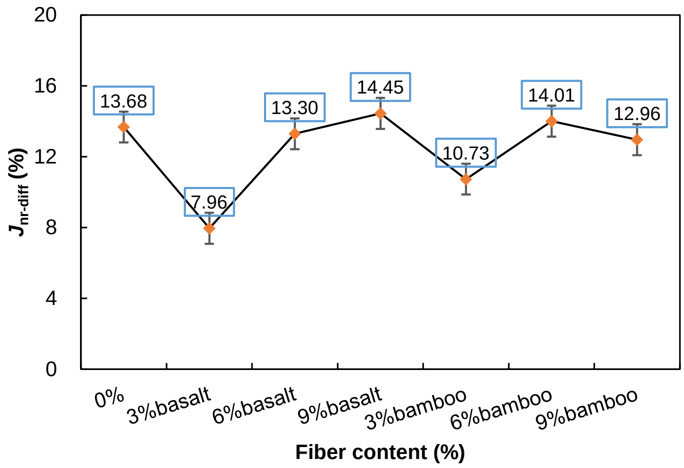

Figure 21. Effect of fiber modification on asphalt mastic $J_{\text{nr-diff}}$.

3.7. Elastic Recovery (ER) Capability

As shown in Figure 22, the effect of fiber content on the elastic recovery ability of modified asphalt mastic at 20 °C is a complex issue. Generally, at low fiber content, with the increase in fiber content, the interaction between fiber and asphalt increases, and the dispersion of fibers in the asphalt mastic deteriorates, resulting in a decrease in the elastic recovery ability of the mastic. With the further increase in fiber content, the interaction between fiber and asphalt reaches a certain balance, and the dispersion of fibers in the asphalt mastic gradually improves, leading to an increase in the elastic recovery ability of the mastic. However, when the fiber content continues to increase, the interaction between fibers becomes stronger, resulting in a deterioration of the dispersion of fibers in the asphalt mastic, and the elastic recovery ability of the mastic begins to decrease. Therefore, a better elastic recovery ability can be obtained at an appropriate fiber content. It should be emphasized that in addition to fiber content, other parameters such as fiber length, fiber shape, and asphalt type also influence the elastic recovery of fiber-modified asphalt mastics. Consequently, it is essential to fully consider the combined effects of several aspects of research.

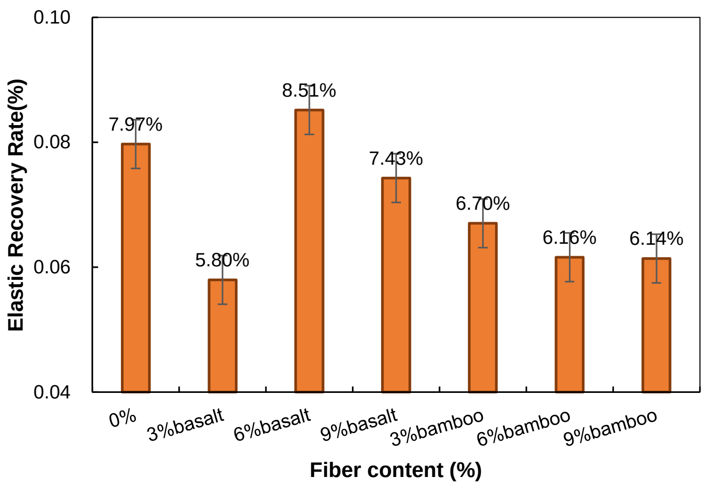

Figure 22. Elastic recovery rate of asphalt mastics.

3.8. Low-Temperature Cracking Resistance

This research used two BBR test indicators to assess the effectiveness of asphalt mastics in subfreezing conditions: the flexural creep strength modulus S and the slope of the creep curve m. Low S values in asphalt mastics suggest increased elasticity, increased deformation tolerance, and improved resistance to low-temperature cracking. The results in Figure 23 are consistent with the conclusion of the previous study by Wu et al. that the addition of fibers elevated the creep stiffness values [41]. This suggests that increasing fiber content may not be beneficial for enhancing the asphalt mastic's performance at low temperatures, since it can lead to poor low-temperature crack resistance. The experimental results also show that as the temperature increases, asphalt mastic's *S* value drops quickly. Raising the temperature can make asphalt mastic less likely to crack at low temperatures.

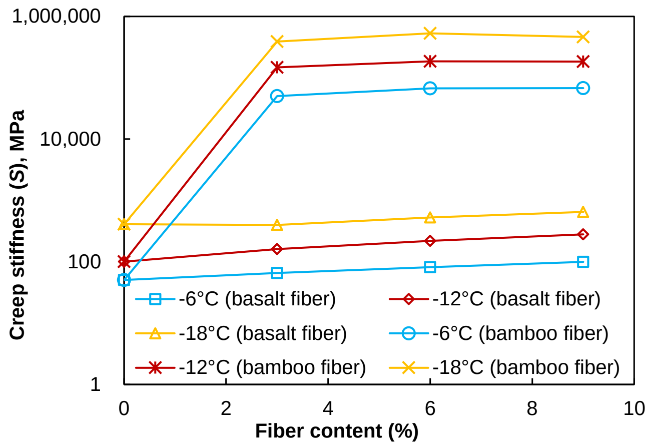

Figure 23. Creep stiffness of fiber-modified asphalt mastics.

The creep curve slope, represented by the *m* value, is an indicator of the relaxation capability of asphalt mastics. A higher *m* value suggests faster stress release and better crack resistance at low temperatures, indicating a greater ability to withstand cracking. Figure 24 illustrates the influence of fiber content on the m value of asphalt mastics. This shows that the addition of basalt fibers slightly reduces the slope value (*m*) of the creep curve. This finding is consistent with the results reported by Wu et al. [42], indicating that fiber content has minimal detrimental effects on the low-temperature cracking resistance of asphalt mastics. On the other hand, the inclusion of bamboo fibers increases the *m* value, indicating improved resilience to low-temperature cracking as the number of bamboo fibers increases.

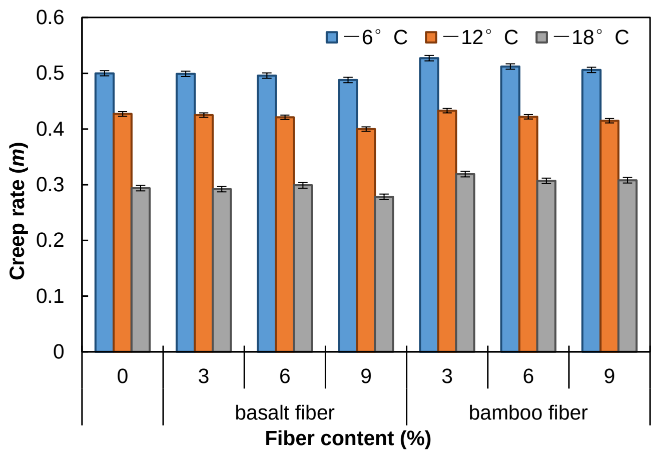

Figure 24. Effects of fiber modification on creep rate of asphalt mastics.

Moreover, the m value of asphalt mastics exhibits a rapid increase with rising temperature, significantly enhancing the material's resistance to low-temperature cracking. In summary, the research findings suggest that the incorporation of bamboo fibers provides more favorable results in terms of the low-temperature properties of asphalt mastics compared to basalt fibers.

4. Conclusions

This study used a DSR rheometer and a BBR rheometer to conduct several experiments to examine the effect of basalt and bamboo fibers on the modification of asphalt mastic. The following conclusions were obtained:

(1) The addition of fibers increases the stiffness and composite viscosity of the asphalt mastic, while the increase in temperature leads to an increase in the flow index, resulting in an asphalt mastic with near-Newtonian fluid-like behavior.
(2) Basalt and bamboo fibers in asphalt mastic had a positive effect on the rutting resistance and a negative effect on the fatigue resistance. Basalt fibers did not have a positive effect on the low-temperature cracking of asphalt mastic, but the addition of bamboo fibers as a modifier effectively improved the low-temperature cracking performance of asphalt mastic. In addition, increasing the temperature had a positive effect on the performance of asphalt mastic.
(3) Bamboo fiber as a modifier in asphalt mastic produced a better enhancement effect compared to basalt fiber.

Natural plant fibers are widely recognized for their superior oil-holding, stabilization, anti-diffusion, and reinforcement properties compared to other types of fibers, thanks to their large surface area and rough surface texture. Although natural plant fibers have numerous advantages, they do have certain drawbacks, such as low compatibility, hydrophilicity, and heat stability. To address these issues, future research should focus on developing surface modification techniques for plant fibers, particularly for use in hot mix asphalt mixtures where heat resistance is essential for construction safety. Furthermore, it is important to conduct more comprehensive and systematic studies on non-wood waste fibers, such as crop straw, bagasse, and coconut shells, to help reduce pollution, preserve forest resources, and promote their rational use in asphalt mixtures.

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