Arabian Journal for Science and Engineering (2019) 44:4629–4638
https://doi.org/10.1007/s13369-018-3490-x

RESEARCH ARTICLE - CIVIL ENGINEERING

Laboratory Investigation on the Use of Bamboo Fiber in Asphalt Mixtures for Enhanced Performance

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Received: 29 March 2018 / Accepted: 30 July 2018 / Published online: 9 August 2018

Abstract

This study evaluated the use of bamboo fiber, which is a new member in the natural fiber category, in dense-grade (DG) and stone matrix asphalt (SMA) mixtures for enhanced performance. Bamboo fiber has high tensile strength in fiber direction, and it also has rough surface texture comparable to that of a commonly used lignin fiber. Moreover, bamboo fiber exhibits sufficient thermal stability, which is a typical concern of plant-based materials. Marshall mix design procedure was followed to select optimum asphalt binder contents of DG and SMA mixtures that contain various amounts of bamboo fiber. Effects of bamboo fiber on mixture moisture susceptibility, rutting and low-temperature cracking performance were evaluated using the immersion Marshall, freeze-thaw cycling tests, wheel tracking test and three-point bending beam test, respectively. Testing results showed the use of bamboo fiber effectively enhanced the above-mentioned mixture performance. In addition, the optimum bamboo fiber contents for DG and SMA mixtures were found to be 0.2–0.3% and 0.4% (by weight of mixture). Finally, mixtures with bamboo fiber exhibited equivalent or better performance than the same mixtures with polyester fiber and lignin fiber, indicating the applicability of bamboo fiber in asphalt mixtures.

Keywords Bamboo fiber · Thermostability · Low-temperature cracking · Rutting · Polyester fiber · Lignin fiber

1 Introduction

Nowadays, most hard-surface pavements are constructed with asphalt mixes, due to its relatively low cost, its ability to provide comfort riding with low noise, and its ease of construction. However, increase in traffic loading density typically associated with heavy vehicles induces great challenges on asphalt pavement performance [1–3]. Moreover, the consistently rising material, production, and construction costs have stimulated the asphalt industry to accept/increase the use of recycled materials (i.e., reclaimed asphalt pavement and recycled asphalt shingle), which stiffen the mixes and potentially accelerate the initiation and propagation of pavement distresses [4–6].

Binder modification is one main approach to mitigate the occurrence and severity of distresses (e.g., rutting and cracking) and to increase pavement service life. In general, asphalt modifiers can be classified as polymers, fibers, extenders, oxidants and antioxidants, anti-stripping agents, and hydrocarbons [7,8]. Polymers (i.e., elastomers and plastomers) are the most common type of binder modifications because of their achievements in mitigating rutting and cracking for asphalt mixture [9]. For example, mixture with elastomer polymer (e.g., styrene-butadiene-styrene) modified binder typically exhibited reduced rate of damage accumulation and slightly enhanced fracture limit, indicating better cracking performance as compared to the same mixture with an unmodified binder [10,11].

Fibers are another type of reinforcing materials, which have been reported to improve mixture resistance to rutting and reflective cracking [12]. Fibers can be divided into two main classes: synthetic fibers and natural fibers [13]. Synthetic fibers include polyester, carbon, and glass fibers. Wu et

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al. [14] found that polyester fiber improved the fatigue property of asphalt mixture, especially at low stress levels. Carbon fiber has been reported to be one of the most compatible and best performing fibers for binder modification because of its high melting point (over 1000 °C), carbon composition (whereas asphalt is a hydrocarbon) and high tensile strength [15]. Glass fiber has low elongation (approximately 3–4%) and high elastic recovery (100%). Thus, adding glass fiber not only enhances mixture strength, fatigue characteristics but also promotes the mixture ductility [16].

Natural fibers such as sisal, jute, lignin and hemp fibers have also been successfully used for the reinforcement of asphalt mixtures. Natural fibers typically exhibit considerable mechanical properties, but they are more environmental-friendly and much cheaper than synthetic fibers [13]. Coated jute fiber could replace synthetic fibers in stone matrix asphalt (SMA) mixture with equivalent rutting performance [17]. Sisal fiber was found to not only prevent the asphalt drain down but also increase the tensile strength of SMA mixtures [18]. Bamboo fiber, which is cellulose fiber extracted from naturally available bamboo stem, is a new member in the category of natural fibers. It has high tensile strength in fiber direction, and it is durable in nature with low manufacture cost. More than 1400 bamboo species in more than 80 genera grow worldwide. Bamboo is a fast-grown species and a perennial plant. Depending on the species, bamboo can mature within three years. Phyllostachys edulis used in this study is one of the most abundant species and widely distributed throughout Southeast Asian countries. Phyllostachys edulis can grow to heights of 20 m feet and have culm diameter of 15 cm [19]. Limited studies on using bamboo fiber as road materials were identified during the literature review of this study. It was reported that bamboo fiber increased the flexural strength and modulus of elasticity of concrete beams [20]. Also, the use of bamboo fiber resulted in higher stability of SMA mixture than those with cellulose fiber or no fiber [21]. Nevertheless, natural fibers may exhibit characteristics (e.g., high moisture absorption, high hydrophilicity and low degradation temperature) that potentially restrict or challenge a broad use of these materials in asphalt pavement.

2 Objective

The main objective of this study was to determine whether bamboo fiber can be used in asphalt mixtures (both DG and SMA mixtures) with enhanced performance. More specific objectives of this study included:

- Characterize the thermal stability of bamboo fiber by evaluating its weight loss, tensile strength and surface morphology after heat treatment.
- Determine the optimum content of bamboo fiber for utilization in asphalt mixtures and evaluate the moisture susceptibility of resultant mixtures.
- Evaluate the effect of bamboo fiber on mixture rutting and low-temperature cracking performance and determine its applicability by comparing with the same mixtures containing commonly used lignin and polyester fibers.

3 Research Approach

This study firstly evaluated thermal stability of bamboo fiber by measuring tensile strength and weight loss after heat treatment to determine whether this natural fiber is appropriate for use in asphalt mixtures. Then, two mixture types including one SMA and one dense-grade (DG) were designed following the Marshall method to introduce various bamboo fiber contents. Moisture susceptibility of resultant mixtures was evaluated using the immersion Marshall and freezing-thaw cycling tests. Finally, wheel tracking and three-point bending beam (3PB) tests were performed to determine the effect of bamboo fiber on mixture rutting and low-temperature cracking performance. Mixtures with no-fiber, lignin and polyester fibers were included as controls and their testing results were compared to these obtained from mixtures with bamboo fiber.

4 Bamboo Fiber Characterization

Figure 1 shows the bamboo fiber, lignin fiber and polyester fibers used in this study. Table 1 lists typical ranges/values of length, diameter, density and oil-absorptive property of these fibers. Fiber length is an important parameter that affects mixture performance. Fibers that are too short may not provide sufficient reinforcement and only act as expensive filler. Conversely, too long fibers may create a problem called "balling," i.e., some fibers may lump together and not blend well in mixtures. The typical length for basalt and polyester fibers that are commonly used in asphalt mixtures is 6 mm; therefore, the similar length (6 ± 2 mm) of bamboo fiber was used. The oil-absorptive property of fiber was quantified using the weight ratio between the fiber and absorbed oil following the JT/T 533 Method, *Plant fibers used in asphalt pavement* [22]. This property strongly affects the mixture stability at high temperatures. In addition, fibers with high oil-absorptive property can prevent flushing and liquate.

4.1 Weight Loss

A fixed amount (i.e., 100 g) of bamboo fiber was heated in a high-temperature furnace with the weight changes being monitored. Heating temperature increased from 140 °C to 380 °C at an interval of 20 °C and the residue weight of

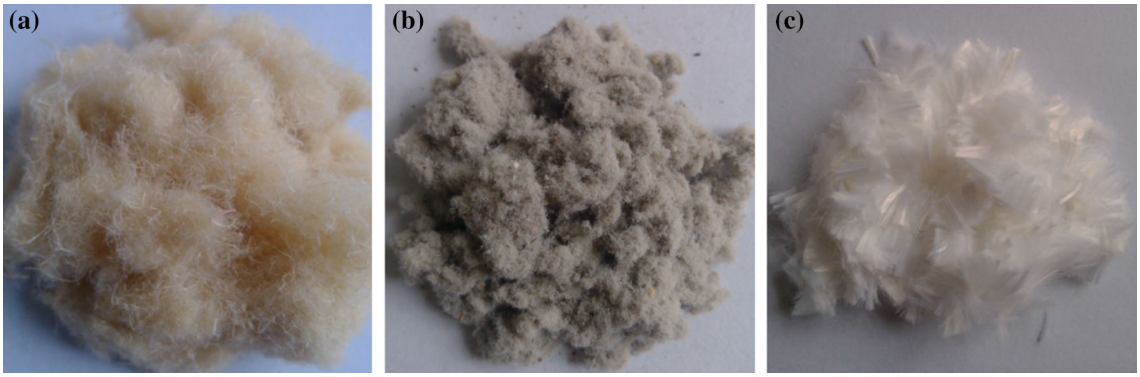

Fig. 1 Three fiber types: **a** bamboo fiber, **b** lignin fiber and **c** polyester fiber

Table 1 Physical properties of fibers

Properties	Bamboo fiber	Lignin fiber	Polyester fiber
Fiber length (mm)	6 ± 2	0–1.5	6
Fiber diameter (μm)	20–60	10–80	20
Density (g/cm^3)	1.36	1.28	1.38
Oil-absorptive properties	5.7	7.5	3.2

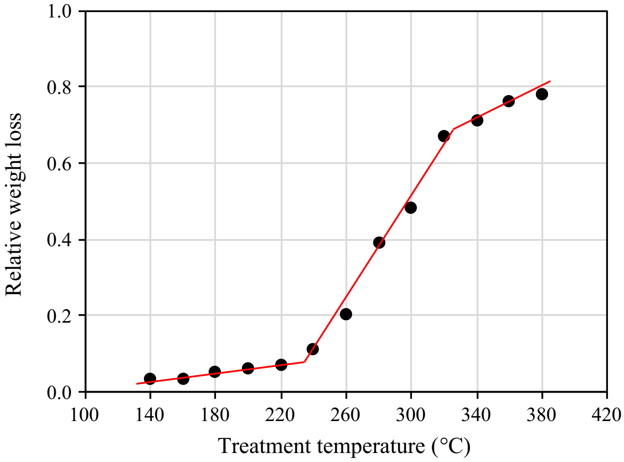

Fig. 2 Weight loss of bamboo fiber during heat treatment

bamboo fiber was recorded after 2 hours heating at each temperature. Figure 2 shows that there were three stages with respect to the loose of fiber integrity during the heating process. At the first stage, up to 230 °C of heat only yielded a small reduction of approximately 8% of fiber weight. Then, an abrupt increase in weight loss was observed once the heating temperature was above 230 °C and this second stage finished at 320 °C. Finally, the rate of fiber weight loss slowed again, though bamboo fiber almost completely decomposed at the end of this stage. Nevertheless, the mixing and compacting temperatures of asphalt mixtures typically range from 150 °C to 180 °C, which falls in the first stage where a minor reduction in specimen weight was observed.

4.2 Tensile Strength

Bamboo fiber was too fine to be fixed in a conventional instrument; thus, this study adopted a simple tool developed by Chen and Xu [23] to measure the fiber tensile strength (Fig. 3a). A rectangular paper with two same size hollow windows (10 mm × 6 mm) and a fold mark was prepared (Fig. 3b). Then, the paper was folded and a monofilament bamboo fiber (4–5 cm) placed in the middle of one hollow window with two fiber ends glued to the paper edges. Finally, two papers edges (without fiber) are cut in the middle and the entire unit (paper and fiber) was pulled at a speed of 5 mm/min until the fiber broke by using microcomputer control electronic universal testing machine(UTM) (Fig. 3c). Then, the diameter of the fiber after fracture was measured by optical microscope. The tensile strength of monofilament bamboo fiber was determined using Eq. 1.

$$\text{The tensile strength} = \frac{F}{\pi\left(\frac{D}{2}\right)^2} \qquad (1)$$

where F was the tensile force (N) when the fiber fractured; D was the diameter (mm) of the fiber after fracture.

Bamboo fiber was treated at five temperatures (25 °C, 100 °C, 150 °C, 175 °C and 190 °C) for 2 h before measuring its tensile strength. For each heating level, five treated fiber replicates were pulled at the ambient temperature (25 °C) and average tensile strength value was reported. Figure 4 plots the changes in tensile strength of bamboo fiber with increased heating temperatures. Bamboo fiber had an initial tensile strength of approximately 619 MPa at 25 °C, which

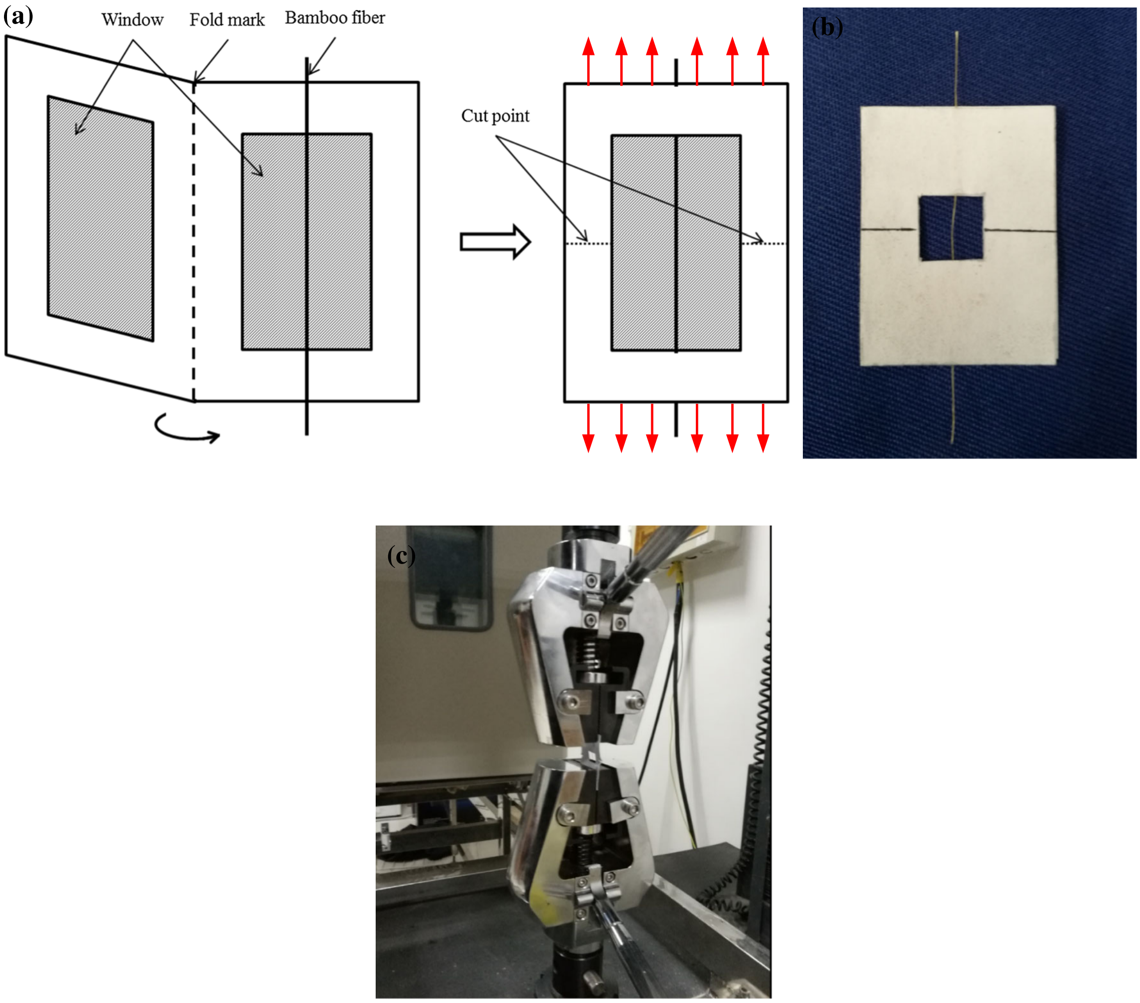

Fig. 3 Use of paper folder to measure tensile strength of monofilament bamboo fiber (**a**, **b**) and the specimen tested by UTM (**c**)

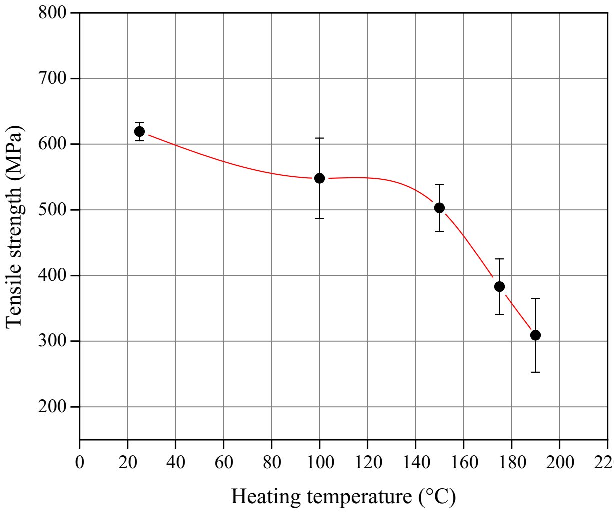

Fig. 4 Tensile strength of bamboo fiber after heat treatments

slightly decreased as the temperature increased to 150 °C. Even at 190 °C, the upper limit of asphalt mixture production and construction temperature, bamboo fiber still had a high tensile strength value closing to 309 MPa.

4.3 Surface Characteristic

A scanning electron microscope was used to capture the changes in surface microstructure of bamboo fiber before and after the heat treatment (i.e., 200 °C for 2 h). As shown in Fig. 5, the heating process appeared to increase the fiber surface roughness without destroying its morphology. The hemicellulose of bamboo fiber decomposed during the heating process and created irregular interspaces for binder absorption which potentially improves the adhesion between bamboo fiber and asphalt binder.

Overall, bamboo fiber exhibits satisfactory thermal stability (i.e., small reductions in weight and tensile strength and rougher surface for binder absorption after heat treatment),

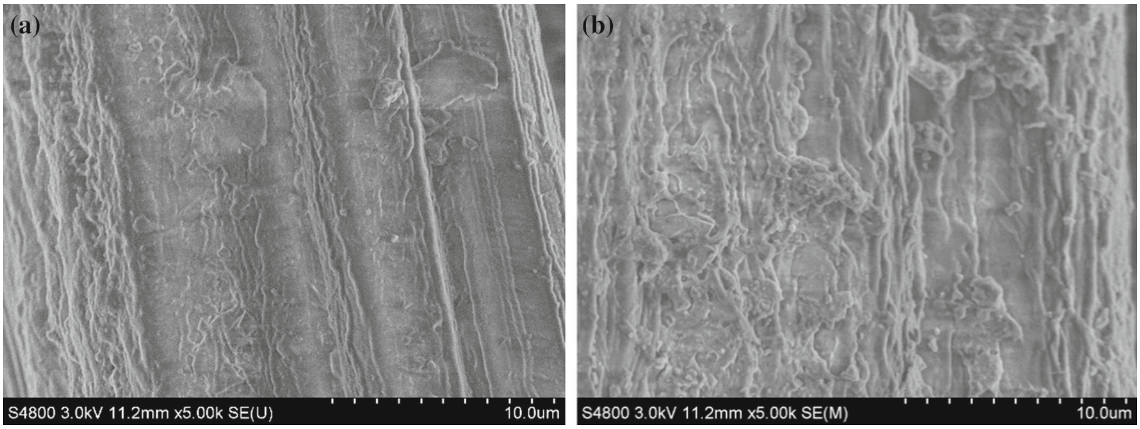

Fig. 5 Morphology of bamboo fiber surface, **a** before and **b** after heat treatment

Table 2 Physical properties of asphalt binder

Property	Value	
	Unmodified asphalt	SBS modified asphalt
Penetration at 25 °C (0.1 mm)	86	72
Penetration index	− 0.77	0.46
Softening point (°C)	47	88.5
Ductility (cm)	> 100	39.7 (5 °C)
Flash point (°C)	269	291
Solubility (%)	99.9	109
Viscosity (Pa s)	210 (60 °C)	1.3 (135 °C)
Specific gravity (g/cm^3)	1.002	1.021

which indicates the feasibility of being used in asphalt mixtures.

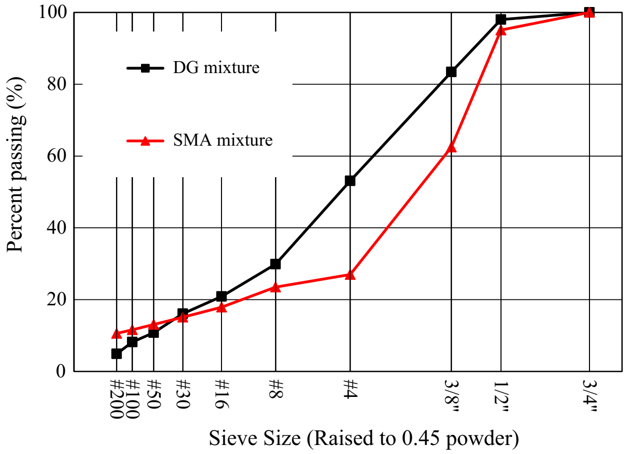

Fig. 6 Aggregate gradation of dense-graded (DG) and stone matrix (SMA) mixtures

5 Mixture Designs

5.1 Aggregate and Asphalt Binder

Crushed basalt coarse and fine aggregates used in this study were obtained from a quarry located in Northwestern China. The mineral filler used was limestone powder with particle size ranged from 0 to 0.3 mm (93.1% passing 0.15 mm sieve and 81.5% passing 0.075 mm sieve). A neat binder was used for design and specimen fabrication of DG mixtures, whereas SMA mixtures used the SBS binder as per requirement. Table 2 illustrates the basic properties of two binders.

5.2 Mixture Design

Figure 6 depicts the gradations of the DG and SMA mixtures. Optimum asphalt content (OAC) of each mixture was determined following the Marshall design procedure. Mixture samples were prepared using an asphalt mixture's mixing machine and a Marshall compactor following the Method T0702 listed in *JTG E20* [24]. Bamboo fibers were firstly mixed with aggregate at specified temperatures (165–175 °C for DG mixtures and 170–180 °C for SMA mixtures) for 90 s. Then, preheated asphalt binder was added into the pan mixer and blended with aggregate and fiber for another 90 s. After that, the mineral filler was added to the mixtures and blended for 90 s. Finally, loose mixes were poured into a hot mold and compacted with 75 blows each side. Mixing temperature was maintained throughout the whole process, and the pills were 101.6 mm in diameter and 63.5 mm in height.

The amounts of bamboo fibers added in DG mixtures were 0%, 0.1%, 0.2%, 0.3% and 0.4% (by weight of the mixture). Likewise, bamboo fiber contents in SMA mixtures were 0.2%, 0.3%, 0.4% and 0.5%. Of note, the use of fiber (typically 0.3% lignin fiber) as a stabilizer is required for SMA mixtures. Table 3 presents the mixture design parameters at 4% air voids. Higher bamboo fiber contents increased the binder absorption and resulted in greater mixture OAC values. Bamboo fiber increased the DG mixture stability; however, this trend was reversed when more than 0.2% fiber was added. The flow of DG mixtures constantly increased as fiber content increased. Although further research is needed to better explore the mechanism, it appears that too much fiber might disrupt the contact of coarse aggregates and negatively affect their interlocking. Similar observation was made on stability result of SMA mixtures, and the inference made on DG mixtures may also be applicable for SMA mixtures.

5.3 Moisture Susceptibility

Moisture susceptibility is a primary cause of distresses in hot mix asphalt pavement. This becomes even more critical when plant fibers which potentially have high hydrophilicity are added into mixtures. Thus, moisture susceptibility tests were conducted to estimate the potential for moisture damage of mixtures with bamboo fiber. In this study, both immersion Marshall test and freezing-thaw cycling test were performed. For each mixture type, eight Marshall compacted samples were prepared for the immersion Marshall test. Four samples were submerged in a water bath at 60 °C for 30 min and the other four were kept at the ambient temperature until testing. All tests were conducted following the *Method T0709 in Chinese standard JTG E20-2011* [23], and the Marshall stability ratio of each mixture was determined using Eq. 2.

$$\text{Marshall stability ratio} = \frac{\text{MS}_1}{\text{MS}} \times 100 \tag{2}$$

where MS_1 was average Marshall stability value (kN) of the four conditioned samples; MS was average Marshall stability values (kN) of the four unconditioned samples.

For the freezing-thaw cycling test, eight Marshall compacted pills were prepared. Similar to the immersion Marshall test, these eight samples were divided into two groups. The first group of four samples was firstly put into a plastic bag with 10 ml water and kept at −18 °C for 16 h. Then, they were removed from the bag and submerged in a water bath at 60 °C for 24 h. Right before testing, the four conditioned samples and the other four unconditioned ones were submerged in a water bath at 25 °C for 2 h. These tests were conducted in accordance with the *Method T0729 in Chinese standard JTG E20-2011* [25], and the tensile strength ratio of each mixture can be obtained by using Eq. 3.

$$\text{Tensile strength ratio} = \frac{R_{T2}}{R_{T1}} \times 100 \tag{3}$$

where R_{T2} is the average tensile strength (MPa) of freezing-thaw conditioned samples; R_{T1} is the average tensile strength (MPa) of unconditioned samples.

Figure 7a shows the Marshall stability ratio and tensile strength ratio results of the DG mixtures, and Fig. 7b illustrates these values of the SMA mixtures. For DG mixtures, both parameters reached peak value when 0.2% bamboo fiber was added and higher fiber content (greater than 0.2%) induced a negative effect on moisture susceptibility. Similarly, up to 0.4% bamboo fiber notably increased the Marshall stability ratio and tensile strength ratio of SMA mixtures; however, further increment in two parameters associated with the additional 0.1% bamboo fiber was almost negligible. Of note, all mixtures met the minimum requirements listed in Table 4, except for the DG mixture containing 0.4% bamboo fiber that was marginal for the use in an area with annually rainfall over 500 mm. Overall, there appeared to be optimum bamboo fiber contents for DG and SMA mixtures and following mixture performance tests were conducted to identify the corresponding thresholds.

6 Effects of Bamboo Fiber on Mixture Performance

6.1 Rutting Performance

Rutting resistance of asphalt mixtures was evaluated using the wheel tracking test per Method T0719 *Chinese standard JTG E20-2011* [26], which effectively simulates the application of actual wheel load on pavement structure in high-temperature condition. Loose mixes were compacted into a square slab with the dimension of 300×300×50 mm. These slab specimens were placed in the testing chamber at 60 °C for 6 h. Then, a solid rubber tire moved back and forward on the slab surface with the travel distance of 230 ± 10 mm. The travel speed was of 42±1 cycles/min, and the rut depth was recorded every 20 s. The dynamic stability (DS) parameter, which is an indicator of mixture rutting resistance, can be determined using Eq. 4.

$$\text{DS} = \frac{(t_2 - t_1) \times N}{d_2 - d_1} \tag{4}$$

where t_1 and t_2 are time that correspond to 45 min and 60 min, respectively; N is the wheel traveling speed, in this study $N = 42$ cycles/min; d_2 and d_1 are the rutting depth recorded at t_1 and t_2, respectively.

Table 3 Volumetric parameters of Marshall mixtures

Mixture type	Fiber type	Fiber content (%)	OAC (%)	Air void (%)	VMA (%)	VFA (%)	Stability (kN)	Flow (0.1 mm)
DG mixtures	Lignin	0.3	5.10	4.3	16.0	72.7	11.9	31.3
	Polyester	0.2	4.90	4.2	15.2	72.4	13.1	33.5
	Bamboo	0.0	4.85	4.3	15.0	71.7	11.0	24.1
		0.1	5.05	4.1	15.1	72.7	11.5	25.9
		0.2	5.21	4.1	15.9	74.4	12.0	27.4
		0.3	5.30	4.0	15.9	74.8	11.6	31.1
		0.4	5.43	4.0	15.9	74.9	10.4	39.9
SMA mixtures	Lignin	0.3	5.99	4.0	17.5	77.0	9.2	NA*
	Bamboo	0.2	5.79	4.1	16.6	75.5	9.9	
		0.3	5.87	4.0	17.0	76.6	10.5	
		0.4	5.95	3.9	17.4	77.1	10.2	
		0.5	6.03	3.8	17.6	77.6	9.7	

*Flow test is not measured for SMA mixtures

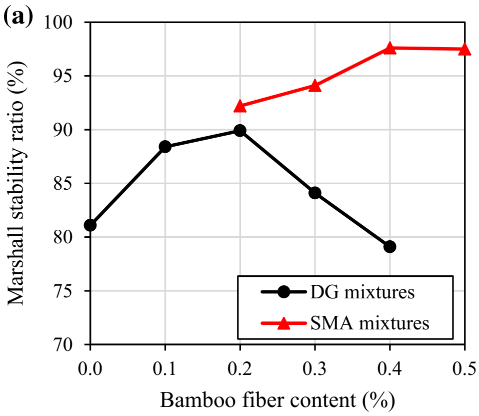

Fig. 7 **a** Marshall stability ratio and **b** tensile strength ratio of DG and SMA mixtures containing various bamboo fiber contents

Figure 8 shows that bamboo fiber increased the DS value of the control mixture indicating enhanced mixture rutting resistance. It appears that bamboo fiber was well distributed in mixtures resulting in a three-dimensional reinforcement. Although the trend was reversed when 0.4% bamboo fiber was added, this mixture still exhibited DS value greater than that of the control mixtures (nanofiber and lignin fiber mixtures). The reduction indicated that 0.4% bamboo fiber may be too much to agglomerate and consequently reduce mixture strength by causing stress concentration. The polyester fiber mixture yielded the highest DS value, which was comparable to that of the 0.3% bamboo fiber mixture.

Figure 9 depicts the DS values of SMA mixtures. Up to 0.4% bamboo fiber had a positive effect on the DS values of SMA mixtures. The use of 0.5% bamboo fiber resulted in a reduction in SMA DS value, although it was still higher than the control, 0.3% lignin fiber. Results indicated that bamboo fiber can be used to improve mixture rutting performance.

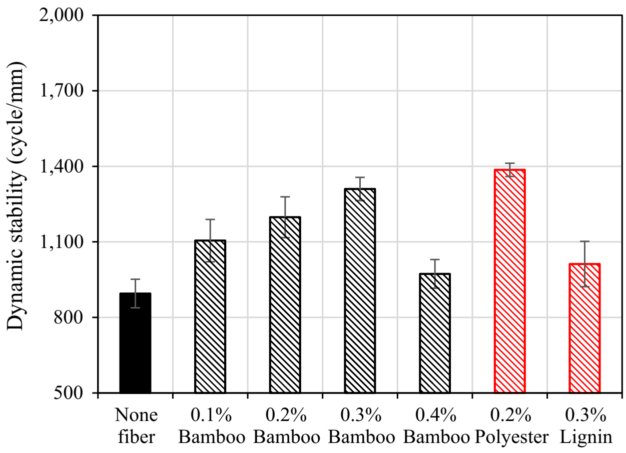

Fig. 8 Dynamic stability values of DG mixtures (one standard deviation as error bar)

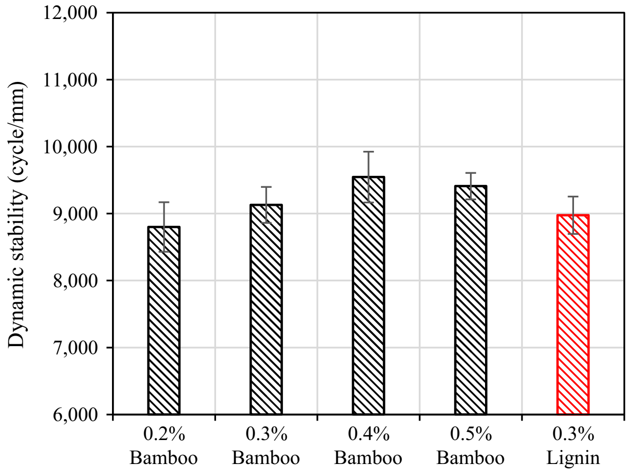

Fig. 9 Dynamic stability values of SMA mixtures (one standard deviation as error bar)

6.2 Low-Temperature Cracking Performance

The three-point beading beam (3PB) tests were conducted in accordance with the *Method T0715 in Chinese standard JTG E20-2011* [27] to evaluate the effects of bamboo fiber on the low-temperature cracking performance of DG and SMA mixtures. Loose mixtures were compacted into square slabs (300×300×50 mm) and then sawed into beam samples (250×30×35 mm). Before testing, beam samples were conditioned in an environmental chamber at −10 °C for 2 h. The span length was 200 mm (80% of the beam length), and the load was applied through a loading ring at a rate of 50 mm/min. The mid-span deflection was recorded, and the maximum deflection at failure was used to determine the flexural strain using Eq. 5. For each mixture type, three beams were tested and the average flexural strain value was reported.

$$\varepsilon_B = \frac{6 \times h \times d}{L^2} \tag{5}$$

where ε_B is the flexural strain ($\mu\varepsilon$); h is the height of cross section (mm); d is the mid-span deflection at failure (mm); L is the span of beam (mm).

The effect of bamboo fiber on mixture low-temperature cracking performance was evident such that bamboo fiber mixtures all had flexural strain values greater than that of the nanofiber mixture (Fig. 10). The use of 0.2% bamboo fiber yielded the highest strain value indicating greatest improvement in mixture resistance to cracking at low temperatures. Interestingly, adding higher than 0.2% bamboo fiber gradually decreased the flexural strain although they were all greater than that of none fiber mixture. The effect of the lignin fiber was almost negligible, whereas the use of polyester fiber achieved improvement comparable to the 0.2% bamboo fiber.

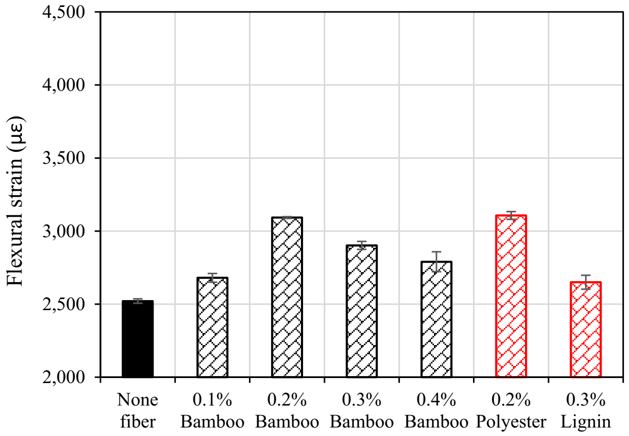

Fig. 10 Flexural strain values of DG mixtures (one standard deviation as error bar)

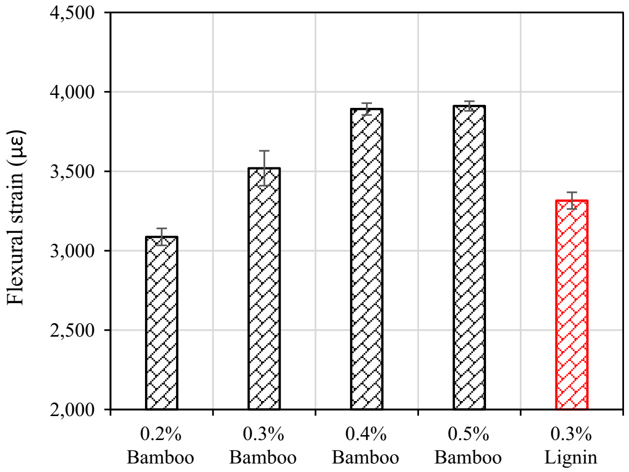

Fig. 11 Flexural strain values of SMA mixtures (one standard deviation as error bar)

Bamboo fiber also induced a notable improvement in flexural strain of SMA mixtures, as shown in Fig. 11. Higher bamboo fiber content resulted in greater flexural strain values, although the increment between the mixtures with 0.4% and 0.5% bamboo fiber was minor (only 19$\mu\varepsilon$). All mixtures, except for the one with 0.2% bamboo fiber, exhibited greater flexural strain values than that of the control mixture (0.3% lignin fiber), indicating the applicability of the bamboo fiber in SMA mixtures.

7 Findings and Conclusions

This study evaluated the applicability of using bamboo fiber in DG and SMA mixtures for enhanced mixture performance. Findings may be summarized as follows:

- Weight loss of bamboo fiber against increased heating temperatures can be divided into three stages. Within the first stage, only approximately 5% bamboo fiber decomposed at 180 °C which is the upper limit of mixture mixing and compacting temperatures.
- Tensile strength of bamboo fiber started to decrease when the heating temperature was above 150 °C; however, less than 10% reduction was observed at 180 °C.
- SEM captured the surface characteristics of bamboo fiber before and after the heating treatment. The fiber became much rougher which potentially promoted the adhesion between fiber and asphalt binder by increasing the binder absorption.
- As expected, higher bamboo fiber content resulted in greater mixture OAC due to the increased binder absorption. Based on the immersion Marshall and freeze-thaw cycling testing results, all mixtures exhibited satisfactory moisture susceptibility.
- The use of bamboo fiber improved the rutting and low-temperature cracking performance of asphalt mixtures. The optimum contents of bamboo fiber were 0.2–0.3% for dense-graded mixtures and 0.4% for SMA mixtures.
- Equivalent or even better mixture performance (as indicated by the DS and flexural strain results) of bamboo fiber mixtures was observed comparing to the ones with polyester and lignin fibers.

Based on laboratory testing results of this study, bamboo fiber appears to be a promising road material for asphalt pavement construction. As a first attempt, this manuscript characterized the bamboo fiber and then evaluated the effect of bamboo fiber on rutting and low-temperature cracking performance of asphalt mixtures, which already involved a significant amount of laboratory tests and yielded several important findings. Further research is recommended to evaluate the effect of bamboo fiber on mixture cracking performance at intermediate temperatures.

Acknowledgements The research is supported by the funds of Natural Science Found Committee (NSFC) of China (No. 51608045). The authors thank Qinghai Transportation Science and Technology Project (No. 2017-ZJ-763, No. 2017-ZJ-764 and No. 2017-ZJ-715), Fundamental Research Funds for the Central Universities of China (No. 310831153409, No. 300102218502 and No. 300102318401).

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