

Optimization of Bamboo Fiber Content for Improving Durability-Related Performance of Asphalt Mixtures in Luzhou, Sichuan

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Abstract

Asphalt pavements in Luzhou, Sichuan, suffer from severe durability problems including thermal shrinkage cracking and high-temperature rutting due to the subtropical humid monsoon climate and a traffic overload rate exceeding 30%. Bamboo fiber, a green renewable material with abundant local resources, offers potential for improving asphalt mixture durability; however, the optimal Cizhu fiber content for Luzhou's conditions remains insufficiently defined. This study investigated the performance of Cizhu fiber-reinforced AC-13 dense-graded hot-mix asphalt mixtures under Luzhou's hot-humid and heavy-traffic conditions. Five bamboo fiber mass fractions (0.00–0.40%) were evaluated through Marshall tests and high-temperature rutting resistance tests in accordance with Chinese highway engineering specifications. The results indicated that bamboo fiber incorporation significantly improved Marshall stability by up to 19.5% and dynamic stability by 51.8%, while reducing rutting depth by 40.5% at the optimal dosage. Among the investigated mixtures, a fiber content of 0.30% by mass demonstrated the optimal balance between high-temperature stability, deformability, and constructability, providing practical guidance for durable and resource-localized asphalt pavement design in Luzhou.

Keywords: Bamboo fiber asphalt mixture; hot-humid climate; heavy traffic; durability; fiber content optimization

Introduction

only increased maintenance and repair costs but also affected traffic safety and operational efficiency, making the improvement of asphalt mixture durability a critical engineering challenge in local road construction. Previous studies have confirmed that asphalt pavements in hot and humid regions are particularly vulnerable to rutting and moisture-induced damage (Shi et al., 2022; Wang et al., 2024), and that the combination of high temperature and heavy traffic loading significantly accelerates pavement deterioration (Liu et al., 2024).

Fiber-reinforced asphalt mixtures have been widely adopted to enhance the crack resistance, fatigue resistance, and high-temperature stability of asphalt pavements (Xia et al., 2021). Among various fiber types, bamboo fiber, a natural plant fiber with high cellulose content, excellent toughness, and a high oil absorption rate exceeding 400%, exhibited superior interfacial bonding with asphalt binders and significant reinforcement effects in asphalt mixtures. Luzhou possessed abundant bamboo resources, with a bamboo forest area of approximately 667,183 acres and Cizhu as the dominant species, and had formed a complete bamboo product processing industrial chain, providing sufficient raw material support for the application of bamboo fiber in asphalt mixtures. Although numerous studies had investigated the performance of bamboo fiber-reinforced asphalt mixtures under laboratory-controlled conditions, most research focused on the dry and cold climatic conditions of northern China, with limited attention given to applications in the hot-humid and heavy-traffic environments of

southern Sichuan where high-temperature rutting and moisture damage were intensified (Li et al., 2024). Furthermore, the optimal dosage of local Cizhu fiber that could balance durability enhancement, mechanical performance, and practical constructability for Luzhou's asphalt pavements remained insufficiently defined. This gap highlighted the need for a systematic performance evaluation of Cizhu fiber-reinforced asphalt mixtures specifically designed for pavement applications under Luzhou's unique climatic and traffic conditions.

Accordingly, this study aimed to optimize the bamboo fiber content for improving the durability-related performance of asphalt mixtures in Luzhou. The research focused on (1) assessing the high-temperature stability performance, including Marshall stability and flow value; (2) investigating the high-temperature rutting resistance through dynamic stability and rutting depth measurements; and (3) determining the optimal Cizhu fiber content adapted to Luzhou's hot-humid climate and heavy-traffic characteristics. By identifying the optimal fiber dosage that provided a balanced improvement in high-temperature stability, deformability, and constructability, this study sought to provide practical mix design guidance for durable and resource-localized asphalt pavements in Luzhou.

To achieve these objectives, a controlled laboratory experimental program was designed, including material characterization, mix proportioning, specimen preparation, performance testing, and data analysis, as described in the following Materials and Methods section.

Materials and Methods

1. General

This study employed a controlled laboratory experimental design to determine the optimal Cizhu fiber content for AC-13 dense-graded hot-mix asphalt mixtures under simulated Luzhou's hot-humid and heavy-traffic conditions. The methodology included material characterization, mix design, specimen preparation, Marshall testing, and high-temperature rutting resistance testing. All procedures complied with the Chinese highway engineering specifications JTG E20-2011 and JTG 3410-2025 to ensure reliability and reproducibility. The experimental work was conducted in the Materials Training Laboratory at Jiangyang Urban Construction Vocational College, which was equipped with advanced asphalt mixture design and performance testing instrumentation.

2. Materials

In this study, the selection of constituent materials was carried out to ensure consistency with local pavement construction practices in Luzhou and to maintain experimental reliability. All materials were typical local construction materials selected based on compliance with relevant national standards and suitability for producing AC-13 asphalt mixtures for pavement applications. As summarized in Table 1, four main materials were used, including asphalt binder, aggregates, Cizhu fiber, and mineral powder, together with their corresponding specifications and key properties.

The local Cizhu bamboo used as the raw material for fiber production was presented in Figure 1, while the processed bamboo fibers applied in the asphalt mixtures were shown in Figure 2. The asphalt binder used in this study was 70# A-grade road petroleum asphalt, as illustrated in Figure 3. The coarse aggregate and fine aggregate employed for the AC-13 mixture were shown in Figure 4 and Figure 5, respectively. In addition, limestone mineral powder, which was used as filler in the asphalt mixture to improve gradation and mixture stability, was presented in Figure 6.



Figure 1. Local Cizhu from Luzhou



Figure 2. Bamboo Fiber



Figure 3. 70# A-grade road petroleum asphalt



Figure 4. Coarse Aggregates



Figure 5. Fine Aggregate



Figure 6. Mineral Powder

Table 1. Specifications and Key Properties of Materials Used in the Experimental Program

Material	Specification
Asphalt Binder	Grade A 70# road petroleum asphalt; Penetration (25°C): 72×0.1mm; Softening Point: 48°C; Ductility (10°C): 25cm
Coarse Aggregate	Rolled limestone stone 2.36–9.5 mm; Crushed Value: 22.5%; Angularity: 88%; Apparent Density: 2.72g/cm ³
Fine aggregate	Manufactured sand 0–2.36 mm; Fineness Modulus: 2.8; Clay Content: 0.8%; Apparent Density: 2.70g/cm ³
Mineral Powder	Limestone powder <0.075 mm; Apparent Density: 2.71g/cm ³ ; Water Content: 0.5%
Bamboo Fiber	Local Cizhu fiber, length 7mm; Cellulose content:75%; Oil absorption rate:420%; Tensile strength:350MPa; Moisture content:<2%

3. Concrete Mix Proportion

To accurately evaluate the effect of bamboo fiber content, the base AC-13 asphalt mixture was kept constant for all specimens, with only the fiber mass fraction being varied. The aggregate gradation adopted the median specification limits specified in JTG F40-2004, which was the most widely used gradation type in local pavement engineering, as presented in Table 2.

The optimal asphalt content (OAC) of the base mixture was determined to be 4.8% using the Marshall design method, and the volumetric indices met the national specification requirements, including Void Volume (4.0%), Mineral Aggregate Voids (14.5%), and Asphalt Saturation (70%).

As summarized in Table 3, five bamboo fiber mass fractions ranging from 0.00% to 0.40% were adopted, while all other mixture components remained unchanged to ensure a consistent comparison of fiber effects on asphalt mixture performance. The maximum fiber content of 0.40% by mass was selected based on findings from previous studies on bamboo fiber-reinforced asphalt mixtures (Li et al., 2024; Xia et al., 2021), which reported that fiber dosages exceeding 0.40% typically led to severe fiber agglomeration, significant workability reduction, and difficulty in achieving uniform fiber dispersion during mixing and compaction. Preliminary trial mixes in this study also confirmed that fiber contents above 0.40% produced unacceptable compaction quality and visible fiber clumping. The selected range of 0.00–0.40% was therefore considered representative of the practically applicable fiber dosages for dense-graded hot-mix asphalt mixtures in pavement applications.

During specimen preparation, the asphalt mixtures were produced using a laboratory asphalt mixture mixer to ensure uniform dispersion of bamboo fibers within the mixture. The asphalt mixture mixing equipment used in the experiment is shown in Figure 7, while the prepared asphalt mixture before specimen compaction is presented in Figure 8..

Table 2. Aggregate Gradation of AC-13 Dense-Graded Asphalt Mixture (Median of JTG F40-2004)

Sieve Aperture (mm)	13.2	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075
Median Passing Rate (%)	100	95	70	42	27	17	12	8.5	6

Table 3. Asphalt Mixture Mix Proportions for Different Bamboo Fiber Mass Fractions

Bamboo Fiber Mass (%)	Asphalt Content (%)	Coarse Aggregate	Fine Aggregate	Mineral Powder	Bamboo Fiber (mass %)
0.00	4.8	580	340	80	0
0.10	4.8	580	340	80	1
0.20	4.8	580	340	80	2
0.30	4.8	580	340	80	3
0.40	4.8	580	340	80	4

Note: Based on a total mixture mass of 1000 kg, the precise mass proportion of each material is given for different bamboo fiber content levels.



Figure 7. Asphalt Mixture Mixer



Figure 8. Asphalt Mixture

4. Experimental Program

4.1. Specimen Preparation

Asphalt mixture specimens were prepared using a standard asphalt mixture mixer to ensure uniform fiber dispersion, following a standardized heating, dry mixing, and wet mixing process. Marshall cylindrical specimens (101.6 mm × 63.5 mm) were cast for the Marshall test with 75 blows per side, and slab specimens (300 mm × 300 mm × 50 mm) were prepared by wheel compaction for the high-temperature rutting resistance test in accordance with JTG E20-2011. All specimens were cured at room temperature (25 °C) for 24 hours before testing to ensure performance stability. As shown in Table 4, each fiber dosage group consisted of three Marshall specimens and three rutting specimens to ensure statistical reliability and reduce experimental error.

Table 4. Experimental Groups and Specimen Allocation

Group	Bamboo Fiber Mass (%)	Marshall Specimens	Rutting Specimens	Total Specimens
G1	0.00	3	3	6
G2	0.10	3	3	6
G3	0.20	3	3	6
G4	0.30	3	3	6
G5	0.40	3	3	6

Each fiber dosage group consisted of multiple cube and prism specimens to ensure statistical reliability and minimize experimental error.

4.2. Marshall Test

Marshall stability and flow value were measured according to JTG T 0710-2011 using a Marshall testing machine, which served as the primary performance indicators for evaluating the high-temperature stability and deformability of asphalt mixtures. The Marshall testing apparatus used in the experiment is shown in Figure 9.

Prior to testing, the specimens were preconditioned in a 60 °C constant-temperature water bath for 30–40 minutes and were then loaded at a constant speed of 50 mm/min until failure occurred. Marshall stability (MS, kN) and flow value (FL, 0.1 mm) were recorded to assess the mechanical performance of the mixtures.



Figure 9. Marshall Test

4.3. High-Temperature Rutting Resistance Test

High-temperature rutting resistance was evaluated according to JTG T 0718-2011 at 60 °C (simulating Luzhou's extreme summer temperature) using a wheel track tester. The wheel tracking testing equipment used in the rutting resistance experiment is shown in Figure 10.

Slab specimens were preconditioned in a 60 °C environmental test chamber for 5 hours, after which a wheel load with a contact pressure of 0.7 MPa was applied at a speed of 42 passes per minute. Dynamic stability (DS, passes/mm) and rutting depth (mm, measured at 60 min) were calculated to quantify the high-temperature rutting resistance of the mixtures. Dynamic stability served as the key index representing the number of wheel load applications required to produce 1 mm deformation of the specimen.



Figure 10. Rutting Test

Data Analysis

Test results were evaluated using comparative statistical analysis. For each test, the mean value of three specimens was calculated, together with the standard deviation, to ensure data reliability. Marshall stability, dynamic stability, and other performance indices were compared across different fiber dosages and were expressed as improvement percentages relative to the control mix (0.00% fiber content). Rutting depth results were used to assess the high-temperature deformation resistance of asphalt mixtures. Statistical significance was evaluated at a 95% confidence level, and abnormal values were eliminated using the Grubbs criterion. Data processing and analysis were performed using Excel, Origin, and SPSS software.

Results

1. Workability Observation

The experimental workability observation results indicated that increasing bamboo fiber dosage gradually reduced the workability of hot-mix asphalt mixtures. This reduction was attributed to fiber interlocking, increased internal friction within the mixture, and the adsorption of asphalt binder by bamboo fiber. Mixtures containing fiber mass fractions $\leq 0.30\%$ maintained acceptable workability suitable for local pavement construction and compaction. When the fiber content exceeded 0.30%, the workability decreased significantly due to fiber agglomeration, which affected the uniform dispersion of fiber and the compaction performance of the mixture.

2. Marshall Stability and Flow Value

The addition of bamboo fibers exhibited a dosage-dependent influence on the Marshall stability and flow value of asphalt mixtures, as summarized in Table 5 and illustrated in Figure 11. Marshall stability increased significantly with increasing fiber content, reaching a peak value of 9.8 kN at 0.30% fiber content, which represented a 19.5% improvement compared

with the control mixture (0.00% fiber content, 8.2 kN). Concurrently, the flow value decreased gradually from 28×0.1 mm for the control mixture to 24×0.1 mm at 0.30% fiber content, indicating that the incorporation of bamboo fiber enhanced the stiffness of the asphalt mixture while maintaining adequate deformability. These findings are consistent with those reported by Xia et al. (2021), who observed that bamboo fiber additions at moderate dosages improved Marshall stability by 15–20% due to the fiber’s high oil absorption rate and strong interfacial bonding with the asphalt binder. The improvement mechanism can be attributed to the three-dimensional network structure formed by bamboo fibers within the asphalt matrix (Elsevier, 2023), which enhances load transfer and restricts lateral deformation under compressive loading. The performance decline at 0.40% fiber content further supports the findings of Li et al. (2024), who reported that excessive fiber dosages disrupted the homogeneity of the asphalt mixture and weakened interfacial adhesion.

When the fiber content exceeded 0.30% (0.40% content), the Marshall stability slightly decreased to 9.5 kN due to fiber agglomeration, which resulted in uneven fiber dispersion and reduced interfacial bonding between the fiber and the asphalt binder. The volumetric indices of the mixtures remained within the specification requirements after the addition of bamboo fiber, with a slight decrease in void volume (VV) and mineral aggregate voids (VMA) and a slight increase in asphalt saturation (VFA).

The variation trends of Marshall stability and flow value with different bamboo fiber contents are presented in Figure 11, which further illustrates the influence of fiber dosage on the mechanical performance of the asphalt mixtures.

Table 5. Marshall Test Results of Bamboo Fiber-Modified Asphalt Mixtures

Group	Bamboo Fiber Mass (%)	Marshall Stability MS (kN)	Flow Value FL (0.1mm)	Void Volume VV (%)	Mineral Aggregate Voids VMA (%)	Asphalt Saturation VFA (%)
G1	0.00	8.2 ± 0.15	28 ± 0.8	4.0 ± 0.1	14.5 ± 0.2	70.0 ± 0.5
G2	0.10	8.9 ± 0.12	26 ± 0.6	3.8 ± 0.1	14.3 ± 0.2	71.2 ± 0.4
G3	0.20	9.4 ± 0.18	25 ± 0.7	3.7 ± 0.1	14.1 ± 0.3	72.5 ± 0.6
G4	0.30	9.8 ± 0.10	24 ± 0.5	3.6 ± 0.1	14.0 ± 0.2	73.1 ± 0.4
G5	0.40	9.5 ± 0.14	23 ± 0.6	3.5 ± 0.1	13.9 ± 0.2	74.0 ± 0.5

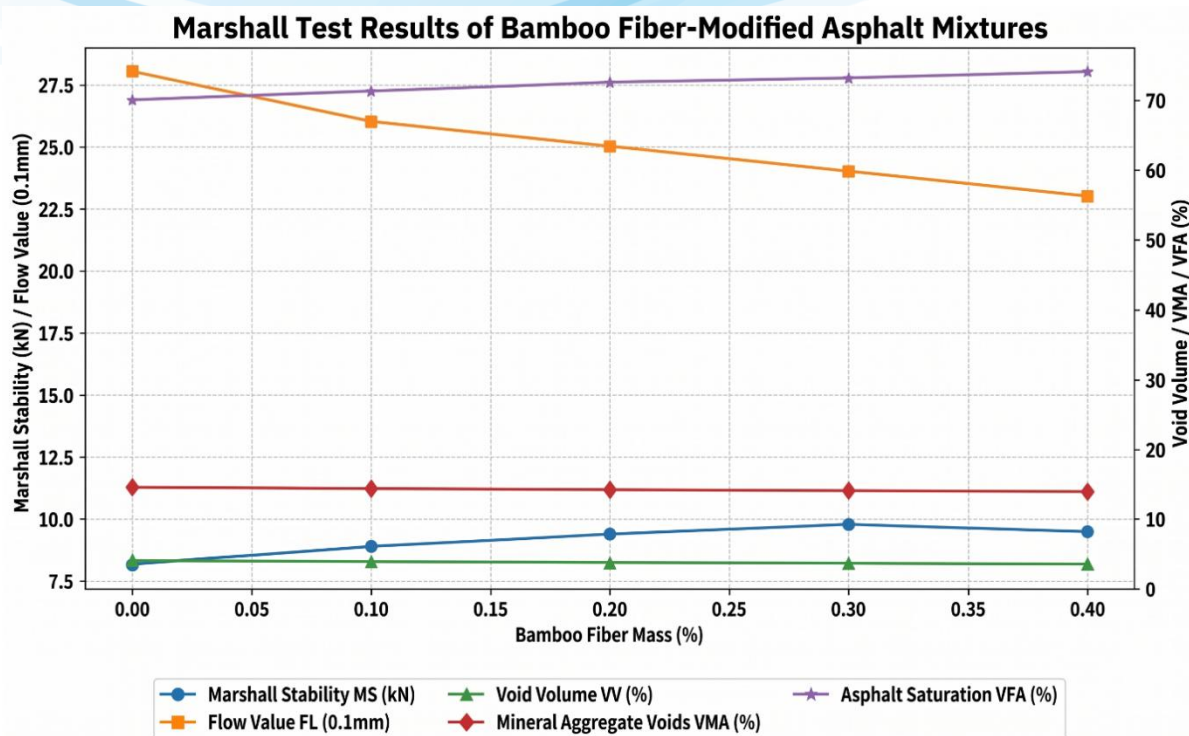


Figure 11. Marshall Test Results Line Chart

3. High-Temperature Rutting Resistance

Bamboo fibers significantly enhanced the high-temperature rutting resistance of asphalt mixtures due to their efficient adsorption stabilization and crack-bridging mechanisms, as summarized in Table 6 and illustrated in Figure 12. Dynamic stability increased continuously with increasing fiber content and reached a peak value of 1290 passes/mm at 0.30% fiber dosage, which represented a 51.8% improvement compared with the control mixture (850 passes/mm) and far exceeded the minimum specification requirement of 800 passes/mm specified in JTG F40-2004. The substantial improvement in dynamic stability is comparable to the results reported by Sheng et al. (2019), who demonstrated 40–50% improvements in rutting resistance in field trials of bamboo fiber-modified asphalt pavements in Sichuan Province. The adsorption mechanism of bamboo fiber in stabilizing the asphalt binder, as described by Granada University (2025), explains the enhanced high-temperature resistance at moderate fiber dosages. From a practical implementation perspective, the recommended 0.30% fiber dosage is readily achievable using standard asphalt mixing equipment, and the use of locally sourced Cizhu fiber from Luzhou’s bamboo processing industry offers cost advantages of approximately 30–40% compared with synthetic fiber alternatives (Tang et al., 2021), while simultaneously reducing the carbon footprint of pavement construction.

Correspondingly, the rutting depth decreased from 4.2 mm for the control mixture to 2.5 mm at 0.30% fiber content, effectively mitigating the high-temperature rutting problems commonly observed in Luzhou. When the fiber content increased to 0.40%, the dynamic stability slightly decreased to 1250 passes/mm, while the rutting depth increased to 2.7 mm, which was consistent with the trend observed in the Marshall stability results. This finding further confirmed that excessive fiber content led to fiber agglomeration and a reduction in overall performance.

The variation trends of dynamic stability and rutting depth with different bamboo fiber contents are presented in Figure 12, which clearly illustrates the influence of fiber dosage on the high-temperature rutting resistance of asphalt mixtures.

Table 6. High-Temperature Rutting Test Results of Bamboo Fiber-Modified Asphalt Mixtures

Group	Bamboo Fiber Mass (%)	Dynamic Stability DS (passes/mm)	Rutting Depth (mm, 60 min)	Relative Improvement Rate (%)
G1	0.00	850 ± 22.4	4.2 ± 0.15	—
G2	0.10	1020 ± 18.6	3.5 ± 0.12	20.0
G3	0.20	1180 ± 25.1	3.0 ± 0.18	38.8
G4	0.30	1290 ± 16.7	2.5 ± 0.10	51.8
G5	0.40	1250 ± 20.3	2.7 ± 0.14	47.1

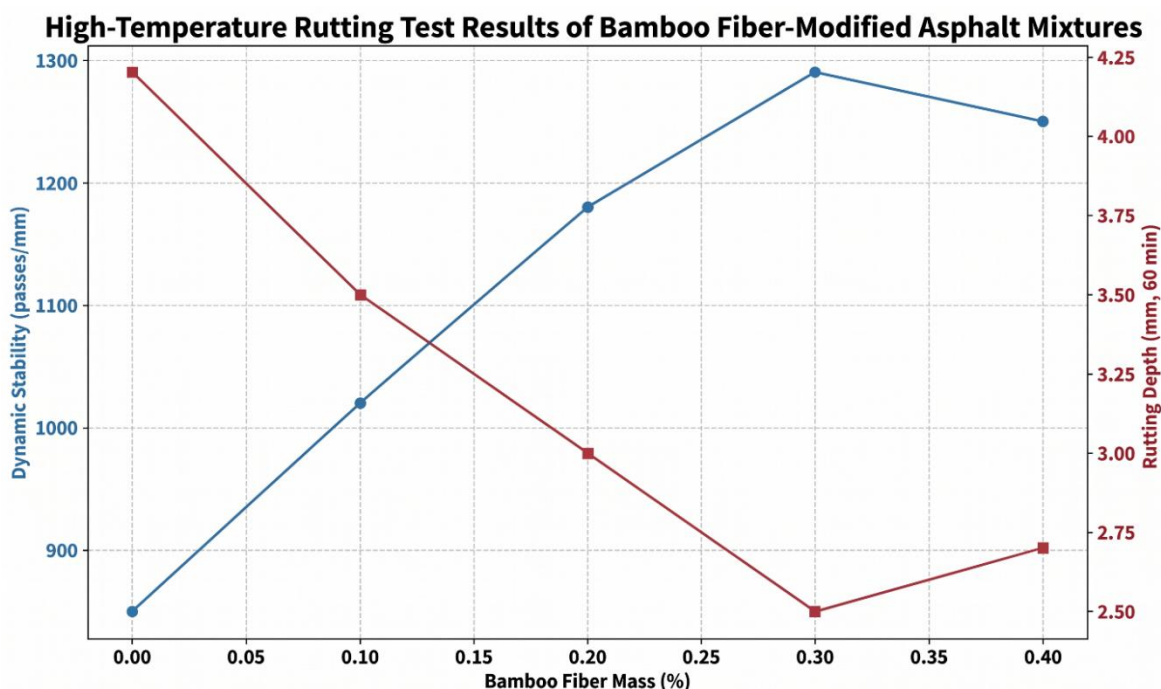


Figure 12. Rutting Test Results Line Chart

4. Overall Performance Evaluation

Considering Marshall stability, flow value, dynamic stability, and rutting depth together, the results indicated that 0.30% bamboo fiber by mass provided the most balanced performance for AC-13 asphalt mixtures in Luzhou, achieving simultaneous improvements of 19.5% in Marshall stability and 51.8% in dynamic stability, as well as a 40.5% reduction in rutting depth compared with the control mix. This fiber content ensured that the mixture exhibited excellent high-temperature stability and rutting resistance while maintaining appropriate deformability and constructability, which was well adapted to Luzhou's hot-humid climate and heavy traffic conditions.

Conclusions

This study was limited to laboratory-scale specimens and controlled high-temperature testing conditions, and the long-term field performance under actual climatic and traffic conditions in Luzhou required further verification.

In summary, the experimental results demonstrated that the incorporation of local Cizhu fiber significantly enhanced the high-temperature stability and rutting resistance of AC-13

dense-graded hot-mix asphalt mixtures under simulated Luzhou's hot-humid and heavy-traffic conditions. Among the investigated mixtures, a fiber dosage of 0.30% by mass provided the most balanced improvement in Marshall stability, dynamic stability, rutting resistance, and constructability. Bamboo fiber enhanced the durability of asphalt mixtures through four synergistic mechanisms: adsorption stabilization and asphalt reinforcement, crack bridging and anti-cracking, fatigue mitigation and toughening, and skeleton reinforcement and integrity improvement. Fiber contents exceeding 0.30% reduced workability and led to performance inefficiency due to fiber agglomeration and reduced interfacial bonding between the fiber and asphalt binder.

The use of local Cizhu fiber also realized the high-value utilization of Luzhou's abundant bamboo resources, reduced the carbon footprint of pavement construction, and offered significant economic and environmental benefits compared with traditional synthetic fiber and SBS-modified asphalt technologies.

These findings provided practical guidance for climate-adaptive and resource-localized mix design in durability-critical pavement applications in Luzhou and laid a theoretical and experimental foundation for the broader application of bamboo fiber-reinforced asphalt mixtures in the hot-humid regions of southern Sichuan.

Future Work

1. For practical asphalt pavement construction in Luzhou, a Cizhu fiber dosage of 0.30% by mass is recommended for the AC-13 surface layer to achieve balanced improvements in high-temperature stability, rutting resistance and deformability while maintaining acceptable workability and constructability. Strict quality control during construction is essential to ensure uniform fiber dispersion and prevent agglomeration.

2. Future research should investigate long-term field performance of bamboo fiber-reinforced asphalt pavements under actual traffic and climatic conditions in Luzhou, including moisture resistance and fatigue resistance tests to construct a comprehensive durability evaluation system.

3. Further study should be conducted on the effects of different bamboo fiber lengths, surface treatment methods and processing technologies on the performance of asphalt mixtures to optimize the fiber modification technology and improve the interfacial bonding between fiber and asphalt binder.

4. A comprehensive life-cycle assessment (LCA) and cost-benefit analysis should be carried out to quantify the economic and environmental advantages of bamboo fiber-reinforced asphalt mixtures over traditional asphalt pavements, and provide data support for local policy formulation and industrial promotion.

These future investigations will support the practical implementation of bamboo fiber-reinforced asphalt mixtures in real road construction environments and promote the sustainable development of Luzhou's bamboo industry and road construction industry.

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