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Review

Straw Fiber-Reinforced Asphalt Mixtures for Sustainable Pavements: Performance Enhancement, Multiscale Mechanisms, and Engineering Perspectives

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Abstract

Agricultural straw is a renewable agricultural residue with potential for sustainable pavement applications, but research on its use as reinforcement in asphalt mixtures remains fragmented. This review systematically summarizes the characteristics, modification methods, pavement performance, and multiscale reinforcement mechanisms of straw fibers in asphalt materials. The literature indicates that appropriate straw fiber incorporation can improve high-temperature stability, low-temperature cracking resistance, moisture stability, and fatigue performance, although the magnitude of improvement depends strongly on fiber type, dosage, length, surface treatment, dispersion, and mixture characteristics. The reported reinforcement effects are mainly associated with fiber-network formation, fiber-asphalt interfacial interactions, crack bridging, asphalt-component retention, and changes in internal structural organization. However, direct evidence for aging resistance remains limited, and several proposed mechanisms still require quantitative cross-scale validation. Practical challenges, including moisture control, storage, plant-scale dispersion, mixing and feeding procedures, production consistency, and field-quality control, also restrict wider engineering application. Quantitative life-cycle evidence for straw fiber-reinforced asphalt mixtures is still insufficient. Future research should integrate advanced characterization, numerical modeling, long-term field validation, and life-cycle assessment to establish more reliable structure-performance relationships and support the sustainable engineering application of straw fiber-reinforced asphalt mixtures.

Keywords: road engineering; straw fiber; asphalt mixture; green pavement materials; pavement performance; multi-scale mechanism

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1. Introduction

Asphalt pavement is extensively adopted because it provides a smooth riding surface, good driving comfort, limited traffic noise and dust, satisfactory wear resistance, rapid construction and maintenance, and convenient repair [1], accounting for more than 90% of paved roads in China, North America, and Europe [2,3]. However, during long-term service, asphalt mixtures are simultaneously subjected to temperature fluctuations,

repeated traffic loading, and moisture exposure, which may lead to durability-related distresses such as permanent deformation, low-temperature cracking, and moisture damage [4,5], thereby compromising pavement performance and shortening service life. It has been reported that carbon emissions associated with road construction and maintenance account for approximately 15–20% of total emissions from the transportation sector [6]. Reducing this burden is therefore closely linked to carbon-peaking and carbon-neutrality objectives [7], creating strong demand for reinforcement materials that can improve pavement performance without imposing a high environmental cost.

Meanwhile, agricultural modernization has led to a substantial increase in crop straw production, with annual straw generation in China reaching hundreds of millions of tonnes, thereby placing increasing pressure on resource utilization and environmental management [8]. As a widely available and renewable biomass resource, crop straw has traditionally been disposed of through open burning or low-value utilization, resulting not only in resource waste but also in increased environmental burdens [9,10]. Against this background, the value-added utilization of crop straw has become an important research topic. In pavement engineering, crop straw can be directly incorporated into asphalt mixtures in fibrous form or converted into biochar through pyrolysis for asphalt modification [11], and both approaches represent promising pathways for its value-added utilization. In particular, straw fibers exhibit favorable flexibility and a relatively high specific surface area [12], which provide potential for enhancing the performance of asphalt mixtures.

A life-cycle assessment of wheat-straw resource utilization reported a carbon-emission reduction of 1.5752 million tons over the 1-year assessment period [13], demonstrating the considerable low-carbon potential of wheat straw valorization. In pavement applications, nano-montmorillonite bagasse fiber composite-modified asphalt pavement was reported to reduce maintenance-stage carbon emissions by 26.79% and total carbon emissions within the defined life-cycle boundary by 12.23% compared with conventional base-asphalt pavement [14]. Together, these findings provide quantitative support for the potential sustainability of agricultural-residue-based pavement materials, although dedicated life-cycle assessment is still required to quantify the environmental benefits of straw fiber-reinforced asphalt mixtures.

Research on straw fiber-reinforced asphalt mixtures has progressively expanded from basic fiber preparation to surface treatment, parameter optimization, and pavement-performance evaluation. Nevertheless, the available literature remains dominated by comparisons of macroscopic performance indicators, while the mechanisms responsible for the different responses produced by straw species, fiber geometry, dosage, and pretreatment remain insufficiently resolved. In particular, quantitative understanding of fiber dispersion, fiber asphalt interfacial interactions, mesoscale structural evolution, and their relationships with macroscopic pavement performance is still limited. Moreover, the considerable variation in the best-performing fiber parameters reported within individual studies complicates the establishment of consistent mixture-design criteria and hinders the translation of laboratory findings into engineering practice.

Against this background, the present review combines bibliometric analysis with a structured synthesis of the literature to consolidate current knowledge on straw fiber-reinforced asphalt mixtures. First, the physicochemical characteristics and modification methods of representative straw fibers are reviewed, followed by a comparative evaluation of the effects of fiber type, dosage, length, and pretreatment on high-temperature stability, low-temperature cracking resistance, moisture stability, fatigue behavior, and aging resistance. The reported performance responses are then interpreted from the perspectives of physical reinforcement, fiber asphalt interfacial interactions, and multiscale struc-

tural regulation, as summarized in Figure 1. Particular attention is given to the relationships among fiber characteristics, dispersion, interfacial behavior, mesoscale structure, and macroscopic pavement performance. Finally, current limitations and future research priorities are discussed to support the optimization and potential engineering application of straw fiber-reinforced asphalt mixtures.

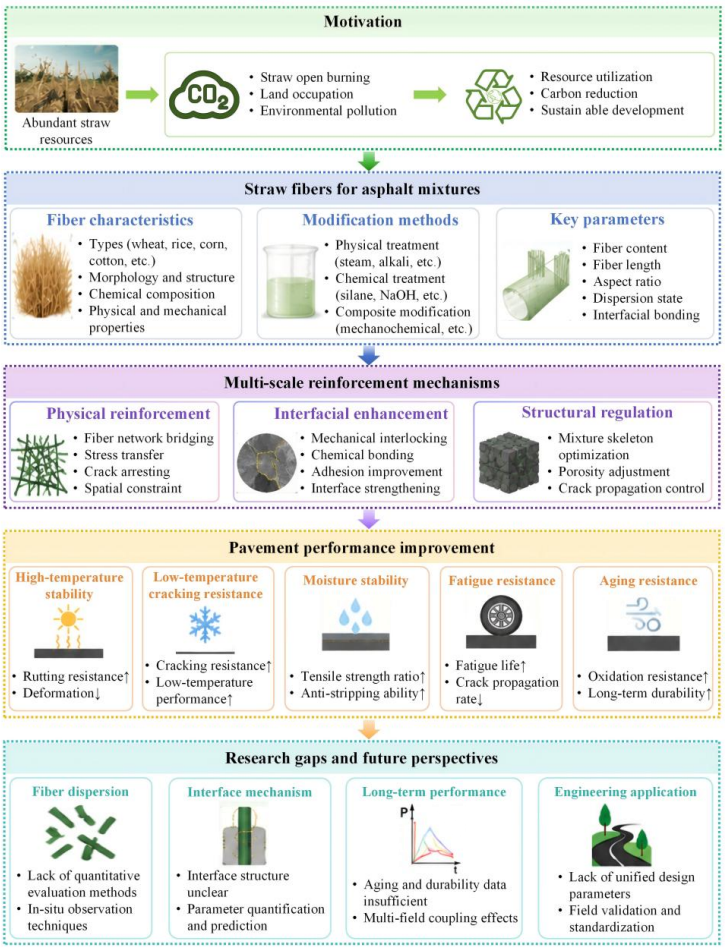


Figure 1. Framework of the review on straw fiber-reinforced asphalt mixtures. **Note:** In the schematic diagrams, the arrows "↑" and "↓" indicate an increase and decrease in the corresponding performance, respectively. In the "Long-term performance" schematic, P and t denote performance and time, and the arrows denote their increasing directions; the different colored curves represent the general evolution trends of performance under different conditions.

2. Research Methodology and Bibliometric Analysis

2.1. Literature Search and Screening Strategy

A structured literature search was conducted using the Web of Science Core Collection (WoSCC) and China National Knowledge Infrastructure (CNKI), covering publications available up to 9 May 2026, in English or Chinese. The search focused on combinations of terms related to straw fibers and asphalt materials. Representative keywords included "straw fiber", "wheat straw", "corn straw", "rice straw", "cotton straw", "asphalt", "asphalt mixture", and "pavement performance", together with their corresponding Chinese terms.

The database search identified 182 records, including 98 records from WoSCC and 84 records from CNKI. The retrieved records were screened based on titles, abstracts, and,

where necessary, full texts. Studies were included when they addressed straw fiber preparation or modification, straw fiber-modified asphalt binders or mixtures, pavement performance, reinforcement mechanisms, durability, or related engineering applications. Duplicate records, studies unrelated to asphalt materials, and publications lacking sufficient relevance to the scope of this review were excluded.

In addition to the literature identified through the structured database search, supplementary references were incorporated where necessary to support background information, methodological discussion, cross-material mechanistic comparisons, and revisions made in response to reviewer comments. These supplementary references were not included in the database-search statistics or bibliometric analysis. Accordingly, the final manuscript contains 106 references, which should not be interpreted as the number of records retrieved through the structured WoSCC and CNKI search. The overall literature identification and screening procedure is summarized in the PRISMA-style flow diagram shown in Figure 2.

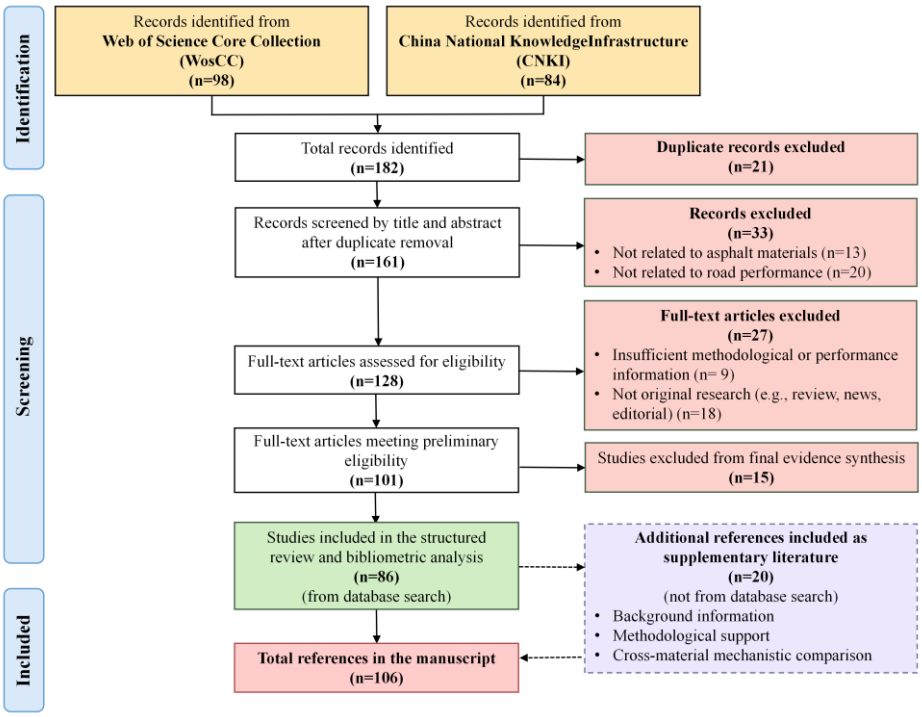


Figure 2. PRISMA-style flow diagram of the literature identification and screening process.

2.2. Bibliometric Analysis

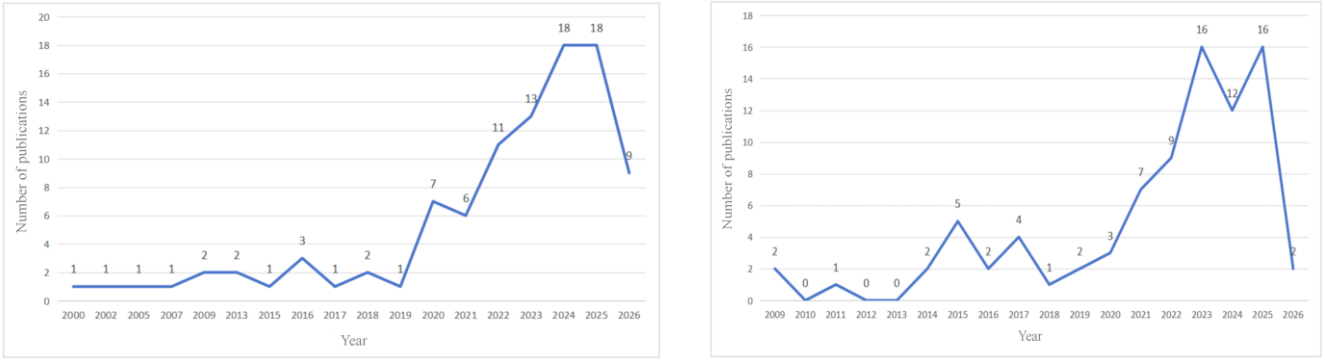
Annual publication trends were analyzed separately based on the records retrieved from WoSCC and CNKI. As shown in Figure 3, the two databases provide complementary perspectives on the temporal development of research on straw fiber-modified asphalt materials. The WoSCC dataset comprised 98 records, representing internationally indexed research, whereas the CNKI dataset contained 84 records, reflecting the development of related research in the Chinese literature. The annual publication trends indicate that research activity in this field has gradually increased, particularly in recent years, suggesting growing interest in the use of agricultural straw fibers as sustainable pavement-reinforcement materials.

Keyword co-occurrence analysis was further conducted using CiteSpace v. 6.4.R1 to identify the principal research themes and their relationships. The time slicing was set to 1 year. The keyword was selected as the node type, and the g-index with k = 25 was used for node selection. Prior to network construction, synonymous terms, abbreviations, and

different expressions referring to the same concept were standardized to reduce semantic duplication. The resulting keyword co-occurrence network is presented in Figure 4, where node size represents keyword occurrence frequency and links indicate co-occurrence relationships between keywords.

The bibliometric results indicate a gradual evolution of the research focus from conventional performance evaluation toward mechanism-oriented and sustainability-related investigations. Earlier studies mainly concentrated on fiber preparation, dosage optimization, and conventional pavement properties, including high-temperature stability, low-temperature cracking resistance, and moisture stability. With the development of microstructural characterization and numerical approaches, increasing attention has been directed toward fiber-asphalt interfacial interactions, internal structural evolution, and multiscale reinforcement mechanisms. More recently, emerging topics such as molecular dynamics and life-cycle assessment have become important research fronts. Molecular dynamics provides a potential approach for quantitatively examining molecular-scale adsorption and interfacial interactions, whereas life-cycle assessment extends the evaluation from material performance to environmental benefits and resource efficiency. These trends suggest that current research is gradually shifting from demonstrating whether straw fibers improve pavement performance toward explaining why such improvements occur and whether they can provide sustainable benefits throughout the pavement life cycle.

The final reference list of the revised manuscript comprises 48.1% international peer-reviewed journal articles, 42.5% Chinese journal articles, 8.5% dissertations, and 0.9% conference-proceedings papers. WoSCC was selected because it provides broad coverage of internationally indexed peer-reviewed literature in pavement engineering, construction materials, and related fields, whereas CNKI complements this coverage by including Chinese-language journal articles and dissertations that are particularly relevant to straw fiber-modified asphalt research and engineering applications in China. The two databases therefore provide complementary international and regional coverage. Nevertheless, their combined use does not eliminate potential database, language, regional, and indexing biases, and relevant studies indexed exclusively in other databases may have been omitted. In addition, differences in mixture composition, fiber characteristics, testing conditions, and standards limit direct quantitative comparisons among independent studies. Therefore, cross-study findings are interpreted primarily in terms of study-specific trends and relative performance changes.



(**a**) Web of Science Core Collection (**b**) China National Knowledge Infrastructure

Figure 3. Annual publication trends in research on straw fiber-modified asphalt mixtures: (**a**) annual number of publications indexed in the Web of Science Core Collection (WoSCC); (**b**) annual number of publications indexed in the China National Knowledge Infrastructure (CNKI).

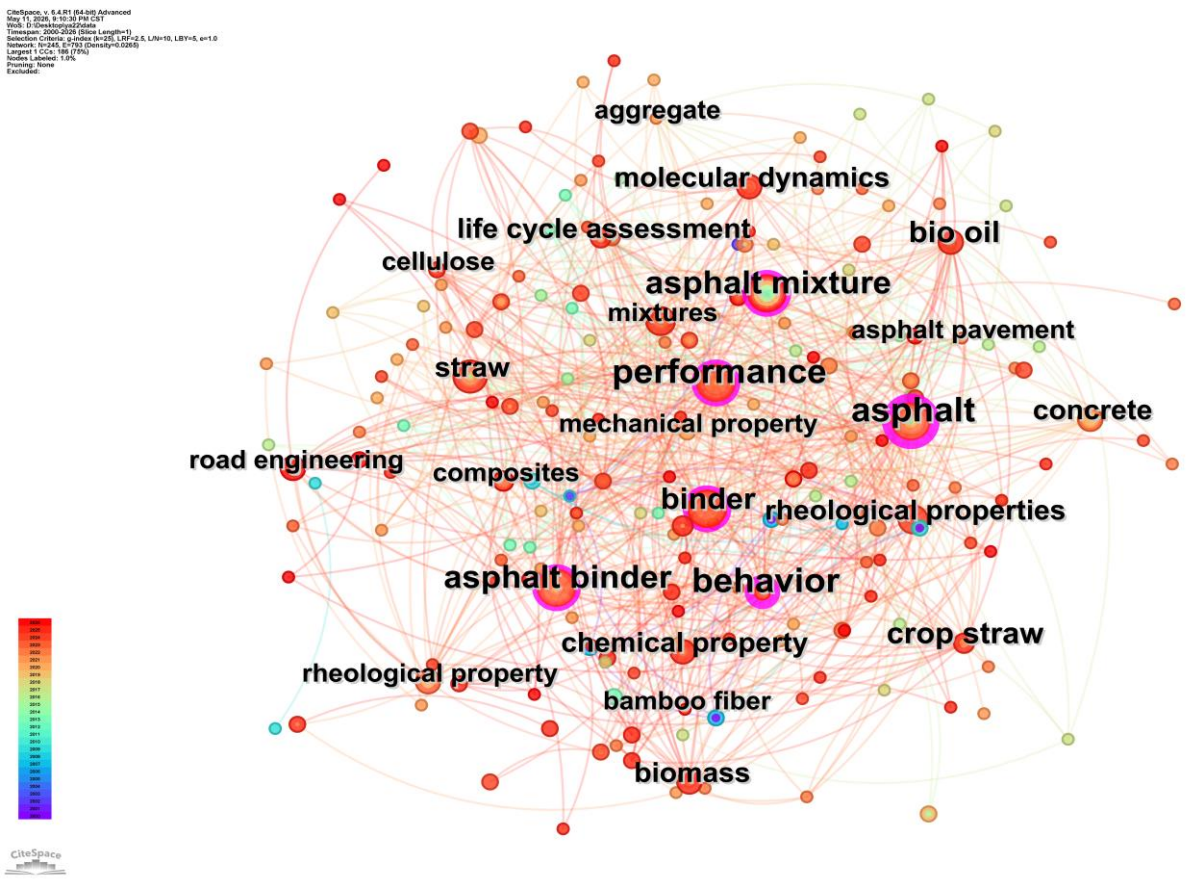


Figure 4. Keyword co-occurrence network for research on straw fiber-modified asphalt mixtures.

3. Straw Fibers in Asphalt Mixtures: Development, Characteristics, and Modification

3.1. Development of Fiber-Reinforced Asphalt Mixtures

Fiber reinforcement has long been used to improve the mechanical integrity of engineering materials. Early applications included natural and metallic fibers in cementitious composites, followed by the development of industrial fiber-reinforced materials. Representative milestones include the use of waste steel in concrete in 1874, the appearance of asbestos fiber cement products in 1879, and the industrial production of asbestos-cement sheets using the Hatschek process in 1900 [15]. In China, systematic research on steel fiber-reinforced concrete began in the 1970s, while polyester and other fibers were increasingly introduced into asphalt materials during the 1990s.

With the development of fiber technology, a wider range of reinforcement materials has been applied in asphalt mixtures, including fast-growing grass, bamboo, ceramic, and basalt fibers [16–19]. Their beneficial effects are commonly associated with asphalt adsorption, stabilization of the asphalt mastic, and restriction of binder flow [20]. Meanwhile, increasing attention to sustainability has promoted the use of renewable plant fibers. According to anatomical origin, plant fibers can generally be classified as wood, bast, seed, leaf, and stem fibers [21]. Wood fibers have been reported to improve aging resistance [22], bast fibers such as jute can enhance stability and rutting resistance [23], while seed-derived fibers such as coconut, kapok, and cotton also show potential for improving deformation and aging resistance [24,25]. Leaf- and stem-derived fibers have likewise demonstrated favorable effects in asphalt mixtures [26].

Straw fibers belong primarily to the stem-fiber category and are particularly attractive because they combine fibrous reinforcement with the value-added utilization of agricultural residues. With the growing emphasis on sustainable pavement materials, research on straw fibers has gradually expanded from basic feasibility evaluation to modification, parameter optimization, pavement-performance assessment, and mechanism investigation. The major stages in this development are summarized in Figure 5.

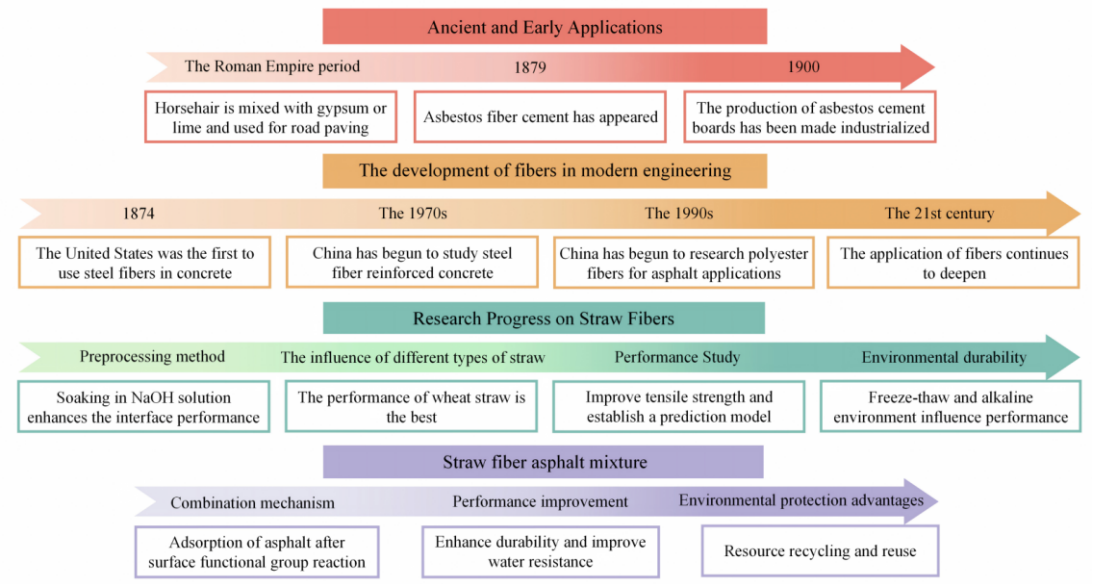


Figure 5. Development of fiber reinforcement and straw-fiber applications in asphalt mixtures.

3.2. Types and Basic Characteristics of Straw Fibers

Straw fibers used in pavement materials are mainly derived from crop stalks such as wheat, corn, rice, cotton, and highland barley. Although these agricultural residues share a lignocellulosic structure, their engineering properties differ because of variations in chemical composition, internal morphology, density, ash content, and mechanical strength. These differences can influence fiber-asphalt interactions and reinforcement efficiency. Following the general evaluation framework adopted for other sustainable construction materials, mechanical properties should be interpreted together with material condition, processing history, environmental conditioning, and testing protocol rather than as isolated strength values [27,28]. Accordingly, Table 1 summarizes representative physical and mechanical properties of straw fibers together with the available testing basis and moisture-condition information. Because the mechanical properties of natural lignocellulosic fibers are sensitive to moisture content, environmental conditioning, and testing procedures, the reported values should be interpreted as study-specific results rather than directly comparable intrinsic material properties.

Cellulose, hemicellulose, and lignin are the principal structural constituents of straw fibers. Cellulose provides the main load-bearing framework and is closely related to fiber strength and structural integrity, whereas hemicellulose and lignin influence flexibility, polarity, surface chemistry, and interfacial interaction with asphalt. Among the straw fibers currently investigated for asphalt-mixture modification, wheat, corn, rice, and cotton-stalk fibers are the most common. Cotton-stalk fiber has also been investigated in both AC-13 and SMA-13 mixtures, with reported improvements in high-temperature stability and low-temperature deformation capacity while maintaining satisfactory moisture stability [29]. Fiber type, dosage, length, and modification method have been identified as important factors governing reinforcement effectiveness [30]. Wheat straw fibers generally exhibit relatively low density and good flexibility, whereas rice-straw fibers tend to

have higher ash contents and therefore different surface characteristics. The potential of straw fibers for sustainable applications has also been demonstrated in other construction materials [31].

Studies on straw fiber-reinforced cementitious composites further indicate that surface treatment can significantly alter fiber-matrix interactions. Thermo-alkaline treatment has been reported to improve the bonding performance of wheat straw fibers [32], while NaOH treatment can enhance the mechanical properties of straw fiber-reinforced composites [33]. Reducing matrix alkalinity may also mitigate fiber degradation and improve composite performance [34]. Although these findings are derived from cementitious systems rather than asphalt mixtures, they are cited here only as supplementary evidence illustrating the potential influence of surface treatment on fiber-matrix interactions. They should not be interpreted as direct evidence of straw fiber behavior in asphalt materials.

Table 1. Representative physical and mechanical properties of different straw fibers and their reported testing conditions.

Straw Fiber Type	Density ($g \cdot cm^{-3}$)	pH	Ash Content (%)	Tensile Strength (MPa)	Testing Standard and Conditioning State	Ref.
Cotton stalk fiber	1.50	7.4	18.20	-	JT/T 533-2020; moisture content: 3.7%	[35]
	1.51	6.7	17.30	-	JT/T 533-2020; moisture content: 3.9%	
Wheat straw fiber	0.51	6.9	6.30	112.16	JT/T 533-2020; -	[36,37]
Highland barley straw fiber	1.45	-	10.34	500.00	-	[38]
Rice straw fiber	1.33	7.2	14.30	-	JT/T 533-2020; moisture content: 2.6%	[39]

Note: The reported properties were obtained from different studies and therefore should not be interpreted as directly comparable intrinsic material properties. "-" indicates that the corresponding information was not reported in the cited source.

3.3. Modification Methods of Straw Fibers

Natural straw fibers generally possess a waxy surface layer and a certain degree of hydrophilicity, which may limit their compatibility and interfacial bonding with asphalt. Therefore, physical, chemical, thermal, and combined modification methods are commonly used to improve fiber surface characteristics and reinforcement efficiency, as illustrated in Figure 6.

Physical modification mainly involves cleaning, drying, cutting, crushing, and surface roughening. These treatments can remove contaminants and moisture, control fiber dimensions, increase surface roughness, and promote mechanical interlocking with the asphalt matrix. Chemical modification, such as alkali treatment or the use of coupling agents, can alter the surface composition of straw fibers, remove part of the waxy layer and impurities, and improve fiber-asphalt interfacial adhesion.

However, the sustainability benefits of chemical modification should not be evaluated solely in terms of the resulting improvement in fiber-asphalt compatibility. Alkali treatment generally requires chemical reagents, subsequent washing and neutralization, and additional drying, while silane coupling treatment introduces further chemical and processing inputs. These procedures may increase water and energy consumption, wastewater generation, and treatment costs, thereby partially offsetting the environmental and economic advantages associated with the direct utilization of agricultural residues [12]. Therefore, the net benefit of chemical pretreatment should be assessed from a life-cycle perspective by balancing performance improvement against the additional environmental and economic burdens introduced during fiber treatment. At present, quantitative life-cycle and cost assessments specifically for chemically modified straw fibers in asphalt mixtures remain limited.

Chemical treatment may also modify fiber surface morphology, pore structure, and transport pathways, which can influence moisture penetration and interfacial durability under aggressive environmental exposure. Pore-scale visualization and multiscale characterization methods, including CT and NMR, have been successfully used in other porous bio-based material systems to quantify pore evolution, connectivity, and transport behavior [40,41]. Although these studies involve hydrogel-modified soils rather than asphalt materials, their characterization frameworks provide useful methodological references for future investigation of treatment-induced pore-structure evolution and moisture transport in straw fiber–asphalt systems.

Thermal treatment represents another modification approach for straw fibers. The temperature range of 120–200 °C shown in Figure 6 refers to controlled thermal pretreatment rather than the actual production temperature of asphalt mixtures. During hot-mix asphalt production, straw fibers are exposed to elevated temperatures for a certain period, and their thermal stability therefore becomes an important prerequisite for maintaining the intended reinforcing effect. Previous studies on corn stalk fibers have shown that appropriate pretreatment can improve their heat resistance and delay thermal degradation [42]. Similar heat-resistance and thermogravimetric evaluations of other agricultural lignocellulosic fibers, such as bagasse fibers, further indicate that thermal stability is an important prerequisite for their application in hot-mix asphalt [43]. Recent reviews on natural fibers in asphalt pavement have also emphasized heat resistance, dispersibility, preparation conditions, and durability as key considerations for practical application [44]. Prolonged exposure to elevated temperatures may alter the lignocellulosic structure and consequently affect fiber morphology, flexibility, asphalt adsorption, and crack-bridging capacity. Therefore, processing temperature and mixing duration should be considered jointly during mixture production. However, systematic studies quantitatively linking the coupled temperature-time history of hot-mix asphalt production to the retained structural and reinforcing properties of straw fibers remain limited.

In addition to surface treatment, fiber geometry and dosage strongly influence the modification effect. Fibers must be sufficiently long to interact with the surrounding matrix and bridge developing cracks, whereas excessive length may cause entanglement. Similarly, increasing fiber dosage can initially promote the formation of a reinforcing network, but excessive content may lead to agglomeration and reduced mixture homogeneity. Consequently, the reinforcement effect generally exhibits a non-monotonic relationship with fiber length and dosage and may decrease once the practical dispersion limit is exceeded [45].

Despite the potential benefits of modification, straw fibers also present inherent material-related limitations. Their hydrophilicity, surface waxes, and impurities may reduce fiber-asphalt compatibility, while variations in crop source, morphology, and chemical composition can lead to inconsistent reinforcement efficiency. Excessive fiber length or dosage may further promote entanglement, agglomeration, and nonuniform dispersion.

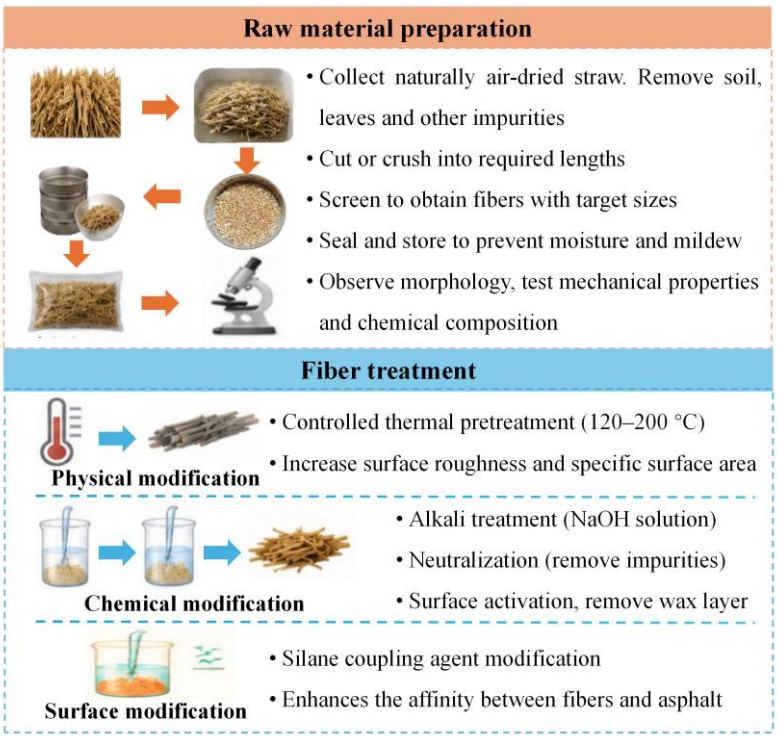


Figure 6. Schematic illustration of the preparation and modification methods of straw fibers for asphalt-mixture applications.

4. Pavement Performance of Straw Fiber-Reinforced Asphalt Mixtures

The incorporation of straw fibers can influence multiple aspects of asphalt-mixture performance, although the magnitude and direction of these effects depend strongly on fiber type, dosage, geometry, surface treatment, mixture composition, and testing conditions. It should also be recognized that straw fiber incorporation does not necessarily lead to uniform performance improvement, because excessive asphalt absorption, poor dispersion, fiber agglomeration, or inappropriate fiber parameters may adversely affect mixture homogeneity and workability. This section reviews the available evidence regarding high-temperature stability, low-temperature cracking resistance, moisture stability, fatigue resistance, and aging resistance, with particular attention to the relationships between fiber parameters and reported performance responses.

The numerical data summarized in the following tables are intended to illustrate study-specific performance changes after straw fiber incorporation. Because the reported results were obtained using different mixture compositions, fiber parameters, specimen preparation procedures, test temperatures, and standards, they should not be interpreted as directly comparable values across independent studies.

4.1. High-Temperature Stability

Rutting is a major high-temperature distress of asphalt pavements and develops through the progressive accumulation of irreversible deformation under elevated temperatures and repeated traffic loading [46–48]. Severe rutting reduces pavement smoothness and may adversely affect driving comfort and traffic safety [49,50]. High-temperature performance is evaluated at different material levels. At the binder and mastic levels, commonly used indicators include softening point, complex modulus, phase angle, and other rheological parameters, whereas mixture-level performance is generally evaluated using rutting-related indicators such as dynamic stability (DS) and rut depth. Representative

results at these different material levels are summarized in Table 2. Because these indicators characterize different material responses, binder- and mastic-level parameters should not be directly compared with mixture-level rutting indicators. Moreover, absolute DS values reported in different studies should not be directly compared because they are affected by differences in binder grade, mixture design, fiber dosage, and testing temperature. Therefore, where corresponding control data are available, Table 2 reports the relative change with respect to the control group tested under the same experimental conditions; absolute values are retained only when an appropriate baseline is unavailable.

Table 2. Normalized high-temperature performance of straw—fiber-modified asphalt materials under reported testing conditions.

Fiber Type	Material/Mixture Type	Dosage/Test Temperature	High-Temperature Indicator	Control Value	Modified Value	Relative Change	Ref.
Straw-based composite fiber	SMA	0.30%; 60 °C	Dynamic stability	-	3610 cycles/mm	-	[51]
Cotton straw fiber	AC-13	0.20%; 60 °C	Dynamic stability	3390 cycles/mm	4436 cycles/mm	+30.9%	[52]
	SMA-13	0.30%; 60 °C		4580 cycles/mm	6180 cycles/mm	+34.9%	
	AC-13/70# neat asphalt	0.30%; 60 °C		-	2245.09 cycles/mm	-	[53]
Modified corn/cotton straw fiber	Asphalt mastic/70# asphalt	1.5–2.0%; -	Softening point Shear resistance	Untreated-fiber mastic	Modified-fiber mastic	+6.5% on average +23.1% on average	[54]
Corn stalk fiber	Binder/AH-90 (PG64-28)	2%; 70 °C	Rutting factor $G^*/\sin\delta$	0.554 kPa	0.616 kPa	+11.2%	[55]
		4%; 70 °C			0.861 kPa	+55.4%	
		6%; 70 °C			0.967 kPa	+74.5%	
		8%; 70 °C			1.047 kPa	+89.0%	
		10%; 70 °C			1.188 kPa	+114.4%	

Note: Relative change was calculated using the corresponding control group reported within the same study. "-" indicates that the required baseline or testing information was not explicitly reported. Absolute values from different studies should not be directly compared because of differences in binder grade, mixture design, fiber dosage, and testing conditions.

Existing studies generally indicate that appropriate incorporation of straw fibers can improve the high-temperature deformation resistance of asphalt mixtures. Within the same experimental study, straw-based composite fiber exhibited a DS comparable to those of polyester and polypropylene fibers and higher than that of lignin fiber [51]. In another study, straw fiber incorporation increased DS by approximately 28.79% while reducing rutting deformation [56]. The magnitude of the improvement also depends on mixture structure. Corn straw fiber has also been applied in high-void asphalt mixtures, indicating that the reinforcing effect of straw fibers should be considered together with the internal structural characteristics of the mixture [57]. The magnitude of the improvement also depends on mixture structure. Cotton straw fiber enhanced DS in both AC-13 and SMA-13 mixtures, while the stone-on-stone skeleton of SMA-13 was more favorable for fiber bridging and restriction of aggregate movement [52].

At the binder scale, high-temperature performance is mainly associated with changes in asphalt-component adsorption and rheological response. Corn stalk fiber has been reported to reduce penetration and increase the softening point of asphalt binder. DSR results further showed that, at 70 °C, the rutting factor increased progressively with corn stalk fiber content, from 0.554 kPa for the control binder to 0.616, 0.861, 0.967, 1.047, and

1.188 kPa at fiber contents of 2%, 4%, 6%, 8%, and 10%, respectively [54]. At the mastic scale, surface modification can further alter high-temperature response; modified corn straw and cotton straw fibers produced an average increase of approximately 6.5% in softening point relative to the corresponding untreated straw fiber mastics, together with an average increase of approximately 23.1% in shear resistance [55]. These binder- and mastic-level results support the beneficial effect of straw fibers on high-temperature rheological behavior, but they should not be directly equated with mixture-level DS results.

However, the high-temperature reinforcement effect is not proportional to fiber content and is jointly controlled by fiber type, dosage, length, asphalt content, and dispersion state. Within an appropriate range, fibers can form an effective reinforcing network and restrict the movement of asphalt mastic and aggregate particles. Excessive fiber content or length, however, may promote entanglement, agglomeration, and nonuniform dispersion, thereby reducing the expected reinforcement effect [53,58,59]. Optimization of fiber dosage, length, and asphalt content is therefore necessary to achieve favorable high-temperature performance [53]. Straw fibers have also been reported to improve the creep-recovery behavior of asphalt mastic and reduce non-recoverable deformation [60], while comparative studies of fiber-reinforced AC-13 mixtures further support their beneficial contribution to high-temperature stability [61].

Overall, the available evidence suggests that improved rutting resistance results from several coupled effects rather than a single mechanism. Straw fibers can retain part of the asphalt components and reduce mastic mobility, while fibers distributed between aggregate particles provide additional restraint against relative displacement. When sufficient dispersion is achieved, these local effects develop into a spatial reinforcing network that helps stabilize the load-bearing skeleton. As illustrated in Figure 7, binder softening and aggregate rearrangement promote permanent deformation in unmodified mixtures, whereas the introduction of straw fibers can restrict both mastic flow and aggregate movement, thereby slowing the accumulation of rutting deformation. Nevertheless, quantitative relationships among fiber geometry, dispersion characteristics, and rutting resistance remain insufficiently established. Future comparisons should therefore report normalized performance changes together with binder grade, mixture composition, fiber dosage, and testing conditions to improve cross-study comparability.

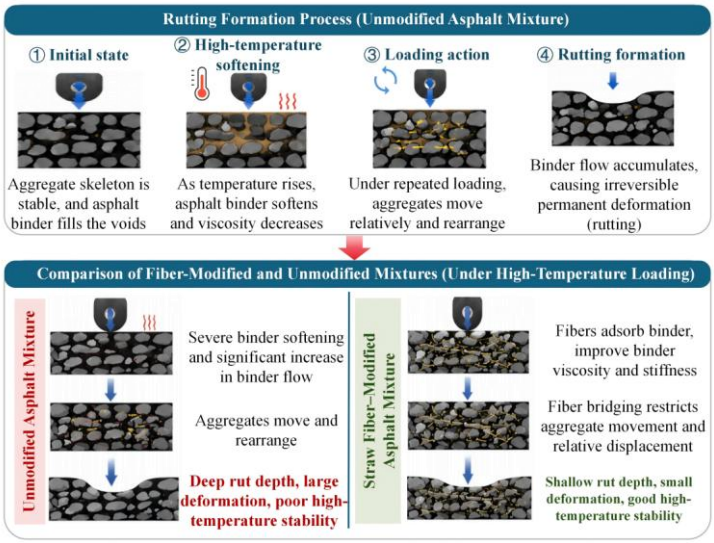


Figure 7. Schematic illustration of the high-temperature rutting-resistance mechanism of straw fiber-reinforced asphalt mixtures. **Note:** In the schematic diagrams, the downward blue arrows indicate the direction of applied loading, the circular blue arrows represent the repeated loading action, and the vertical arrows in the lower section denote the progressive deformation of the mixtures.

4.2. Low-Temperature Cracking Resistance

Low-temperature cracking occurs when asphalt stiffening and thermal contraction reduce the deformation capacity of the pavement. As temperature decreases, thermally induced tensile stresses accumulate within the mixture, and cracking may initiate once the local tensile resistance is exceeded. These cracks can subsequently provide pathways for water infiltration and accelerate interfacial deterioration and secondary pavement distress [62]. Low-temperature performance is commonly evaluated using indicators such as flexural tensile strength, maximum flexural tensile strain, flexural stiffness modulus, and fracture toughness. Because asphalt mixtures exhibit strongly temperature- and rate-dependent viscoelastic behavior, these indicators should be interpreted together with the corresponding testing temperature and loading rate. Representative experimental results and their reported test conditions are therefore summarized in Table 3.

Table 3. Representative experimental results on the low-temperature cracking resistance of straw-fiber-reinforced asphalt mixtures.

Fiber Type	Gradation	Dosage/Length	Test conditions (Temperature/Loading Rate)	Flexural Tensile Strength (MPa)	Maximum Flexural Tensile Strain (με)	Flexural Stiffness Modulus (MPa)	Ref.
Wheat straw pieces	AC-13	0%; -	−10 °C/-	7.48	4156	1799	[63]
		0.1%; 7 mm		9.18	3589	2558	
		0.2%; 7.5–19 mm	−10 °C/50 mm·min^{-1}	7.77	3489	2227	[37]
Corn straw fiber	SMA-13	0%; -	-	6.88	2622	2564	[64]
		0.3%; ≤4 mm		7.61	2711	2800	
Rice straw fiber	AC-13	0%; -	-	7.23	2407	3017	[65]
		0.2%; 3 mm		8.40	2523	3355	
Modified rice straw fiber	AC-13	0.2%; 3 mm	-	8.56	2550	3374	

Note: "-" indicates that the corresponding testing temperature or loading rate was not explicitly reported in the original source. No unreported test conditions were inferred from general standards.

The available results indicate that straw fibers can modify low-temperature cracking behavior, although improvements in different mechanical indicators are not always consistent. For wheat straw-reinforced mixtures, an appropriate fiber content can contribute to the formation of a micro-reinforcing structure, whereas excessive fiber addition may cause agglomeration and reduce mixture homogeneity [37]. The incorporation of 0.1% thin, short wheat straw pieces increased flexural tensile strength by approximately 23% and fracture toughness by 27% [63]. However, the corresponding flexural tensile strain reported in Table 3 decreased relative to the control mixture, indicating that an increase in strength does not necessarily imply a simultaneous increase in deformation capacity. These results highlight the need to evaluate low-temperature performance using multiple complementary indicators rather than a single parameter. Cross-study comparisons should also be made cautiously because differences in testing temperature and loading rate can significantly affect the measured strength, strain, and stiffness responses.

At the crack scale, the beneficial effect of straw fibers is generally associated with crack bridging and stress redistribution. As illustrated in Figure 8, cracks in unmodified asphalt mixtures can propagate rapidly along weak regions under thermal contraction and localized stress concentration. After fiber incorporation, fibers crossing developing

cracks can participate in tensile-load transfer and delay crack propagation, while improved fiber-asphalt interfacial bonding can enhance the effectiveness of stress transfer. The resulting reinforcement therefore depends not only on fiber strength but also on fiber dispersion and interfacial integrity.

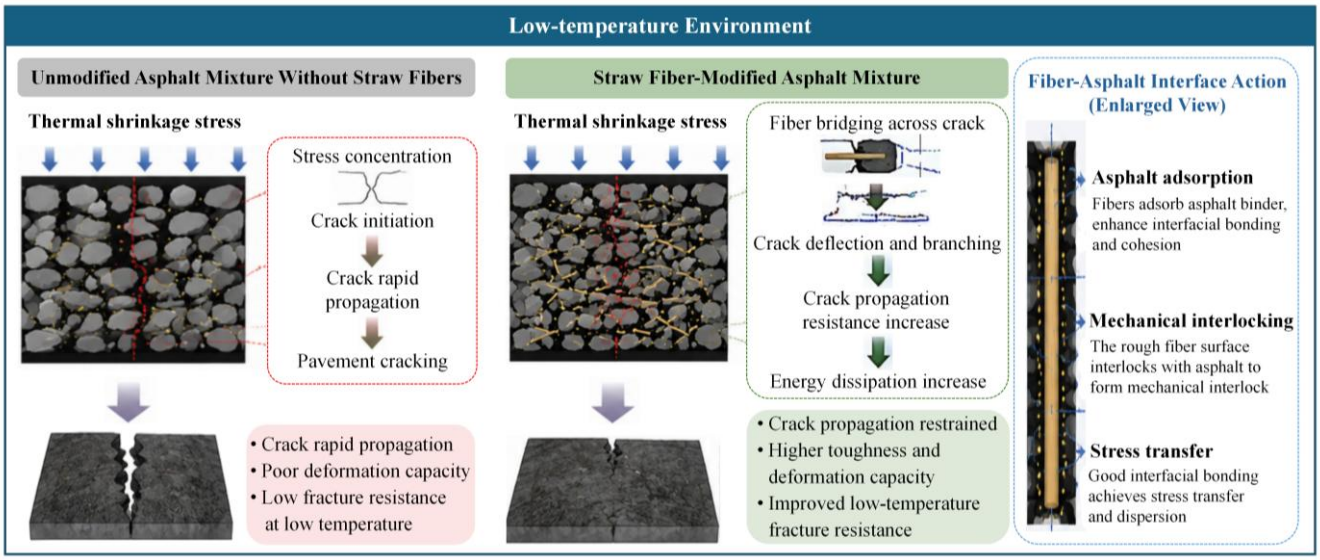


Figure 8. Schematic illustration of the low-temperature cracking-resistance mechanism of straw fiber-reinforced asphalt mixtures. **Note:** In the schematic diagrams, the downward blue arrows represent the thermal shrinkage stress, the large gradient purple arrows indicate the resulting deformation of the pavement, and the green arrows illustrate the micro-evolution process of crack initiation and propagation.

Related studies on other biomass-derived materials provide supplementary evidence for possible changes in the low-temperature response of the asphalt matrix. Bending Beam Rheometer (BBR) testing of modified bamboo fiber systems reported changes in the stiffness parameter and low-temperature rheological performance [66], while rice-husk biochar has been reported to enhance asphalt cohesion and alter stress distribution in semi-flexible pavement materials [67]. Because these studies do not directly investigate straw fiber-reinforced asphalt mixtures, they are cited only as supplementary evidence for possible matrix-level mechanisms and are not used as direct evidence of the low-temperature performance of straw fiber-reinforced asphalt mixtures.

The magnitude of the low-temperature response also varies with straw fiber type and modification conditions. Corn straw fiber has been reported to increase flexural tensile strength and maximum flexural tensile strain while reducing the variability of test results [64]. Surface modification may further enhance fiber-asphalt bonding; however, the effects of fiber length and dosage are non-monotonic, because excessively long fibers or excessive contents can promote entanglement and agglomeration and consequently restrict deformation capacity [36]. Rice straw fiber has also shown favorable effects in recycled asphalt mixtures, where fibers may occupy interfacial regions, fill microvoids, and contribute to an interconnected reinforcing structure. Within the investigated range, a rice straw fiber dosage of 0.3% provided the best low-temperature flexural tensile response among the tested dosages [68].

Overall, low-temperature reinforcement is jointly governed by fiber type, length, dosage, asphalt characteristics, dispersion state, and environmental conditions rather than by fiber content alone. The appropriate fiber dosage is therefore mixture-specific and depends on the material system and service conditions [38]. Excessive fiber incorporation

may increase internal defects and impair cracking resistance, emphasizing the importance of controlling fiber geometry and dispersion uniformity [69]. The available evidence suggests that the principal reinforcement mechanisms involve crack bridging, redistribution of local stresses, formation of a spatial fiber network, and fiber-asphalt interfacial stress transfer. Nevertheless, quantitative relationships among fiber spatial distribution, interfacial properties, crack evolution, and macroscopic low-temperature performance remain insufficiently established.

4.3. Moisture Stability

Moisture damage occurs when water penetrates the mixture and weakens the adhesion between asphalt and aggregate, promoting asphalt-film stripping and progressive structural deterioration. Straw fibers may improve moisture stability through asphalt adsorption, interfacial reinforcement, and internal network formation. Representative experimental results evaluated using residual stability, freeze-thaw splitting tensile strength ratio, and splitting tensile strength are summarized in Table 4.

Table 4. Representative experimental results on the moisture stability of straw fiber-reinforced asphalt mixtures and selected comparison fiber systems.

Fiber Type	Treatment Method	Dosage	Improvement in Residual Stability	Freeze—Thaw Splitting Tensile Strength Ratio	Splitting Tensile Strength (Dry/Wet)	Ref.
Basalt fiber	-	0.4%	22.1%	Without freeze-thaw: increased by 8.6–18.1%. After freeze-thaw: increased by 11.6–34.0%.	-	[70]
	Polyurethane modification	0.3%	10.9%	Increase of 32.3%	-	[71]
	(Applicable to cold regions)	0.45%	$D_5 \geq 79.28$	$C_6 \geq 80.53\%$	-	[72]
Corn stalk fiber	-	0.2%	3.29%	Increase of 3.57%	-	[73]
Betel nut fiber	Alkali treatment	0.256%	-	88.41%	R_dry = 1.48 MPa R_sat = 1.27 MPa	[70]
Carbon fiber	-	0.3%	-	Increase of 11.23%	Dry ITS increase by 24% Wet ITS increase by 37.91%	[74]
Cotton straw fiber	-	0.2%	-	Increased by 3.77% after freeze-thaw	-	[75]

Note: Results for basalt, betel nut, and carbon fibers are presented only as supplementary comparative evidence and should not be interpreted as direct evidence for straw fiber-reinforced asphalt mixtures.

Existing studies indicate that the effectiveness of fiber reinforcement depends strongly on fiber type, dosage, surface characteristics, and treatment method. Corn-straw fiber can retain part of the asphalt components through its porous structure, stabilize the asphalt mastic, and reduce asphalt migration and stripping under moisture exposure, thereby improving moisture-damage resistance [73]. Cotton-straw fiber has also been reported to improve freeze-thaw performance [75]. These findings suggest that appropriate straw fiber incorporation can enhance moisture stability, although the magnitude of improvement varies among material systems.

In field service, moisture damage is not governed by water exposure alone but by the coupled effects of moisture infiltration and repeated traffic loading. Water entering interconnected voids can generate transient pore-water pressure under wheel loading, promoting interfacial debonding and progressive stripping of the asphalt film [65]. This process may be particularly important for straw fiber-reinforced mixtures because natural lignocellulosic fibers are inherently hydrophilic. If the fiber-asphalt interface is insufficiently bonded, moisture can penetrate the fiber and accelerate interfacial stripping, thereby weakening the reinforcing effect of the fiber network [61]. The surface condition of straw fibers may also evolve during long-term environmental exposure. The natural waxy layer provides a certain degree of hydrophobicity, whereas surface modification can alter or partially remove waxes and other surface components [61]. However, how this surface structure and the fiber-asphalt interphase evolve under repeated hygrothermal cycling remains unclear. Once interfacial integrity deteriorates, moisture may penetrate more readily along the fiber-asphalt interface and accelerate debonding. Direct quantitative evidence linking wax-layer evolution to long-term moisture damage in straw fiber asphalt mixtures is still limited. More broadly, durability studies of construction materials under aggressive environmental exposure emphasize the need to evaluate progressive property deterioration and performance retention rather than relying only on short-term mechanical indicators [76]. This evaluation concept provides a useful methodological reference for the long-term hygrothermal durability assessment of straw fiber-reinforced asphalt mixtures.

Studies involving other fiber types provide supplementary evidence for the importance of surface modification and parameter optimization. For example, response surface methodology applied to areca fiber-modified asphalt mixtures identified an optimum combination of fiber content, shearing time, and asphalt-aggregate ratio, resulting in a freeze-thaw splitting tensile strength ratio of 88.41% [70]. Related studies on modified, basalt, and carbon fiber systems further demonstrate that interfacial modification and fiber-network reinforcement can influence moisture resistance [71,72,74]. Although these materials are not straw fibers, their results provide useful supporting evidence for understanding the roles of fiber dispersion and interfacial bonding.

Overall, the improvement in moisture stability can be attributed to the combined effects of asphalt retention, enhanced fiber-asphalt interactions, and formation of a spatial reinforcing network. As illustrated in Figure 9, moisture can migrate through interconnected voids and progressively weaken asphalt-aggregate adhesion in unreinforced mixtures, whereas straw fibers may increase the complexity of transport pathways and provide additional structural restraint. The contribution of three-dimensional fiber networks to mixture durability has also been reported [59]. Nevertheless, the evolution of fiber-asphalt and asphalt-aggregate interfaces under prolonged moisture, freeze-thaw, and other coupled environmental conditions remains insufficiently understood and requires further investigation.

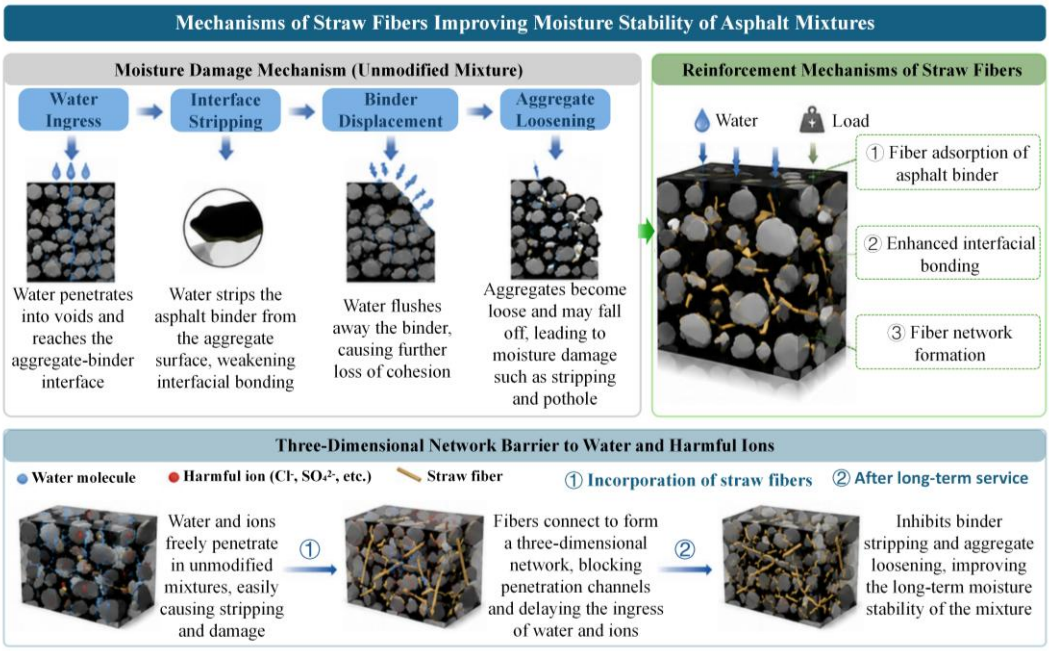


Figure 9. Schematic illustration of the moisture-damage resistance mechanism of straw fiber-reinforced asphalt mixtures. **Note:** In the schematic diagrams, the horizontal blue arrows indicate the sequence of the moisture damage process and the evolution of the fiber network, the vertical blue arrows represent the action of water ingress and applied loading.

4.4. Fatigue Resistance

Fatigue cracking develops through the progressive accumulation of damage under repeated traffic loading and is a major factor limiting the long-term durability of asphalt pavements. Straw fibers can influence this process through crack bridging, stress redistribution, and modification of the viscoelastic response of the asphalt mastic [77]. Appropriate fiber contents can form an effective internal reinforcing network and retard damage accumulation, whereas excessive dosages may promote agglomeration and weak local interfaces, thereby reducing the expected fatigue benefit [77].

The interpretation of fatigue performance should also distinguish between stress-controlled and strain-controlled loading modes. Under stress-controlled loading, the applied stress amplitude is maintained approximately constant during cyclic loading, whereas under strain-controlled loading, the imposed strain amplitude remains constant. Because asphalt mixtures undergo progressive stiffness degradation during fatigue loading, these two control modes produce different stress-strain responses and may consequently result in different measured fatigue lives [78]. Previous studies comparing stress-, strain-, and energy-controlled four-point bending fatigue tests have confirmed that loading mode plays an important role in the fatigue-performance evaluation of asphalt mixtures [78]. Therefore, fatigue results obtained under different loading-control modes should not be directly compared without considering the corresponding loading conditions. For fiber-reinforced mixtures, this distinction is particularly relevant because fiber bridging, interfacial stress transfer, and stiffness retention may influence the fatigue response differently under constant-stress and constant-strain conditions.

As illustrated in Figure 10, dispersed microcracks in unreinforced mixtures gradually propagate and coalesce under cyclic loading. After straw fiber incorporation, fibers spanning developing cracks can carry part of the tensile load and interrupt crack propagation, while the surrounding fiber network provides additional restraint. Supplementary evidence from other plant-based fibers suggests that crack bridging and fiber network formation may contribute to delayed fatigue deterioration; however, these findings are used

only for mechanistic comparison and are not regarded as direct evidence of straw fiber fatigue performance [79].

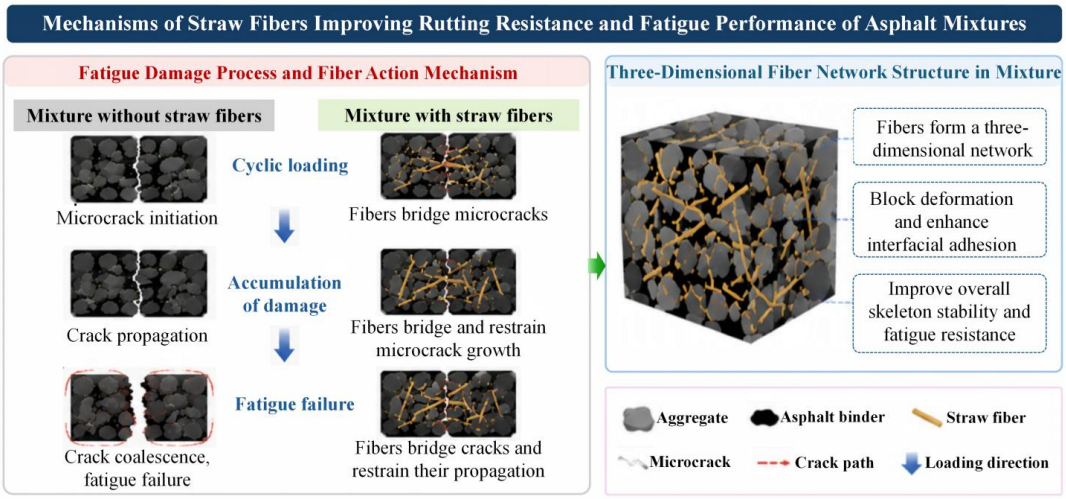


Figure 10. Schematic illustration of the fatigue-resistance mechanism of straw fiber-reinforced asphalt mixtures.

Experimental studies provide direct evidence of the fatigue-reinforcement effect of straw fibers. After freeze-thaw cycling, a corn straw fiber-modified recycled asphalt mixture exhibited a fatigue life of 5017 loading cycles, representing increases of 37.15% and 29.16% relative to the control asphalt mixture and the unmodified recycled asphalt mixture, respectively [80]. As supplementary mechanistic evidence, studies on other biomass fibers have reported retardation of crack propagation through microscale bridging effects [81]. In AC-13 mixtures, 0.2% modified corn straw fiber increased the number of load cycles to failure by 75.8% compared with the control mixture and by 9.2% compared with the lignin fiber-modified mixture [61,82]. Parameter optimization further indicates that fiber dosage, length, and asphalt content jointly influence fatigue performance [53,83].

Straw fibers have also shown fatigue-reinforcement potential in road materials incorporating solid wastes [84]. Beyond conventional fatigue-life indicators, dissipated-energy-based analysis provides a useful framework for characterizing the progressive development of fatigue damage in asphalt materials [78,85]. From an energy perspective, the energy dissipated during cyclic loading contains contributions from viscoelastic deformation and irreversible damage processes. Dissipated-energy partitioning can therefore be used to separate the energy associated with recoverable or non-damaging responses from the portion increasingly associated with irreversible damage and crack development, thereby providing additional information on different stages of fatigue evolution [85]. For straw fiber-reinforced asphalt mixtures, such an energy-based framework may be particularly useful for quantifying how crack bridging, fiber-matrix interfacial slip, stress redistribution, and crack retardation influence energy dissipation during cyclic loading. However, direct dissipated-energy-partitioning studies specifically focused on straw fiber-reinforced asphalt mixtures remain limited.

Overall, the available evidence indicates that crack bridging, stress redistribution, and fiber-network reinforcement are the principal mechanisms contributing to improved fatigue resistance. Nevertheless, the measured fatigue response depends not only on fiber characteristics but also on the loading-control mode and the associated damage-evolution process. Quantitative relationships among fiber spatial distribution, interfacial damage evolution, energy dissipation, and fatigue-crack propagation remain insufficiently estab-

lished. Future studies should therefore combine controlled-stress and controlled-strain fatigue testing with energy-based damage analysis to establish more reliable relationships between fiber reinforcement and fatigue-damage evolution.

4.5. Aging Resistance

Asphalt aging involves progressive oxidation, volatilization, and redistribution of lighter components, and changes in the chemical and colloidal structure of asphalt, generally resulting in increased stiffness and reduced cracking resistance [86–88]. Compared with the evidence available for high-temperature stability, low-temperature cracking resistance, moisture stability, and fatigue performance, direct studies specifically addressing the aging behavior of straw fiber-reinforced asphalt materials remain relatively limited. Based on the physicochemical characteristics of straw fibers and their interactions with asphalt, several potential aging-related pathways have been proposed, including retention of mobile asphalt components, interfacial protection, and structural stabilization. These pathways are summarized conceptually in Figure 11. However, they should be regarded as proposed mechanisms rather than fully validated causal relationships.

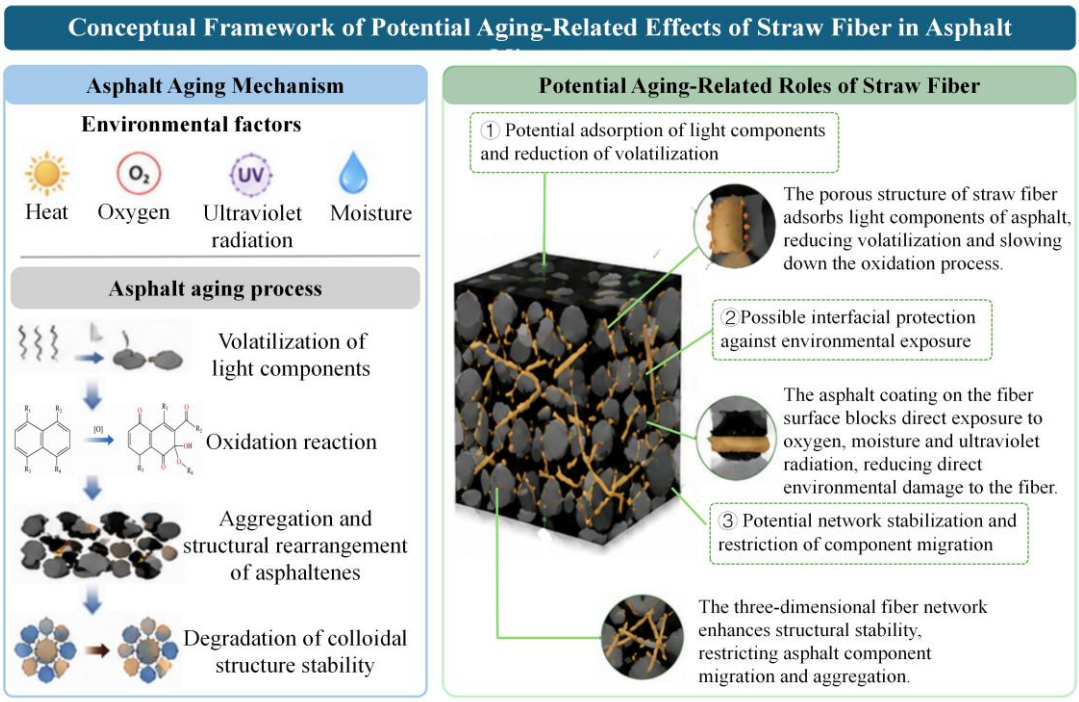


Figure 11. Conceptual illustration of the proposed aging-related mechanisms of straw fiber-reinforced asphalt materials.

The porous structure of straw fibers may retain part of the mobile or lighter asphalt components and thereby influence their migration and volatilization, while the asphalt coating surrounding the fiber surface may provide a certain degree of interfacial protection against environmental exposure. Fiber-matrix interactions and the spatial fiber network may also contribute to maintaining structural integrity during aging. Nevertheless, plant fibers themselves can undergo deterioration under prolonged hygrothermal exposure, indicating that their long-term contribution to aging resistance cannot be assumed solely from short-term laboratory behavior [79]. Therefore, these potential mechanisms still require direct verification through chemical, microstructural, and mechanical characterization of straw fiber-asphalt systems before and after aging. In particular, FTIR-based carbonyl and sulfoxide indices are commonly used to characterize the degree of asphalt

oxidation and can provide quantitative chemical evidence for evaluating thermo-oxidative aging [89]. However, direct quantitative evidence showing that straw fibers suppress the development of these oxidation-related functional groups remains limited. At present, asphalt-component adsorption and fiber-asphalt interfacial interactions are supported by published experimental observations on straw fiber-asphalt systems. In contrast, their direct contribution to long-term aging resistance, including reduced volatilization, delayed oxidative deterioration, and sustained structural stabilization, remains insufficiently verified and should therefore be regarded as hypothetical or partially supported mechanisms.

Studies on straw-derived hydrochar and bio-oil provide additional, but indirect evidence regarding the aging-related effects of biomass-derived modifiers. Corn straw hydrochar produced by hydrothermal carbonization has been reported to improve the aging resistance of asphalt [90]. In recycled asphalt materials, the combined use of hydrothermally liquefied bio-oil and natural fibers has also been associated with favorable aging-related responses [91]. However, hydrochar and bio-oil differ substantially from direct straw fiber reinforcement in chemical composition, morphology, and modification mechanism. Their reported anti-aging effects therefore cannot be directly extrapolated to straw fibers and are considered here only as supplementary evidence.

Overall, the currently available direct evidence is insufficient to establish a definitive anti-aging effect of straw fibers. Further studies combining long-term thermal-oxidative aging, ultraviolet exposure, moisture conditioning, and repeated environmental loading with chemical and microstructural characterization are required to determine whether straw fibers can provide sustained aging resistance under realistic service conditions. Future studies should also quantify carbonyl and sulfoxide indices before and after aging and correlate these chemical indicators with rheological and mechanical-property changes to establish more reliable evidence of aging resistance.

5. Multiscale Reinforcement Mechanisms of Straw Fibers in Asphalt Mixtures

The pavement-performance improvements discussed above are likely associated with the combined effects of fiber-network reinforcement, fiber-asphalt interfacial interactions, and multiscale structural regulation. Based on the available experimental observations and mechanistic studies, these effects may operate across different length scales, linking fiber morphology and surface characteristics with internal load transfer, crack evolution, and macroscopic pavement performance. However, because direct quantitative evidence linking these mechanisms across scales remains limited, the mechanisms discussed in this section should be regarded as an evidence-based conceptual framework rather than fully validated causal relationships. This section therefore discusses the proposed reinforcement mechanisms of straw fibers from the perspectives of mechanical network formation, interfacial enhancement, and multiscale structural evolution.

5.1. Fiber-Network Formation and Mechanical Reinforcement

Straw fibers are randomly dispersed within asphalt mixtures and can overlap, interlock, and interact with surrounding matrix components to form a three-dimensional reinforcing network. According to the principles of fiber-reinforced composites, fibers embedded in the matrix may carry part of the applied load and alter local stress-transfer pathways, thereby improving the overall load-bearing capacity of the composite system [92]. Their relatively high aspect ratio and irregular surface morphology may promote mechanical interlocking with neighboring fibers and surrounding components, enhancing the continuity and stability of the internal reinforcing structure [51].

Under external loading, the fiber network is proposed to contribute to stress redistribution through crack-bridging and shear-lag effects. Fibers located across highly stressed regions can transfer part of the load to the surrounding matrix, reducing local stress concentration and improving deformation compatibility [93]. The contribution of this mechanism varies with environmental and loading conditions. At high temperatures, the interconnected fiber network can restrict asphalt-mastic flow and relative aggregate movement, thereby improving resistance to permanent deformation. At low temperatures, fibers can bridge developing cracks, transfer tensile stresses across crack surfaces, and delay crack propagation [37,56,59,68]. These observations suggest that the fiber network may function not only as a passive filler but also as a potential internal load-transfer system within the mixture.

Mesostructural observations provide further evidence for this mechanical reinforcement mechanism. X-ray computed tomography (CT) studies have shown that an appropriate amount of straw fiber can alter the internal void structure, reduce the proportion of isolated voids, and improve structural compactness [94]. These structural changes may enhance aggregate-mastic continuity and contribute to more stable load-transfer paths within the mixture. However, the effectiveness of network reinforcement depends strongly on fiber dispersion. Insufficient fiber content may fail to establish effective connectivity, whereas excessive content can promote entanglement and local clustering, resulting in structural heterogeneity. Therefore, the reinforcing effect of straw fibers is closely related to the formation, continuity, and spatial distribution of the internal fiber network.

5.2. Fiber-Asphalt Interfacial Reinforcement

The effectiveness of straw fiber reinforcement depends strongly on the formation of a stable fiber–asphalt interface. Owing to their porous surface morphology and relatively large specific surface area, straw fibers may adsorb selected asphalt components and promote the formation of a structured asphalt layer around the fiber surface, thereby enhancing the cohesive and adhesive characteristics of the surrounding mastic [95]. Studies on corn straw fibers further indicate that their porous surface structure facilitates asphalt-component adsorption and the development of a well-bonded fiber-asphalt interface, contributing to improved pavement performance in SMA mixtures [96].

The adsorption behavior of straw fibers may restrict the migration of mobile asphalt components and may contribute to mechanical interlocking and interfacial adhesion between the fibers and asphalt. These effects may contribute to the observed improvements in moisture-damage resistance and fatigue performance by promoting more effective stress transfer and maintaining interfacial integrity [73,80]. However, untreated straw fibers generally contain a waxy surface layer and impurities that can hinder direct interaction with asphalt and reduce interfacial bonding efficiency.

Surface modification therefore plays an important role in improving fiber-asphalt compatibility. Alkali treatment can remove surface impurities, increase fiber roughness, and expose additional reactive sites, thereby strengthening interfacial interactions [55,97–99]. Because straw fibers from different crop sources vary in surface morphology, chemical composition, and pore structure, their adsorption capacity and interfacial reinforcement efficiency can also differ considerably. These differences indicate that effective interfacial reinforcement depends not only on the presence of straw fibers but also on fiber type and surface condition, which should be considered in the optimization of straw fiber-modified asphalt mixtures.

5.3. Multiscale Structural Evolution and Damage Regulation

The reinforcement effect of straw fibers cannot be fully explained at a single scale, but instead arises from interactions across molecular, mesoscale, and macroscale levels. At the molecular scale, molecular dynamics (MD) simulations of fiber-related asphalt-aggregate interfacial systems have indicated that fiber-derived components can enhance asphalt-aggregate adhesion and improve interfacial stability, providing a possible molecular-level basis for interpreting the observed changes in moisture resistance and durability [100]. The diffusion behavior of cellulose-related molecules in asphalt is also strongly temperature-dependent, while intermolecular aggregation may contribute to the formation of locally reinforced regions within the asphalt matrix [101].

At the mesoscale, the spatial distribution of fibers and their interaction with aggregates, mastic, and voids directly influence the internal structural response of the mixture. X-ray computed tomography (CT), digital image processing, and stochastic aggregate reconstruction provide effective approaches for characterizing fiber distribution, void structure, and particle-contact configurations [94,102]. Discrete element method (DEM) simulations can further describe particle movement, contact-force transmission, and damage evolution after fiber incorporation, thereby providing a mechanical link between fiber-network formation and the macroscopic performance of asphalt mixtures.

However, the interpretation of DEM results depends strongly on the adopted particle representation, contact constitutive model, parameter calibration, and boundary conditions. Different contact laws govern the transmission of normal and tangential forces, interparticle bonding, sliding, and debonding, whereas the imposed boundary conditions determine the confinement and loading path of the numerical specimen. Therefore, contact-force chains, particle rearrangement, and predicted damage evolution should be interpreted together with the corresponding model assumptions rather than regarded as model-independent responses. Recent DEM studies of heterogeneous pavement-related materials have demonstrated that calibrated contact parameters and force-chain evolution can provide useful insight into mesoscale load-transfer paths and damage development [103]. Although these systems differ from straw fiber-reinforced asphalt mixtures, the same methodological framework is applicable to future investigation of aggregate-mastic-fiber interactions.

In addition to particle-contact behavior, pore structure should be characterized beyond total air-void content. The connectivity and continuity of internal voids can influence moisture transport, local stress concentration, and damage propagation during loading. Multiscale characterization combining CT and NMR has been used in other porous material systems to quantify pore distribution, connectivity, and their relationship with mechanical response [41]. Although these studies involve different material systems, they provide a useful methodological reference for future three-dimensional characterization of void connectivity and transport pathways in straw fiber-reinforced asphalt mixtures.

Overall, the available evidence suggests that straw fiber reinforcement may involve a multiscale synergistic process. At the molecular and interfacial scales, adsorption and interfacial interactions influence adhesion and component mobility; at the mesoscale, fiber distribution and network formation may influence load-transfer paths, void structure, and crack development; and at the macroscale, these effects are reflected in improved resistance to rutting, cracking, moisture damage, and fatigue, as summarized in Figure 12. However, current studies remain dominated by macroscopic performance evaluation and qualitative mechanism interpretation. Quantitative relationships among fiber dispersion, interfacial properties, mesoscale structural evolution, and macroscopic pavement performance remain insufficiently established. Existing FEM-DEM studies have linked realistic tire-pavement contact loads with particle displacement, contact-force transmission, and force-chain evolution in asphalt mixtures [104], while pavement-scale dynamic-response

models have demonstrated the influence of vehicle operating conditions on structural responses under moving loads [105]. These studies provide an established multiscale framework for interpreting how straw fiber-induced changes in force transmission, void structure, and local damage may contribute to macroscopic deformation and fatigue performance under traffic loading, although direct coupled simulations specifically for straw fiber-reinforced asphalt mixtures remain limited.

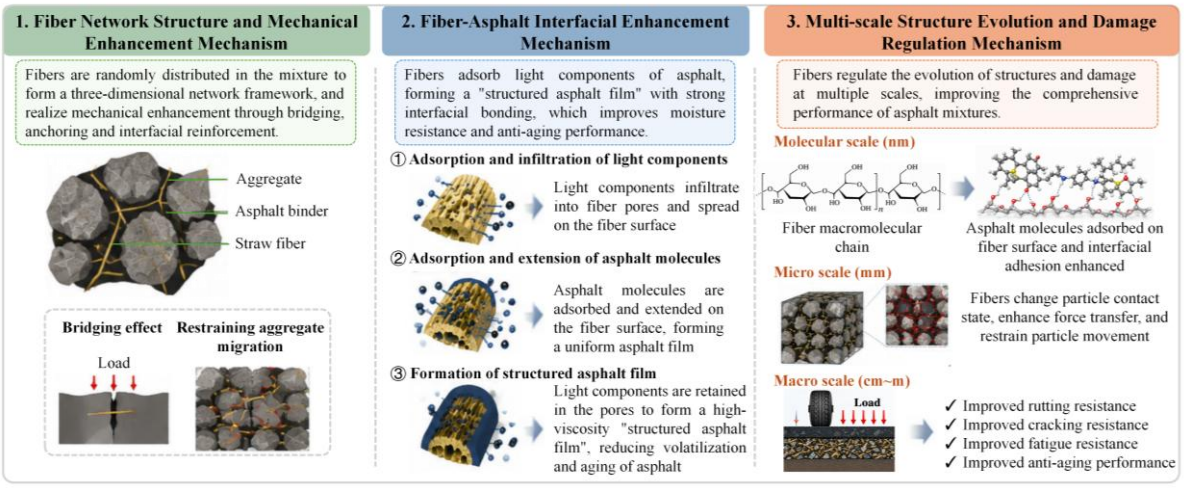


Figure 12. Synergistic effects of physical reinforcement, interfacial enhancement, and structural regulation in straw fiber-reinforced asphalt mixtures.

6. Conclusions and Future Perspectives

6.1. Conclusions

By combining bibliometric analysis with evidence on material characteristics, pavement performance, and reinforcement mechanisms, this review draws the following main conclusions:

1. Straw fibers can improve the overall performance of asphalt mixtures through the combined effects of fiber-network reinforcement, fiber-asphalt interfacial interactions, and internal structural regulation. When adequately dispersed, the fibers can participate in load transfer, restrict aggregate movement, bridge developing cracks, and help stabilize the asphalt mastic. These effects are reflected in reported improvements in high-temperature stability, low-temperature cracking resistance, moisture stability, and fatigue resistance under selected experimental conditions. In contrast, direct evidence regarding the aging resistance of straw fiber-reinforced asphalt mixtures remains limited, and the potential anti-aging effect requires further verification.
2. The reinforcement efficiency of straw fibers is strongly influenced by fiber type, dosage, length, and pretreatment method. Differences in microstructure, surface morphology, and chemical composition among straw sources lead to variations in asphalt adsorption, interfacial bonding, dispersion, and network formation. Appropriate optimization of these parameters is therefore essential for achieving stable and reproducible performance enhancement.
3. Research on straw fiber-reinforced asphalt mixtures is gradually progressing from macroscopic performance evaluation toward multiscale mechanism analysis. X-ray CT, microscopic characterization, molecular simulation, and numerical modeling provide useful approaches for investigating fiber spatial distribution, fiber-asphalt interfacial interactions, internal structural evolution, and damage development.

However, quantitative relationships linking fiber characteristics and mesoscale structural parameters with macroscopic pavement performance remain insufficiently established.

6.2. Future Perspectives

From an engineering perspective, several practical issues also require further investigation, including fiber moisture control and storage stability, mixing sequence, plant-scale dispersion, fiber feeding equipment, changes in binder demand, compaction requirements, production consistency, construction cost, recyclability, and field quality control. These factors have received limited systematic investigation and should be further evaluated through plant-scale production and field validation before large-scale engineering application.

1. Future research should strengthen multiscale characterization and modeling by integrating X-ray CT, molecular dynamics, and discrete element methods. Particular attention should be given to quantifying fiber spatial distribution, interfacial behavior, contact-force transmission, and damage evolution, thereby establishing clearer structure-interface-performance relationships and improving the mechanistic basis for performance prediction.
2. A more systematic framework is needed for optimizing fiber type, dosage, length, and pretreatment method. The best-performing parameters reported in individual studies vary considerably because of differences in fiber characteristics, mixture composition, and testing conditions. Future studies should therefore develop quantitative relationships among fiber dispersion, interfacial properties, and pavement-performance indicators to support more consistent mixture design and facilitate comparison among different straw fiber systems.
3. Greater attention should be paid to long-term durability and engineering-scale validation under coupled service conditions. Actual pavements are simultaneously subjected to temperature variation, moisture, oxidation, and repeated traffic loading, whereas most existing studies investigate these effects separately. Future work should therefore combine long-term aging, environmental conditioning, field or pilot-scale validation, service-life prediction, and life-cycle assessment to evaluate both durability and potential environmental benefits within a unified engineering framework.

Overall, the renewability, wide availability, and potential resource-utilization advantages of straw fibers provide a promising basis for their application in sustainable pavement materials. Further progress in material modification, multiscale mechanism quantification, standardized mixture design, and field validation will be essential for translating laboratory findings into reliable engineering applications.

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Data Availability Statement: The bibliometric data analyzed in this study were obtained from the Web of Science Core Collection (WoSCC) and China National Knowledge Infrastructure (CNKI).

Owing to database licensing restrictions, the original bibliographic records are not publicly available. The derived data supporting the findings of this study are available from the corresponding author upon reasonable request.

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Conflicts of Interest: Ruimin Liu was employed by the company Shaanxi Construction Engineering Group Corporation Limited, Yulin. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

WoSCC	Web of Science Core Collection
CNKI	China National Knowledge Infrastructure
DS	Dynamic Stability
AC-13	Asphalt Concrete with a nominal maximum aggregate size of 13.2 mm
SMA-13	Stone Mastic Asphalt with a nominal maximum aggregate size of 13.2 mm
BBR	Bending Beam Rheometer
ITS	Indirect Tensile Strength
CT	Computed Tomography
MD	Molecular Dynamics
DEM	Discrete Element Method

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