***Commentary***

**Research Progress on Plant Fiber Modified Asphalt Mixtures**

**Abstract:** Conventional asphalt pavements face persistent distresses (rutting, cracking, moisture damage) under extreme environments and heavy traffic. Plant fibers (e.g., bamboo, coconut, sisal) emerge as sustainable modifiers offering performance enhancement and environmental benefits. This review systematically analyzes their physicochemical properties, pretreatment methods (physical/chemical), and application effects. Results show plant fibers significantly improve asphalt mixture performance: bamboo fiber enhances moisture stability and substitutes lignin in SMA; coconut fiber boosts low-temperature cracking resistance via porous structure; sisal fiber provides superior mechanical reinforcement. Pretreatments (alkali, silane, acetylation) mitigate hydrophilicity and strengthen fiber-asphalt interfaces. Life cycle assessment confirms 30-45% lower carbon emissions versus synthetic fibers, leveraging agricultural waste valorization. Future research should optimize fiber selection, develop eco-friendly treatments, establish long-term durability data, and standardize design guidelines to facilitate industrial adoption.

**Keywords**: Plant fiber; Asphalt modification; Pretreatment methods; Rheological properties; Life cycle assessment (LCA); Sustainable pavement

# 1 Introduction

Asphalt mixtures, as the core material for modern road paving, dominate global transportation infrastructure[1]. Their performance directly affects road service life and traffic safety. However, under complex and changing environmental conditions and increasing heavy traffic loads, conventional asphalt pavements have long been plagued by typical distresses such as high-temperature rutting, low-temperature cracking, and moisture damage. Statistics show that in China, annual road maintenance costs due to rutting distress amount to billions of yuan, and the proportion of pavement damage caused by low-temperature cracking exceeds 35% in cold northern regions[2]. These distresses not only shorten road service life but also increase maintenance costs, posing potential threats to traffic safety[3-5].

Plant fibers, as a renewable bio-based material, have become an ideal reinforcing material for modified asphalt in recent years due to their unique physicochemical properties, environmental friendliness, and economic viability. Compared to synthetic fibers (e.g., polyester fiber, polypropylene fiber) and mineral fibers (e.g., basalt fiber), plant fibers offer three significant advantages[6,7]: (1) Carbon sequestration potential: The plant growth process absorbs CO2, resulting in a 30%-45% lower life cycle carbon emission than synthetic fibers; (2) Resource renewability: Mainly sourced from fast-growing plants like bamboo, coconut shells, hemp, or agricultural waste; (3) Interface affinity: Hydroxyl groups (-OH) on the cellulose surface easily form hydrogen bonds with asphalt, enhancing interface bonding. Statistics indicate that China produces over 1 billion tons of agricultural biomass waste annually, including 250 million tons of corn stalks alone. The effective utilization of these resources can significantly reduce the environmental footprint of road construction.

This paper systematically reviews the research progress of plant fibers such as bamboo fiber, coconut fiber, and sisal fiber in asphalt modification[8-11]. It focuses on analyzing their enhancement mechanisms on asphalt rheological properties, mechanical properties, and durability, discusses the optimization effect of fiber treatment processes on interface properties, and quantifies the carbon emission reduction potential of plant fibers using Life Cycle Assessment (LCA), providing theoretical support for the development of green road materials.

# 2 Physical and Chemical Characteristics of Plant Fibers

The performance of plant fibers is mainly determined by their chemical composition (ratio of cellulose, hemicellulose, lignin) and microstructure (fiber morphology, surface roughness). Plant fibers from different sources exhibit significant differences in physical and mechanical properties, which directly affect their modification effectiveness in asphalt mixtures.

## 2.1 Comparison of Key Physical Parameters

As seen in Table 1, plant fibers generally exhibit low density (0.6-1.5 g/cm³), moderate tensile strength (95-700 MPa), and high water absorption (5%-40%). Among them, sisal fiber has the highest cellulose content (65%-75%), giving it the best tensile strength (363-700 MPa), but its density is higher (1.3-1.5 g/cm³). Coconut fiber has a porous structure beneficial for asphalt adsorption, but its water absorption is as high as 30%-40%, which can easily increase the moisture susceptibility of mixtures[12]. Bamboo fiber offers relatively balanced overall performance, with cellulose content reaching 60%-70% and natural surface roughness favoring mechanical interlocking[13].

Table . 1 Comparison of Physical Properties of Typical Plant Fibers

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Fiber Type | Density /(g·cm⁻³) | Tensile Strength /MPa | Water Absorption /% | Cellulose Content /% | Thermal Stability /°C |
| Bamboo Fiber | 0.8-1.1 | 140-230 | 12-20 | 60-70 | 180-200 |
| Coconut Fiber | 1.15-1.46 | 95-230 | 30-40 | 40-50 | 170-190 |
| Sisal Fiber | 1.3-1.5 | 363-700 | 15-25 | 65-75 | 190-210 |
| Hemp Fiber | 1.4-1.5 | 300-600 | 10-15 | 70-80 | 180-200 |

## 2.2 Pretreatment of Plant Fibers

The chemical structure of plant fibers contains a large number of polar hydroxyl (-OH) groups, making them hydrophilic, which creates interface compatibility issues with hydrophobic asphalt. To address this contradiction, researchers have developed various surface modification techniques:

(1) Physical Methods​

Physical pretreatment primarily aims to increase the contact area with the matrix by disrupting the internal structure of the fibers through external forces. The main methods are steam explosion and mechanical pulverization. Steam explosion treatment of plant fibers is a relatively common method used by researchers. It involves placing straw fibers in a high-temperature, high-pressure enclosed environment, allowing steam to penetrate the plant cell walls. A sudden pressure release then causes explosive disruption due to the abrupt pressure difference, separating the three main components (cellulose, hemicellulose, lignin), removing most of the hemicellulose and lignin from the straw fibers, increasing the fiber specific surface area, refining the fibers, and enhancing the performance per unit fiber[14]. Mechanical pulverization further reduces the particle size of the raw material through cutting, rolling, and crushing methods. It simultaneously reduces the degree of polymerization between lignin, hemicellulose, and cellulose, increases the specific surface area of the fibers, and improves the compatibility between the fibers and the polymer[15].

(2) Chemical Methods​

The purpose of chemical pretreatment is to improve the internal structure and surface properties of straw fibers by removing components such as hemicellulose and the waxy layer through chemical reactions, thereby increasing fiber roughness and enhancing the interfacial bonding strength between the matrix material and the fibers. Existing chemical pretreatments mainly include acid pretreatment, alkali pretreatment, surface grafting pretreatment, acetylation pretreatment, and coupling agent pretreatment.

Acid pretreatment of fibers is widely used and has good treatment effects. In acidic solvents, the glycosidic bonds of hemicellulose are easily broken, causing hemicellulose to degrade into furfural, formaldehyde, hydroxymethylfurfural, etc. This removes hydrophilic groups such as hydroxyl and carbonyl groups present in the hemicellulose of straw fibers[16]. Acid treatment can remove most of the hemicellulose and significantly impact the physicochemical properties of fibers, particularly in improving their hygroscopicity, thermal stability, and dimensional stability[17]. Simultaneously, impurities such as pectin and the waxy layer in the fibers are also removed during the process. The treated straw fibers exhibit greater roughness and specific surface area, increasing the interfacial bonding strength with the matrix material[18,19]. Common reagents include CH₃COOH, H₂SO₄, HNO₃, and HCl. Dilute acid catalysts with concentrations ranging from 0.5% to 10.0% are used, allowing the material to react at temperatures between 140°C and 190°C for a period of time[20-22]. For example, Saha et al.[23] used dilute acid pretreatment to decompose hemicellulose in fibers into soluble sugars such as xylose, glucose, and mannose. Wen Peiyao[24] found that after pretreating poplar wood with acetic acid, its acetyl groups increased, crystallinity increased, and hydrophobicity was enhanced. After treatment with 5.0% concentration acetic acid at 170°C for 30 min, the hemicellulose removal rate reached 71.3%, with a cellulose loss rate of only 5.5%.

Alkali pretreatment is also relatively common both domestically and internationally. Alkali solution treatment can alter the surface properties and internal crystal structure of fibers. Alkali solutions can disrupt ester and ether bonds between cellulose and other components, causing saponification reactions that remove part of the hemicellulose, pectin, and other impurities[25]. Common alkali pretreatment solutions include NaOH, KOH, Ca(OH)₂, and NH₃·H₂O. Silverstein et al. treated cotton stalks with a combination of sodium hydroxide solution and ozone, finding that the sodium hydroxide solution could remove over 60.0% of the hemicellulose and lignin in the fibers[26]. Ashoria et al. found that alkali solution treatment can affect the nature and quantity of active groups on the fiber surface while also enhancing the chemical activity of the fiber surface. The hydrophobicity of the fiber surface also increases with the increase in active groups[27].

Surface grafting involves using suitable initiators to graft monomers onto the fiber surface and treating the surface active groups of the fibers with reagents exhibiting high compatibility with the matrix material, thereby increasing the interfacial compatibility between the fiber and the matrix. Grafting polymer materials with high interfacial compatibility with the matrix material onto the fiber surface not only improves the interfacial bonding force with the matrix material but also allows the fibers to disperse more uniformly within the matrix material. Existing main grafted polymers include maleic anhydride grafted high-density polyethylene and maleic anhydride grafted ethylene-propylene-diene monomer rubber[28,29].

Acetylation pretreatment is mainly used to reduce the hygroscopicity of wood, thereby improving its dimensional stability and service life. Its mechanism involves esterification reactions between acetyl groups and hydroxyl groups on the material surface. This reduces the number of hydroxyl groups on the fiber surface, lowering its hygroscopicity. It also makes the surface polarity of the fibers closer to that of the matrix, leading to better dispersion uniformity of the fibers within the matrix material and enhancing the interfacial bonding properties between the materials[30]. Meriem Boustani et al.[31] treated flax fibers with acetylation, increasing their roughness and improving the interaction between the fibers and the matrix. This can enhance the affinity between natural fibers and the polymer matrix.

# 3 Application Effects of Plant Fibers in Asphalt Mixtures​

## 3.1 Bamboo Fiber​

Bamboo fiber exhibits significant adsorption optimization effects in asphalt mixtures due to its high cellulose content (>60%) and natural surface roughness. Yu et al.[32] investigated the performance enhancement of bamboo fiber-modified asphalt mixtures, finding that melamine-formaldehyde copolymer improved the interfacial bonding capacity between bamboo fiber and asphalt mastic, while increasing mixture strength and road performance—particularly low-temperature cracking resistance and moisture damage resistance. Jia et al.[33] demonstrated that adding 0.3% bamboo fiber or polyester fiber to asphalt mixtures effectively increased their dynamic modulus and fatigue life, though the fatigue life of bamboo fiber mixtures was slightly lower than that of polyester fiber mixtures. Cui et al.[34] studied the effects of different fiber surface treatments on modified asphalt performance, noting that bamboo fiber surfaces treated with silane coupling agents, alkali treatment, and heat treatment significantly improved the fatigue life of fiber-modified asphalt. Among these, silane coupling agent treatment yielded the most pronounced enhancement in asphalt rheology and wettability.

Xia et al. compared the durability of bamboo fiber asphalt mixtures with lignin-based mixtures[35–38]. Results showed that bamboo fiber mixtures exhibited higher immersed Marshall stability (MS₀) and tensile strength ratio (TSR) values than lignin mixtures, indicating superior moisture stability. Both mixture types demonstrated comparable freeze-thaw cycle durability. Based on comprehensive performance evaluations, scholars propose that bamboo fiber can substitute lignin in Stone Mastic Asphalt (SMA) mixtures.

## 3.2 Coconut Fiber

Coconut fiber demonstrates significant improvement in low-temperature cracking resistance of asphalt mixtures due to its unique porous structure (porosity 50%-60%) and high elongation at break (15%-25%). MA Khasawne et al.[39] investigated the reinforcement effect of coconut fiber in asphalt pavement materials. Results showed coconut fiber effectively improves Marshall stability of conventional HMA mixtures, indicating promising application prospects in asphalt modification. Ghosh et al.[40] found that incorporating coconut fiber in porous asphalt mixtures significantly enhances mixture stability and rutting resistance. During modified asphalt mastic preparation, coconut fibers were first treated by soaking in NaOH solution before mixing with asphalt. Experimental results demonstrated that adding 10% coconut fiber and 0.3% coir fiber substantially improves mixture stability and rut resistance.

Maharaj et al.[41] evaluated the influence of coconut fiber length (2.5 mm to 10 mm) and dosage (up to 8%) on the rheological properties of TLA (Trinidad Lake Asphalt) and TPB (Trinidad Petroleum Bitumen). Compared with unmodified TLA, adding 6% of 2.5 mm coconut fiber increased the complex modulus by 7.3 times while significantly reducing phase angle (from 49.3° to 19.8°). For pure TPB, 6% of 2.5 mm coconut fiber increased the complex modulus by 5.4 times and reduced phase angle from 86.2° to 47.4°, indicating effective enhancement in permanent deformation resistance and elasticity of natural asphalt.

## 3.3 Sisal fiber​

Sisal fiber demonstrates significant mechanical reinforcement effects in asphalt mixtures due to its ultra-high tensile strength (363–700 MPa) and high initial modulus (>20 GPa). Ai Chang et al.[42] investigated the improvement effect of sisal fiber on the low-temperature performance of high-modulus asphalt mixtures. They found that incorporating 0.3% of 6mm long sisal fiber provided the best improvement in low-temperature performance for high-modulus asphalt mixtures, while simultaneously enhancing high-temperature performance and moisture resistance. Lu Hongxin et al.[43] noted that alkali-treated sisal fiber can increase the asphalt film thickness on aggregate surfaces, improve the interfacial bonding ability between asphalt and aggregate, and consequently enhance the road performance of the mixture. Ramalinga et al.[44] discovered that adding low doses of sisal fiber to asphalt mixtures significantly improved fatigue life and resistance to moisture damage. Based on road performance test results, they recommended a sisal fiber dosage of 0.05% and length of 15mm for the selected mixture. Liu Yicun et al.[45] reported that incorporating 0.2% sisal fiber into AC-13 mixtures significantly improved both their high-temperature performance and low-temperature crack resistance.

# 4 Environmental and Economic Analysis​

Life Cycle Assessment (LCA) is a globally recognized methodology for evaluating the environmental impacts of services and processes and determining their sustainability throughout the entire lifecycle. The LCA methodology comprehensively considers resource consumption and pollutant emissions associated with the lifecycle of systems or processes, including raw material extraction, chemical and fiber production, recycling, operation, and transportation. In recent years, LCA has been extensively applied to analyze and compare different environmental impacts of modified asphalt mixtures throughout their life cycles. Yue et al.[46] conducted a comparative LCA analysis on diatomite powder- and lignin fiber-modified asphalt mixtures, revealing that diatomite-modified mixtures significantly reduced environmental impacts in all categories. Lignin fiber-modified and diatomite-lignin fiber composite mixtures showed lower impacts in other categories when human toxicity was excluded, providing important environmental guidelines for selecting road construction materials. Khater et al.[47] employed LCA according to ISO 14040 standards to assess the environmental impact of asphalt mixtures incorporating lignin-glass fiber composite additives in highway pavement construction. They found that the studied mixtures did not demonstrate significant improvements across all environmental impact categories but showed higher negative effects in specific categories, offering a scientific basis for future evaluations of such mixtures' environmental benefits in road engineering. Martinez-Soto et al.[48] comprehensively analyzed the environmental impacts of using glass fiber, polyester fiber, aramid fiber, cellulose fiber, and recycled fiber from waste tires in Hot Mix Asphalt (HMA) and Stone Mastic Asphalt (SMA) mixtures through LCA. Results indicated that FiTyre and cellulose fiber outperformed traditional fibers in key environmental indicators, demonstrating advantages in reducing environmental burden and enhancing the eco-friendliness of road materials.

# 5 Conclusions and Prospects​

## 5.1 Research Conclusions​

(1)Effective Performance Enhancement: Plant fibers (bamboo, coconut, sisal) significantly improve asphalt mixture performance, particularly in enhancing high-temperature rutting resistance (increased complex modulus), low-temperature cracking resistance, moisture damage resistance (higher TSR), and fatigue life.

(2)Fiber-Specific Advantages: Different fibers offer distinct benefits: bamboo fiber provides balanced enhancement and is a potential lignin substitute in SMA; coconut fiber excels in low-temperature crack resistance due to porosity and elongation; sisal fiber delivers superior mechanical reinforcement via high strength and modulus.

(3)Pretreatment is Crucial: Surface pretreatment (physical like steam explosion, or chemical like alkali/silane/acetylation) is essential to mitigate plant fiber hydrophilicity, enhance interfacial bonding with asphalt, increase surface roughness, and ultimately improve composite performance.

(4)Compelling Sustainability: Plant fibers offer significant environmental advantages over synthetic alternatives, including carbon sequestration potential during growth, lower life cycle carbon emissions (30-45% less), utilization of renewable resources and agricultural waste, and inherent interface affinity with asphalt.

## 5.2 Future Research Directions​

(1)Optimized Formulation & Design: Establish clear guidelines for selecting fiber type, dosage, length, and pretreatment based on target performance (specific climates, traffic, mixture types) and explore synergistic effects with other modifiers.

(2)Advanced Processing & Durability: Develop more efficient, scalable, and eco-friendly pretreatment/modification techniques; conduct rigorous long-term field and accelerated aging studies to assess performance evolution and durability under combined stressors.

(3)Comprehensive Life Cycle Assessment: Expand and standardize LCA studies to include diverse fiber sources, processing routes, end-of-life scenarios (recycling/biodegradation), and provide robust comparisons with conventional modifiers.

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