***Commentary***

**Enhancing Asphalt Performance with Plant Fibers: A Comprehensive Review**

**Abstract:** Conventional asphalt pavements face persistent distresses (rutting, cracking, moisture damage) under extreme environments and heavy traffic. Plant fibers (bamboo, coconut, sisal) emerge as sustainable modifiers, reducing life cycle carbon emissions by 30%-45% versus synthetic fibers while valorizing agricultural waste. Pretreatments (alkali, silane, acetylation) mitigate hydrophilicity, achieving up to 71.3% hemicellulose removal and enhancing fiber-asphalt interfaces. Performance evaluations demonstrate significant improvements: bamboo fiber enhances moisture stability by 20% and substitutes lignin in Stone Mastic Asphalt; coconut fiber (6% dosage) boosts complex modulus by 7.3 times in Trinidad Lake Asphalt and improves low-temperature cracking resistance; sisal fiber (0.3% dosage) enhances tensile strength by 15%-25% and fatigue life via ultra-high tensile strength (363 MPa-700 MPa). Future research should optimize fiber selection, develop eco-friendly treatments, and establish standardized durability guidelines for industrial adoption.

**Keywords**: Plant fiber; Asphalt modification; Pretreatment methods; Rheological properties; LCA; Sustainable pavement

# 1 Introduction

As the core material of modern road pavement, asphalt mixture occupies a dominant position in the global transportation infrastructure, and its performance is directly related to the service life and driving safety of the road[1]. However, under the complex and changeable environmental conditions and the increasing heavy load traffic, the traditional asphalt pavement has been faced with typical diseases such as high temperature rutting, low temperature cracking and water damage for a long time[2]. According to statistics, the cost of road maintenance caused by rutting disease in China is as high as billions of yuan every year, and the proportion of pavement damage caused by low temperature cracking in the cold regions of the north is more than 35%. These diseases not only shorten the service life of the road, but also increase the maintenance cost and pose a potential threat to traffic safety[3-5].

In order to realize the long life of asphalt pavement, the pavement is required to be ' long-term base, permanent roadbed and durable pavement '. As a renewable bio-based material, plant fiber has become an ideal reinforcing material for modified asphalt in recent years due to its unique physical and chemical properties, environmental friendliness and economy. Plant fiber mainly plays the role of reinforcement, adsorption, stability and viscosity[4]. By changing the material composition of the mixture to improve its road performance, it is an effective way to improve the durability of the pavement and prolong the service life of the road[5]. Therefore, plant fiber modified asphalt mixture has been widely used in pavement engineering.Compared with synthetic fibers (such as polyester fibers and polypropylene fibers) and mineral fibers (such as basalt fibers), plant fibers have three significant advantages : (1) carbon sequestration potential. Plants absorb CO2 during growth, and their life cycle carbon emissions are 30 % -45 % lower than synthetic fibers. (2) Renewability of resources, mainly from bamboo, coconut shell, hemp and other fast-growing plants or agricultural waste ; (3) Interface affinity. Hydroxyl groups on the surface of cellulose are easy to form hydrogen bonds with asphalt to enhance interface bonding. According to statistics, China produces more than 1 billion tons of biomass waste such as crop straw every year, of which 250 million tons are corn straw alone. The effective use of these resources can significantly reduce the environmental footprint of road construction.

At the same time, plant fiber can increase the proportion of structural asphalt and enhance the bonding ability between aggregates[6], so as to effectively control the mutual slip between aggregates. It is often used in asphalt mastic gravel mixture and open-graded surface wear layer asphalt mixture. Compared with the ' wet ' process, the ' dry ' process is more convenient to prepare plant fiber modified asphalt mixture, and it is beneficial to the distribution of plant fiber in the mixture. Most of the practical projects on the road performance of plant fiber reinforced asphalt mixture are usually constructed by the ' dry ' process[7,8].

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 Performance Comparison of Plant Fiber and Synthetic Fiber

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Fiber Type | Fiber Name | Density / (g·cm⁻³) | Tensile Strength / MPa | Young's Modulus / GPa | Elongation / % | Thermal Conductivity / (W·m⁻¹·K⁻¹) | Glass Transition Temperature (Tg) / °C | Melting Point (Tm) / °C |
| Plant Fiber | Bamboo Fiber | 0.60 - 1.10 | 140 - 230 | 11.0 - 17.0 | - | - | - | - |
| Sisal | 1.33 - 1.50 | 363 - 700 | 9.0 - 38.0 | 2.0 - 7.0 | 0.042 | - | - |
| Coconut | 1.15 - 1.46 | 95 - 230 | 2.8 - 6.0 | 15.0 - 51.5 | 0.047 | - | - |
| Palm | 0.07 - 1.55 | 248 | 3.2 | 25 | 0.199 | - | - |
| Synthetic Fiber | Polypropylene | 0.91 | 500 - 700 | 3.5 - 6.8 | 21 | 0.12 | 30 | 165 |
| Polyester | 1.38 | 400 - 600 | 8.4 - 16.0 | 11.0 - 30.0 | 0.13 | 64 | 240 |
| Basalt | 2.60 - 2.70 | 3100 - 4800 | 85.0 - 95.0 | 3.1 | - | - | 1450 |
| Carbon Fiber | 1.80 - 1.90 | 1700 - 2600 | 140.0 - 200.0 | 0.8 - 1.5 | 8.000 - 70.000 | - | 3500 |
| Glass | 2.50 - 2.56 | 1700 - 3500 | 27 | 2.5 - 3.2 | 0.04 | - | 1540 |
| Aramid | 1.4 | 3000 - 3150 | 63.0 - 67.0 | 3.3 - 3.7 | 0.05 | - | 500 |
| Polyacrylonitrile (PAN) | 1.17 | 200 - 400 | 20 | 27.0 - 48.0 | - | 97 | 330 |
| Steel | 7.85 | 400 - 1200 | 200 | 3.5 | 50 | - | 800 |

## 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[16-18].

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[19]. 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[20]. 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[21]. 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[22-24]. For example, Saha et al.[25] used dilute acid pretreatment to decompose hemicellulose in fibers into soluble sugars such as xylose, glucose, and mannose.

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[26,27]. 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[28]. 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[29].

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[30,31].

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[32]. Meriem Boustani et al.[33] 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.[34] 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.[35] 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.[36] 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.



**Figure 1: Bamboo Fiber Chart**

Xia et al. compared the durability of bamboo fiber asphalt mixtures with lignin-based mixtures[37,38]. 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.



**Figure 2: Coconut Fiber Chart**

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.[43] reported that incorporating 0.2% sisal fiber into AC-13 mixtures significantly improved both their high-temperature performance and low-temperature crack resistance.



Figure 3: Sisal Fiber Chart

# 4 Environmental and Economic Analysis​

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 (e.g., plant cultivation or waste collection), fiber processing (including pretreatment as discussed in Section 2.2), chemical and fiber production, recycling, operation, and transportation. Critically, LCA provides a quantitative framework to assess the environmental benefits associated with the performance enhancements of plant fiber-modified asphalt mixtures detailed in Section 3, such as extended service life potentially reducing reconstruction impacts. In recent years, LCA has been extensively applied to analyze and compare different environmental impacts of modified asphalt mixtures throughout their life cycles.

Several studies demonstrate the environmental advantages of bio-based modifiers like plant fibers, validating their sustainability claims derived from their inherent properties (Section 2) and performance benefits (Section 3):

Yue et al.[45] 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. This highlights the potential for natural fibers to offer environmental advantages over some traditional modifiers.

Khater et al.[46] 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. This underscores the importance of comprehensive LCA studies for specific fiber combinations.

Martinez-Soto et al.[47] comprehensively analyzed the environmental impacts of using glass fiber, polyester fiber, aramid fiber, cellulose fiber, and recycled fiber from waste tires in HMA and SMA mixtures through LCA. Results indicated that FiTyre and cellulose fiber (a key component of plant fibers like bamboo and sisal) outperformed traditional synthetic fibers in key environmental indicators, demonstrating advantages in reducing environmental burden and enhancing the eco-friendliness of road materials. This finding directly supports the environmental rationale for using plant fibers (like those reviewed in Sections 2 & 3) over many synthetics.

The compelling sustainability profile of plant fibers, as outlined in the Introduction (Section 1) and reinforced by LCA studies, stems from multiple factors confirmed throughout their lifecycle analysis: carbon sequestration during growth, lower life cycle carbon emissions (30-45% less than synthetics as noted in Section 1), utilization of renewable resources and agricultural waste, and inherent interface affinity with asphalt reducing the need for energy-intensive compatibilizers. While upfront economic costs may vary depending on fiber source and processing, the utilization of abundant agricultural waste streams (e.g., corn stalks, coconut husks) presents significant potential for cost reduction and resource efficiency, contributing to the overall economic viability alongside the environmental benefits quantified by LCA.

# 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.

Disclaimer (Artificial intelligence)

I hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

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