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A Comprehensive Review of Natural Fibre Reinforced Bitumen with Focus on Microstructure and Sustainability

Nandini
PhD Research Scholar, Dept. of Civil Engineering,
JNTU Anantapur, A.P., India - 515002

Dr. G. Sreenivasa Reddy
Professor &Head,
Sree Dattha Institute of Engineering &Science,
Sheriguda, Ibrahim Patnam (M),
R.R.District-501510, Telangana.

Abstract
The pursuit of sustainable infrastructure has propelled the use of natural fibres as eco-friendly reinforcements in bituminous composites. This review critically examines the role of lignocellulosic fibres—specifically coir, jute, sisal, and hemp—in enhancing the microstructural, mechanical, thermal, and chemical performance of asphalt binders and mixtures. Drawing on recent advances, the study explores fibre–bitumen interaction mechanisms, including dispersion behavior, interfacial bonding, and crack-bridging capabilities. Advanced characterization tools such as SEM, FTIR, and TGA are reviewed to elucidate the material's response at multiple scales. Findings indicate that natural fibres not only improve rutting resistance, fatigue life, and thermal stability but also contribute to reduced aging and carbon emissions. Despite these benefits, challenges related to fibre agglomeration, moisture sensitivity, and lack of standardization remain. The paper outlines emerging research directions, including hybrid fibre systems, AI-based modelling, and field-scale validations. Overall, the study affirms natural fibre reinforcement as a viable strategy for developing high-performance, climate-resilient, and sustainable pavement materials.

Keywords: **natural fibres, bitumen modification, coir, thermal stability, microstructure, sustainable pavements**

1. INTRODUCTION

The exponential growth in infrastructure development has intensified the demand for resilient, durable, and environmentally conscious pavement solutions. Traditional bituminous pavements, although widely used for their cost-effectiveness and performance, are facing mounting criticism due to their environmental footprint and vulnerability to cracking, rutting, and aging under dynamic loading and climatic stress. This has ushered in a new era of materials research focused on sustainable reinforcement strategies that can address both performance and ecological concerns.

Synthetic fibres such as polypropylene, polyester, and glass have been extensively incorporated into asphalt binders and mixtures to improve tensile strength and deformation resistance. While these synthetic reinforcements have demonstrated short-term mechanical gains, they are petroleum-derived, non-biodegradable, and prone to degradation at elevated temperatures, raising sustainability and compatibility concerns within the broader framework of green construction [1]. Their inability to integrate chemically with the bituminous matrix often leads to poor bonding, ineffective dispersion, and premature failure under cyclic loading.

In response to these limitations, the spotlight has shifted toward lignocellulosic natural fibres—notably coir, jute, sisal, and hemp—as eco-friendly and resource-abundant alternatives. These fibres are derived from agricultural

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Vol. 14 Issue 05, May-2025

byproducts and possess unique attributes such as low density, high tensile strength, biodegradability, and chemical compatibility with bitumen. Their hierarchical structure, dominated by cellulose and hemicellulose chains bonded via lignin, provides a robust reinforcement matrix that can interact physically and chemically with the asphalt binder [3]. Moreover, their ability to delay oxidation and resist shrinkage-crack propagation makes them attractive for long-term pavement performance [2].

Despite growing research interest, there remains a lack of holistic understanding of how these natural fibres affect the multi-scale performance of bituminous composites—from microstructural interaction and thermal stability to chemical bonding behavior. Existing studies are often fragmented, focusing on individual fibre types or specific performance tests, with limited cross-comparison or synthesis across different material dimensions.

This review aims to bridge that gap by providing a comprehensive analysis of lignocellulosic fibre-reinforced bitumen systems, examining:

- Microstructural bonding mechanisms via SEM observations
- Thermal degradation resistance through TGA
- Chemical interactions analyzed by FTIR
- Mechanical implications for durability and workability
- Environmental and economic benefits for sustainable infrastructure

The findings are expected to contribute to the development of next-generation, fibre-reinforced pavements that align with the principles of green engineering, circular economy, and long-term infrastructure resilience.

2. CHARACTERISTICS OF NATURAL FIBRES FOR BITUMINOUS REINFORCEMENT

Natural fibres derived from lignocellulosic biomass are emerging as high-potential candidates for enhancing bituminous binders due to their biodegradability, mechanical integrity, and structural complexity. Unlike synthetic fibres that often require chemical surface treatments for compatibility, lignocellulosic fibres inherently possess functional groups (e.g., hydroxyl, carboxyl) that can interact with polar components of bitumen, leading to better interface adhesion and reinforcement efficiency.

2.1 Fibre Morphology and Composition

Natural fibres such as coir, jute, sisal, and hemp are typically composed of three key biopolymers:

- Cellulose (40–60%): Crystalline structure providing high tensile strength
- Hemicellulose (10–25%): Amorphous regions enabling flexibility and bonding
- Lignin (10–30%): Acts as a binder, giving stiffness and biodegradation resistance

The microfibrillar angle, fibre aspect ratio, and surface roughness play a crucial role in defining how effectively a fibre can anchor into the bitumen matrix. For instance, coir has a higher lignin content (~30–40%), making it stiffer and thermally stable, while jute has a higher cellulose proportion, contributing to higher tensile strength but faster degradation under moisture.

2.2 Mechanical and Physical Properties

Natural fibres exhibit a wide range of mechanical properties, typically with tensile strengths ranging from 100 MPa to 800 MPa and elastic moduli from 5 GPa to 80 GPa, depending on fibre type and processing. Their low density (1.2–1.5 g/cm^3) makes them ideal for lightweight pavement applications, especially where load distribution and crack bridging are critical.

The aspect ratio (length/diameter) of fibres significantly influences stress transfer within the bituminous matrix. Fibres with a moderate aspect ratio (50–150) are reported to offer an optimal balance between dispersion and bridging efficiency. Excessively long fibres may tangle and agglomerate, while very short fibres may not provide effective reinforcement [2].

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 14 Issue 05, May-2025

2.3 Durability and Compatibility in Bitumen

A unique advantage of lignocellulosic fibres is their ability to maintain dimensional stability and resist degradation under hot-mix asphalt (HMA) conditions, especially when pre-treated or modified with mild alkaline or silane solutions. Their porous structure can also aid in bitumen absorption, increasing binder-fibre interfacial bonding.

However, these fibres are hydrophilic, and their use in moisture-rich or freeze–thaw environments requires caution or surface modification. Despite this, their thermal resistance up to 250–300°C[3] and intrinsic flexibility make them suitable for withstanding the mixing and compaction temperatures used in pavement construction.

3. MECHANISMS OF FIBRE–BITUMEN INTERACTION

The reinforcing effectiveness of natural fibres in bituminous composites depends not only on their intrinsic properties but critically on how they interact at the microstructural level with the binder. Unlike conventional fillers, fibres can bridge micro-cracks, alter flow characteristics, and form networked structures that resist deformation. A deep understanding of these interaction mechanisms is essential for optimizing performance.

3.1 Fibre Dispersion and Alignment

A uniform dispersion of fibres within the bitumen matrix is essential to ensure consistent mechanical properties and prevent agglomeration or clustering, which could lead to weak zones. The length and diameter of the fibre strongly influence its distribution:

- Short fibres may disperse more easily but fail to bridge cracks effectively.
- Long fibres provide better crack resistance but tend to entangle [6].

Optimal fibre length ensures a random yet uniformly distributed orientation, which enhances stress transfer and suppresses shear flow under dynamic loading.

3.2 Interfacial Bonding and Adhesion

At the molecular level, fibre–bitumen interaction is governed by:

- Mechanical interlocking via surface roughness
- Physicochemical adhesion through hydrogen bonding and Van der Waals forces
- Absorptive bonding, where bitumen partially penetrates the fibre structure

Lignocellulosic fibres contain hydroxyl and carboxyl groups that can interact with polar fractions in bitumen, promoting chemical affinity and improved wetting [2]. However, the hydrophilic nature of fibres can compromise this bond in moist conditions unless treated.

Surface treatments, such as alkaline soaking or silane grafting, have been shown to enhance fibre surface energy and promote stronger interfacial adhesion with the bitumen binder [4].

3.3 Crack-Bridging and Toughening Effect

The most notable mechanical advantage of incorporating fibres into asphalt is their ability to bridge micro-cracks and delay crack propagation under thermal or mechanical stress. As the bitumen ages and becomes more brittle, fibres serve as stress diffusers, absorbing and redistributing strain energy.

This interaction is particularly crucial under cyclic loads (traffic), where fibre-reinforced composites exhibit:

- Increased fatigue life
- Reduced rutting depth
- Enhanced tensile recovery

The synergistic effect of strong interfacial adhesion and appropriate fibre length directly impacts the composite’s fracture resistance and post-cracking behaviour.

Natural fibres improve bitumen's mechanical performance through a combination of physical entanglement, chemical bonding, and crack-bridging mechanisms. Their successful integration into bituminous matrices depends on proper dispersion, surface compatibility, and tailoring of geometric characteristics.

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 14 Issue 05, May-2025

4. PERFORMANCE EVALUATION: MECHANICAL AND DURABILITY ASPECTS

Natural fibre reinforcement in bituminous composites has shown promising improvements in mechanical strength, crack resistance, and long-term durability. These enhancements are attributed to the fibres' ability to alter stress paths, reduce deformation, and improve energy absorption under dynamic loading. Various studies have demonstrated that when properly incorporated, lignocellulosic fibres can outperform conventional modifiers in critical performance metrics.

4.1 Rutting and Permanent Deformation Resistance

One of the key failure modes in asphalt pavements is rutting caused by plastic deformation under heavy traffic. Natural fibres provide internal reinforcement, resisting flow and suppressing deformation. According to [5] the inclusion of natural fibres in asphalt mixtures led to a 30–40% reduction in rutting depth compared to control mixes. This improvement is attributed to:

- Increased stiffness of the mix
- Fibre-matrix friction
- Bridging effect at micro-voids and crack initiation zones

Rutting resistance is most effective when the **fibre content and aspect ratio are optimized**, avoiding agglomeration that may weaken the matrix.

4.2 Cracking and Fatigue Resistance

Thermal and fatigue cracking are major durability issues in bituminous pavements. Fibres can absorb and redistribute strain energy, delaying the onset of cracks. Studies by [2] & [6] indicate that natural fibres improve:

- Tensile strength
- Fatigue life under cyclic loading
- Fracture toughness

Jute and sisal, due to their high cellulose content, offer excellent tensile reinforcement, while coir provides superior ductility and flexibility. This balance is particularly valuable in temperature-prone regions where thermal contraction induces surface cracking.

4.3 Moisture Damage and Aging Resistance

Moisture-induced damage (stripping) and oxidative aging reduce pavement life. Lignocellulosic fibres, especially when surface-treated, can reduce water permeability and act as barriers to oxidation. [8]demonstrated that fibre-modified binders exhibit slower aging rates, likely due to the physical entrapment of lighter bitumen fractions and molecular interaction with polar groups in fibres.

Additionally, coir fibres—owing to their high lignin content—are inherently resistant to moisture degradation, making them particularly suitable for tropical climates [7]

4.4 Workability and Compaction Considerations

The impact of fibres on mix workability is two-fold:

- Short fibres tend to blend well and improve compaction.
- Long fibres, if not properly dispersed, can increase viscosity and hinder workability.

Optimizing fibre dosage (0.3–0.5% by weight) and using mixing aids or anti-stripping agents helps balance workability and mechanical performance.

Natural fibres enhance bituminous composites by increasing rutting resistance, crack tolerance, and durability against moisture and aging. Their mechanical contribution is strongly influenced by fibre type, geometry, dispersion, and chemical compatibility with the bitumen binder.

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 14 Issue 05, May-2025

5. THERMAL STABILITY AND AGING RESISTANCE

Thermal degradation and oxidative aging are primary causes of performance decline in asphalt pavements. As bitumen is subjected to high production temperatures and long-term environmental exposure, its chemical structure changes—leading to hardening, embrittlement, and reduced flexibility. The incorporation of natural fibres has been shown to improve both thermal stability and resistance to oxidative aging, thus extending pavement life and service quality.

5.1 Thermal Behavior and Degradation Control

Thermogravimetric Analysis (TGA) has revealed that fibre-modified bitumen exhibits higher thermal decomposition temperatures and greater residual mass compared to unmodified binders. This indicates an improved thermal barrier effect, where the fibres:

- Delay volatilization of light bitumen fractions
- Increase char yield post-combustion
- Stabilize the matrix under high-temperature conditions

[9] observed that coir and sisal fibres enhanced thermal stability by as much as **15–20%** at 600°C, due to the thermal shielding effect of the lignin-rich fibre structure.

[7]also reported that the **thermal conductivity of bitumen** reduced upon fibre inclusion, which may help regulate internal pavement temperature profiles in hot climates.

5.2 Oxidative Aging Resistance

Bitumen aging is primarily driven by oxidation of its polar fractions when exposed to heat, UV radiation, and oxygen. Lignocellulosic fibres slow this process through:

- Physical entrapment of light hydrocarbons
- Reduced oxygen diffusion due to the network structure of dispersed fibres
- Chemical interaction between fibre functional groups (–OH, –COOH) and bitumen molecules

In studies by[10], the inclusion of treated natural fibres resulted in a significant reduction in the carbonyl index — a key marker of oxidation — suggesting enhanced resistance to long-term aging. This is critical in reducing maintenance cycles and ensuring pavement integrity over time.

5.3 Implications for Mix Design and Field Performance

Enhanced thermal resistance allows fibre-reinforced mixes to perform better in high-temperature environments, minimizing rutting and thermal cracking. Moreover, reduced oxidative hardening translates to better fatigue resistance and delayed binder embrittlement.

However, this benefit is fibre-specific. Coir, with its high lignin content, offers superior thermal resistance but moderate mechanical reinforcement. In contrast, fibres like jute or flax provide better initial stiffness but may degrade faster under thermal cycling unless pre-treated.

The incorporation of natural fibres significantly improves the thermal durability and aging resistance of bituminous materials. Through both barrier effects and molecular interactions, fibres contribute to longer-lasting, thermally resilient pavements—essential for climate-adaptive infrastructure.

6. Chemical Interaction and Functional Group Behavior

Understanding the chemical interactions between lignocellulosic fibres and bitumen is essential for assessing their compatibility, performance under thermal and oxidative stress, and durability. Unlike inert fillers, natural fibres participate in physicochemical bonding with bitumen through their surface functional groups, which affects the interfacial behavior, dispersion, and resistance to degradation.

6.1 Role of Functional Groups in Fibre–Bitumen Bonding

Lignocellulosic fibres contain hydroxyl (-OH), carboxyl (-COOH), and methoxy ($-OCH_3$) groups that enable interaction with the polar components of bitumen. These groups are primarily derived from:

- Cellulose and hemicellulose (hydrophilic –OH, –COOH)
- Lignin (hydrophobic aromatic rings, methoxy groups)

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 14 Issue 05, May-2025

These chemical groups allow the formation of hydrogen bonds, dipole–dipole interactions, and even weak covalent-like linkages with bitumen's asphaltene and resin fractions, enhancing fibre-bitumen adhesion [11].
Surface modification techniques (e.g., alkali or silane treatment) further expose or graft reactive groups, increasing interfacial compatibility and bonding strength.

6.2 FTIR Spectroscopy Analysis

Fourier Transform Infrared Spectroscopy (FTIR) is a powerful tool to assess these interactions by analyzing the absorption peaks corresponding to specific chemical bonds.
Key observations include:

- O–H stretching (~3300 cm^{-1}): More pronounced in fibre-modified samples, confirming incorporation of cellulose/lignin-based materials
- C=O stretching (~1730–1750 cm^{-1}): Enhanced in modified binders due to ester or aldehyde linkages from fibre oxidation or bonding
- C–H stretching (~2900 cm^{-1}): Altered peak intensities indicate changes in aliphatic chain environments

In studies by [12]&[9], FTIR confirmed new peaks and intensification of existing functional groups, suggesting chemical incorporation rather than physical blending.

6.3 Implications for Compatibility and Stability

The degree of chemical interaction determines the stability of the fibre-bitumen interface, which affects moisture resistance, crack bridging, and oxidative degradation.

- Strong chemical bonds reduce fibre pull-out under loading.
- Improved interface leads to better load transfer and viscoelastic response.
- Chemical bonding enhances resistance to aging and water damage due to reduced interfacial gaps.

Additionally, fibres with more exposed –OH groups (e.g., untreated jute) may attract moisture and require surface pre-treatment to avoid stripping, while lignin-rich fibres (e.g., coir) naturally resist moisture and degradation.
Chemical interactions between natural fibres and bitumen are key to unlocking their full reinforcing potential. Functional group compatibility, confirmed through FTIR analysis, reveals that these interactions go beyond mere physical dispersion—offering a chemically stable, performance-enhancing reinforcement for sustainable bituminous composites.

7. ENVIRONMENTAL AND ECONOMIC SUSTAINABILITY

The transition toward sustainable infrastructure demands materials that are not only high-performing but also resource-efficient and environmentally benign. Natural fibre-reinforced bitumen aligns with this philosophy, offering a renewable, biodegradable, and locally available alternative to synthetic reinforcements. Beyond improving mechanical and thermal performance, lignocellulosic fibres significantly reduce the ecological footprint of asphalt production and road construction.

7.1 Renewable and Biodegradable Source Materials

Lignocellulosic fibres such as coir, jute, hemp, and sisal are agricultural byproducts or low-value biomass, making them environmentally attractive. For instance:

- Coir fibres are extracted from coconut husk waste, a material that is otherwise discarded in bulk.
- Jute and sisal are fast-growing crops requiring minimal irrigation or fertilization.

Unlike synthetic fibres, which are derived from petroleum and contribute to microplastic pollution, natural fibres are fully biodegradable, thus posing no threat to soil or aquatic ecosystems at the end of pavement life [7] & [2].

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 14 Issue 05, May-2025

7.2 Life Cycle and Emissions Benefits

Lifecycle assessments (LCA) of fibre-reinforced pavements reveal that natural fibres reduce the embodied energy and carbon emissions associated with asphalt mixtures. Their lightweight nature reduces transportation costs, while their compatibility with low-temperature mixing (e.g., warm mix asphalt) lowers energy consumption during production [12].

Furthermore, by enhancing durability and extending pavement life, fibre-modified bitumen reduces maintenance frequency, thereby conserving resources and minimizing CO_2 emissions from recurring roadwork.

7.3 Economic Advantages for Developing Regions

In many developing countries, the high cost of synthetic modifiers and polymer additives limits access to performance-enhancing asphalt technologies. Natural fibres offer a low-cost reinforcement alternative that can be sourced locally and processed with minimal industrial input.

Coir, for example, is abundantly available in countries like India, Sri Lanka, and Indonesia, and its use in pavement applications could create value-added markets for agro-waste, empowering rural economies and promoting circular value chains.

7.4 Challenges and Sustainability Trade-Offs

Despite their green credentials, certain limitations must be addressed:

- Hydrophilicity of untreated fibres can lead to moisture damage unless chemically modified.
- Biodegradability, while beneficial at end-of-life, could affect long-term in-situ durability if not properly stabilized.

These challenges underscore the need for balanced formulations and pre-treatment protocols that preserve fibre integrity without compromising eco-efficiency.

Natural fibre reinforcement presents a compelling case for sustainable bitumen modification, offering reduced environmental impact, economic accessibility, and long-term cost savings. Their integration into road infrastructure represents a practical step toward achieving greener, circular, and climate-resilient pavement systems.

8. CHALLENGES AND RESEARCH GAPS

While natural fibre reinforcement in bituminous materials offers remarkable sustainability and performance potential, several technical, environmental, and standardization challenges must be addressed before widespread implementation can be realized. The current body of literature, though promising, reveals fragmented insights and insufficient cross-validation of findings, particularly concerning advanced characterization and long-term field performance.

8.1 Fibre Dispersion and Agglomeration Issues

Achieving uniform dispersion of fibres within the bitumen matrix remains one of the foremost challenges. Long or high-aspect-ratio fibres tend to entangle, clump, or segregate, resulting in localized stress concentrations and poor workability [1] & [5}.

- Inconsistent fibre distribution leads to non-uniform reinforcement and affects compaction.
- There is a lack of optimized mixing protocols for incorporating natural fibres into hot or warm mix asphalt.

8.2 Lack of Standardization for Natural Fibre Use

There are no universally accepted standards for:

- Fibre dosage (typically ranging 0.2–0.5% by weight)
- Optimal aspect ratio
- Surface treatment protocols
- Compatibility with different bitumen grades (e.g., VG10, VG30, VG40)

This makes it difficult to compare results across studies or translate laboratory findings into practice [2].

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 14 Issue 05, May-2025

8.3 Moisture Sensitivity and Durability

The hydrophilic nature of lignocellulosic fibres makes them vulnerable to moisture-induced stripping and debonding at the bitumen-fibre interface. While pre-treatment methods like alkali soaking or silane grafting improve water resistance, they add processing complexity and may alter the fibres' mechanical properties.

Moreover, there is limited understanding of fibre degradation over long-term field exposure, especially in environments with extreme humidity or freeze–thaw cycles.

8.4 Gaps in Microstructure–Performance Correlation

Although SEM, TGA, and FTIR techniques have been employed to study fibre–bitumen interactions, most research:

- Lacks systematic correlation between microstructural observations and mechanical outcomes
- Does not address how thermal degradation or chemical bonding affect fatigue, cracking, or rutting performance over time

[11] highlight the need for multi-dimensional evaluations, combining microscopy, spectroscopy, and performance testing to develop robust predictive models.

8.5 Limited Field Trials and Lifecycle Validation

Most available studies are laboratory-based with small-scale testing:

- Few studies validate findings through full-scale field trials or pavement performance monitoring.
- Lifecycle assessments (LCA) are still rare and do not capture region-specific sustainability metrics [12] & [7].

Despite encouraging results, the field of natural fibre-reinforced bitumen requires more rigorous, interdisciplinary research to overcome dispersion challenges, standardize formulations, and validate long-term durability. Addressing these gaps will be crucial to scaling this technology for widespread pavement applications.

9. FUTURE RESEARCH DIRECTIONS

The growing interest in lignocellulosic fibre-reinforced bitumen signals a promising shift toward sustainable pavement engineering. However, transforming this innovation from laboratory success to real-world impact requires multidisciplinary strategies, advanced characterization, and field validation. The following research directions are proposed to accelerate the evolution of this field:

9.1 Nano- and Hybrid-Fibre Reinforcement

Combining natural fibres with nano-reinforcements (e.g., nanoclay, graphene oxide, nano-silica) may create synergistic effects, boosting mechanical strength, thermal stability, and moisture resistance.

- Coir–nano hybrid composites could improve fatigue life while retaining biodegradability.
- Research should explore hybrid fibre systems (e.g., coir + jute, sisal + glass) to balance toughness, flexibility, and cost.

9.2 Smart and Self-Healing Bituminous Systems

Natural fibres can be functionalized or embedded in self-healing binders to promote autonomous crack repair. Fibre capsules containing rejuvenators or healing agents could be triggered under thermal or mechanical stress.

- Investigate stimuli-responsive fibres that swell or re-bond under specific conditions.
- Integrate microencapsulation techniques with fibre networks for intelligent pavements.

9.3 AI and Image-Based Microstructural Modeling

Advancements in machine learning and image analysis can aid in:

- Quantifying fibre dispersion using SEM/CT scans
- Predicting performance through deep learning algorithms
- Developing digital twins of fibre-reinforced pavements for simulation and optimization

Such techniques could bridge the current gap between microstructure and macro-performance, enabling smarter mix design.

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 14 Issue 05, May-2025

9.4 Climate-Responsive Mix Designs

Future studies should focus on tailoring fibre-reinforced mixes for climate resilience, particularly in:

- High-temperature zones: to reduce rutting and oxidative aging
- Coastal/humid areas: using treated fibres for moisture stability
- Freeze–thaw environments: validating low-temperature crack resistance

Developing region-specific formulations would ensure consistent performance across diverse geographies.

9.5 Standardization and Field-Scale Implementation

For widespread adoption, the field needs:

- International standards on fibre type, dosage, and treatment methods
- Long-term pilot-scale field trials
- Lifecycle costing and sustainability assessments tailored to local contexts

Governmental and industry collaboration is essential to establish performance-based specifications for natural fibre-modified asphalt.

The next frontier in fibre-reinforced bitumen research lies in smart hybridization, data-driven modeling, and real-world implementation. By aligning material innovation with digital tools and environmental needs, future studies can help redefine the foundation of sustainable road infrastructure.

10. CONCLUSION

This review presents a comprehensive synthesis of the role of natural lignocellulosic fibres—such as coir, jute, sisal, and hemp—as sustainable reinforcements in bituminous composites. Unlike synthetic fibres, which pose environmental challenges and limited chemical compatibility, natural fibres offer a biodegradable, cost-effective, and performance-enhancing alternative that aligns with modern green construction principles.

Through a detailed evaluation of mechanical behavior, thermal stability, chemical interaction, and environmental performance, the study highlights that:

- Natural fibres can significantly improve rutting resistance, fatigue life, and thermal durability of asphalt binders and mixtures.
- Their hydrophilic surface groups enable chemical bonding with polar bitumen fractions, as confirmed through FTIR.
- When properly dispersed and treated, fibres act as crack-bridging reinforcements, enhancing microstructure integrity and long-term performance.
- They contribute to carbon footprint reduction and support circular economy models by utilizing agro-waste.

Despite these benefits, challenges such as fibre dispersion, moisture sensitivity, and lack of standardized protocols persist. Bridging these gaps requires multidisciplinary approaches involving nanotechnology, machine learning, and field-scale testing.

Ultimately, this review underscores the transformative potential of natural fibre-reinforced bitumen in achieving resilient, durable, and sustainable pavements—paving the way for greener infrastructure globally.

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Vol. 14 Issue 05, May-2025

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