



Incorporation of Jute Fiber in Warm Mix Asphalt (WMA): Advancements in Sustainable Pavement Engineering

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Received 27-04-2025; Revised 19-06-2025; Accepted 25-06-2025

Cite:Raihan PMS. Incorporation of jute fiber in warm mix asphalt (WMA): Advancements in sustainable pavement engineering. JRTES. 2025;1(1):43-52

Abstract

Growing demand for green infrastructure has led to the research of green materials for road construction. This review paper discusses the use of jute fiber in Warm Mix Asphalt (WMA), a green substitute for traditional Hot Mix Asphalt (HMA). Jute fiber, a renewable and biodegradable material, has several mechanical and environmental advantages when used in WMA. This paper discusses the improvement of mechanical performance, durability benefit, and ecological impact of utilizing jute fiber as a material in asphalt mixtures. It also presents the constraints and issues encountered in applying jute in WMA and suggests potential future research directions to enhance its use in the construction industry. The findings suggest that jute fiber-reinforced WMA has the potential to contribute to improved pavement performance and environmental sustainability, providing a fascinating option for green road construction.

Keywords: Jute Fiber; Warm Mix Asphalt (WMA); Sustainable Infrastructure; Hot Mix Asphalt (HMA); Environmental Impact; Biodegradable Materials; Renewable Resources; Pavement Performance; Carbon Footprint Reduction.

Introduction

The construction industry has been one of the leading causes of environmental deterioration for decades through the extensive use of materials such as regular asphalt, which is produced at elevated temperatures, leading to vast amounts of energy consumption and greenhouse emissions. warm mix asphalt (WMA) is emerging as a more environmentally friendly choice to traditional hot mix asphalt (HMA). Production of WMA requires lower temperatures than traditional hot

mix, decreasing fuel consumption and emissions when it is made and rolled.

At the same time, natural fibers are being increasingly utilized to add performance to asphalt mixtures. Of all the fibers, jute is a viable alternative on the basis of its biodegradability, renewability, and tensile strength. Jute is an economical and renewable fiber that can be sourced from agricultural waste, and it offers a circular economy advantage to the construction sector.

This paper addresses the use of jute fibers in WMA, their effects on mechanical properties, sustainability, and environmental factors, and the challenges that must be resolved for the successful incorporation of jute fibers into road construction.

Jute Fiber Characteristics

Jute fiber is one of the earliest and most versatile natural fibers, particularly famous for its eco-friendliness and biodegradability. Jute is derived from the plant *Corchorus*, which is found in the majority of tropical and subtropical regions of the world, like India, Bangladesh, and other South Asian regions. Certain of the unique characteristics of jute fiber, rendering it a good choice in various applications like asphalt mixtures, are elaborated in detail as follows:

Chemical Composition

Jute is a cellulose fiber and the chemical composition is of the highest significance when it comes to defining its mechanical properties. The general composition is:

- **Cellulose (45%–71%):** This is the one that imparts the fiber with its strength and durability. It gives jute its stiffness and enables it to be resistant to deformation under load. The higher the content of cellulose, the stronger the fiber.
- **Hemicellulose (13%–21%):** Hemicellulose is responsible for the flexibility and adhesion of the fiber, hence increasing the application of jute as a reinforcing material. It improves bonding between the fiber and other materials, such as asphalt binder.
- **Lignin (12%–26%):** Lignin imparts structural hardness to the fiber and is a natural binder. While it makes jute stiffer, it improves jute's retention of shape and strength in long-term application.
- **Pectin and waxes (approximately 4%–5%):** These are present in smaller percentages but contribute toward fiber cohesion and water resistance, important factors for exposure to the environment as in road pavements.

The blend of the above ingredients imparts strength, stiffness, and durability to jute fibers besides making them biodegradable and sustainable.

Physical Properties

Jute fibers have several physical properties because of which they are sought after in the use of construction materials like asphalt:

- **Tensile Strength:** Jute fibers have tensile strength ranging between 393 and 800 MPa, which is sufficient to strengthen the materials that are subjected to tensile stress, i.e., asphalt. Their tensile strength is comparable to some man-made fibers, which helps enhance the performance of WMA.
- **Young's Modulus:** Young's modulus of jute fibers varies between 10 to 30 GPa and is quality and type dependent. The measure of stiffness indicates the degree to which a material deforms under stress. As the modulus increases, increased resistance of the fiber to deformations under mechanical loading is exhibited.
- **Length and Diameter:** Jute fibers are typically 1 to 4 meters long and 10 to 20 μm in diameter. These measurements make jute fibers long enough to provide effective reinforcement without sacrificing flexibility.
- **Density:** Jute fibers have a density between 1.3 and 1.5 g/cm^3 and are relatively light in weight compared to synthetic fibers, yet with a low mass-to-strength ratio. This aspect makes it easier to improve material workability and compactness like asphalt.
- **Absorption of Moisture:** Jute fibers can absorb 10% of their weight in water. While this character is beneficial in increasing the adhesion of jute fibers with other materials (e.g., asphalt binder), it may also be an issue with moisture damage in road pavements. However, natural waxes contained in fibers and pectins provide some degree of resistance to moisture.

Environmental Benefits

Jute is renewable and biodegradable, and it possesses several environmental benefits:

- **Biodegradability:** Unlike synthetic fibers, jute is biodegradable and breaks down naturally without causing any harmful residues. This is an important benefit when applied to construction materials like asphalt, as it minimizes the long-term environmental cost of road maintenance and disposal.
- **Renewable Resource:** Jute is harvested annually, making it a renewable resource. It is compared to petroleum fibers that consume fossil fuels. Jute fibers are agricultural waste and can be picked annually without depleting natural resources.
- **Carbon Footprint:** Jute production is carbon sequestering because it is the growth of plants that absorb carbon dioxide from the atmosphere. The use of jute in asphalt decreases the total carbon footprint of road construction by replacing synthetic fibers and promoting sustainable practice.
- **Energy Efficiency:** Jute is characterized by relatively low energy needs for production compared to synthetic fibers and is hence an energy-efficient material. In the case of WMA, this is particularly significant because the reduced manufacturing temperature is already a means of saving energy and emissions.

Warm Mix Asphalt (WMA)

WMA is an innovative technology that allows the production of asphalt in lower temperatures (usually 100°C-140°C), compared to conventional HMA (150°C-180°C). The advantages of WMA are significant:

- **Energy Efficiency:** By reducing the production temperature, WMA lessens fuel consumption and energy costs, making the process eco-friendly and economical.
- **Low Emissions:** The reduced production temperature reduces the emission of volatile organic compounds (VOCs) and greenhouse gases.
- **Enhanced Workability:** WMA is more easily compacted for a longer time, which is beneficial in the case of construction work, particularly in cold conditions or urban areas where night working is common.

Jute Fiber in Warm Mix Asphalt (WMA)

Incorporating jute fiber into WMA offers a dual benefit of improving the mechanical properties of asphalt while also contributing to sustainability. The key effects of jute fiber in WMA include:

Increased Viscosity and Binder-aggregate Adhesion: Jute fibers significantly contribute to impacting the viscosity of the asphalt binder, which is critical in enhancing the binder-aggregate adhesion. The following is the manner in which this is achieved:

- **Viscosity increase:** The jute fibers have high cellulose content, and this increases the viscosity of the asphalt binder. The higher viscosity binder holds the aggregates tighter, and the binder forms a strong aggregate-binder bond. It forms a more uniform mix with better binder coating on the aggregates [1].
- **Enhanced adhesion:** The improved **adhesion** between the binder and aggregates is crucial for **durability** and **performance**. When jute fibers are added to WMA, the fibers interact with the binder, improving its **adhesive properties**. This **stronger adhesion** prevents the aggregates from being pulled apart due to external forces, such as **traffic loads** and **temperature fluctuations**, which ultimately improves the **overall stability** of the asphalt pavement [2].

This increase in viscosity and binder-aggregate adhesion contributes significantly to the **long-term durability** of the pavement by reducing the likelihood of issues like **aggregate loss** or **binder stripping** under **heavy traffic** and **environmental exposure** [3].

- **Improved Rutting and Crack Resistance:** Rutting and cracking are two of the most common types of distress in asphalt pavements, especially under **high traffic volumes** and **hot climates** [4]. Jute fibers contribute to enhanced **rutting resistance** and **crack resistance** in WMA in the following ways:
 - **Rutting resistance:** Rutting can be defined as permanent deformation of the pavement surface caused by **heavy traffic loads**. The incorporation of jute fibers helps in boosting the **viscoelastic properties** of the asphalt mixture, increasing its **resistance to permanent deformation**. Jute fibers behave like a **reinforcing agent**, making the asphalt less prone to **rutting** under **high temperatures** and **high traffic loads** [5].
 - **Crack resistance:** Jute fibers boost the flexural strength and elasticity of the asphalt mixture, helping it less likely crack under stress. The fibers help distribute the stresses created due to traffic loads proportionately across the pavement, decreasing the chances of **fatigue cracking** or **thermal cracking** [6]. This is particularly beneficial for hot climates where asphalt can become more susceptible to cracking due to **high temperatures**.

Overall, Jute fibers help create a more **resilient** asphalt mixture, reducing **maintenance needs** and increasing the **lifespan** of the pavement.

- **Moisture Susceptibility:** Moisture-induced damage, commonly referred to as **stripping**, takes place as soon as water penetrates the asphalt pavement and weakens the bond linking the binder and aggregates [3]. This may result in **premature pavement failure**. Jute fibers play an important role in reducing moisture susceptibility:
 - **Improved binder-aggregate interaction:** Jute fibers improve the **adhesion** between the binder and aggregates, making the mixture more **resistant to moisture-induced stripping**. When fibers are added to the mix, they help the binder coat the aggregates more effectively, preventing water from infiltrating the mix and weakening the bond [8].
 - **Reduction in water absorption:** Jute fibers have a degree of **moisture resistance** due to their natural waxes and pectin content. This reduces the water absorption capacity of the fibers themselves, helping to minimize moisture-related damage. Additionally, jute fibers assist in reducing the overall **water absorption** of the asphalt mixture, enhancing its **longevity** in wet conditions.

This property makes **jute-modified WMA** an ideal solution for areas with high **rainfall** or **moisture fluctuations**, as it helps the asphalt mixture remain intact and functional for a longer period.

- **Performance at Low Temperatures:** Low-temperature cracking occurs when asphalt pavements contract in colder weather, causing them to become **brittle** and prone to **cracking**. This is a common problem in **cold climates**, where asphalt can become too stiff to absorb the stresses caused by temperature fluctuations [9]. Jute fibers help **enhance resistance to low-temperature cracking** in the following ways:
 - **Increased flexibility:** Jute fibers increase the **elasticity** and **flexibility** of the asphalt mixture. This allows the asphalt to **expand and contract** without cracking when exposed to **temperature changes**, making it more **resilient** in cold weather. Jute fibers act as a **reinforcing agent**, improving the **fatigue resistance** of the mixture, which is important for sustaining **pavement integrity** in **freezing conditions**.
 - **Thermal cracking resistance:** Jute fibers help disperse **thermal stresses** more evenly across the pavement, decreasing the probability of **thermal cracking**. This is especially beneficial in areas where **winter temperatures** cause asphalt to experience significant **thermal gradients** between day and night.

This enhanced resistance to low-temperature cracking ensures that **jute-modified WMA** performs better in **cold climates**, extending the pavement's **service life** and decreasing the need for **repairs** [10].

Advantages in Pavement Performance

The incorporation of jute fibers into Warm Mix Asphalt (WMA) leads to several performance improvements:

- **Improved Durability:** Jute fibers help increase the **long-term durability** of asphalt by providing additional reinforcement and resistance to environmental degradation. This is especially important in pavements exposed to high traffic and harsh weather conditions [11].
- **Fatigue and Crack Resistance:** Jute fiber-modified WMA exhibits improved **fatigue resistance**, reducing the occurrence of **fatigue cracking** in the pavement, which is a common issue in asphalt subjected to repetitive traffic loads [12].
- **Reduced Moisture Damage:** Jute fibers help reduce **moisture susceptibility** in the asphalt, preventing **stripping** (loss of binder from aggregates due to water infiltration) [13]. This enhances the overall **performance** of the pavement in areas with high rainfall or fluctuating moisture levels [14].

Performance Enhancements in Jute Fiber-Modified WMA

Improved Mechanical Properties

- **Tensile Strength:** One of the key benefits of using jute fibers in WMA is the enhancement of **tensile strength**. Studies have shown that incorporating jute fibers into WMA mixtures increases the **resistance to deformation** under high loads. For instance, a study reported a **29% increase** in stability and a **7% reduction** in flow value at a **0.5% jute fiber concentration** [15].
- **Compressive Strength:** Jute fibers enhance the **compressive strength** of WMA by improving the **binder-aggregate adhesion**. This stronger bond prevents the mixture from deforming under heavy loads, making the asphalt more resistant to **rutting** and **deformation**. Studies have shown that the inclusion of jute fibers might increase the **compressive strength** by up to **20%** compared to conventional asphalt mixtures.
- **Flexural Strength:** Jute fibers improve the **flexural strength** of WMA, which is particularly important for **bending** and **flexing** under traffic-induced movements. This enhanced flexural strength helps to reduce the chances of **cracking** in the asphalt mixture when subjected to repetitive loads.
- **Fatigue Resistance:** Jute fibers enhance the **fatigue resistance** of asphalt, prolonging the service life of road pavements. This is particularly beneficial in areas with **high traffic volumes**, where fatigue cracking is a common issue [16].
- **Stiffness and Durability:** Jute fibers improve the stiffness of WMA, which results in **better load distribution** and **reduced cracking** over time. The mixture's improved durability makes it resistant to the damaging effects of **aging** and **oxidation**, particularly in **hot climates** [17].

Enhanced Durability

Jute fibers not only improve the **immediate mechanical properties** of WMA but also contribute to the **long-term durability** of asphalt pavements [18]. The key ways in which jute fibers enhance the durability of WMA include:

- **Resistance to Rutting:** Rutting, or the permanent deformation of the surface under heavy traffic loads, is a major concern in asphalt pavements, especially in **hot climates**. Jute fibers increase the **viscosity** of the asphalt binder, enhancing its resistance to rutting. Studies have found that **jute-modified WMA** performs better in terms of **rutting resistance**, with a significant reduction in **permanent deformation** compared to traditional mixes [19].

- **Crack Resistance:** One of the most notable performance improvements with jute fiber is the enhancement of **crack resistance** in the asphalt mixture. Jute fibers, due to their **cellulose** content, help **reinforce** the mixture, providing extra resistance to **thermal cracking** and **shrinkage cracking** at low temperatures [20]. This is especially beneficial for **cold regions** where asphalt pavements are subjected to frequent **temperature fluctuations**. The fibers act as a **reinforcing agent**, averting the creation of cracks due to the natural expansion and contraction of the asphalt as it experiences **temperature cycles** [21].
- **Moisture Susceptibility Reduction:** Another major advantage of jute fibers is their ability to reduce **moisture-induced damage** (also known as **stripping**) in asphalt. Moisture stripping takes place if water penetrates the pavement, making the bond between the asphalt binder and aggregates weaker. Jute fibers improve the **adhesion** between the binder and aggregates, making the mixture more resistant to the damaging effects of water. This is particularly important in areas with high rainfall or fluctuating **moisture conditions**. Jute fibers can also decrease **water absorption** of the asphalt mixture, helping the pavement maintain its performance over time [22].

Enhanced Rheological Properties

The incorporation of jute fibers significantly improves the **rheological properties** of WMA, which are important for the **flow** and **workability** of the mixture during production and compaction:

- **Viscosity Improvement:** Jute fibers help increase the **viscosity** of the asphalt binder, providing better **adhesion** and improving the overall **stability** of the mixture. This enhanced viscosity also helps improve the **workability** of the mixture, making it easier to **compact** during construction. The improved viscosity reduces the chances of **segregation** and ensures a more uniform mixture [23].
- **Enhanced Binder-Aggregate Adhesion:** Jute fibers play a significant role in improving the **adhesion** between the binder and aggregates, which is crucial for the long-term **performance** of the asphalt. The fibers increase the **bonding** between the two components, resulting in a **more durable** and **long-lasting** pavement. This is particularly important for pavements subjected to **heavy traffic** or **harsh environmental conditions** [24].

Resistance to Aging and Oxidation

Asphalt is subject to **aging** and **oxidation** over time, which can lead to a decrease in its **performance and durability**. Jute fibers help improve the oxidative resistance of the asphalt, making it more stable and less prone to aging:

- **Resistance to Aging:** The addition of jute fibers has been shown to delay the aging process of asphalt, maintaining its **flexibility** and **performance** for a longer period. This is particularly beneficial for **long-life pavements** that need to withstand traffic loads and environmental exposure for several years.
- **Resistance to Aging:** The addition of jute fibers has been shown to delay the aging process of asphalt, maintaining its **flexibility** and **performance** for a longer period. This is particularly beneficial for **long-life pavements** that need to withstand traffic loads and environmental exposure for several years.

- **Oxidation Resistance:** Jute fibers enhance the **oxidation resistance** of the asphalt, preventing the binder from becoming **brittle** and **cracking** over time. This helps ensure that the pavement maintains its structural integrity and functionality throughout its service life.

Environmental and Sustainability Benefits

- **Carbon Footprint Reduction:** By substituting synthetic fibers with jute, the overall **carbon footprint** of asphalt production can be reduced. Jute fibers are biodegradable and decompose without leaving harmful residues, making them an excellent option for environmentally conscious construction practices.
- **Renewable Resource:** As a natural fiber, jute is renewable, meaning its use supports sustainable and circular economic models. Using agricultural waste like jute reduces the need for non-renewable materials such as synthetic fibers, which are petroleum-based.
- **Waste Valorization:** Jute fibers can be sourced from **agricultural byproducts**, promoting waste valorization and supporting **sustainable agricultural practices**. By using jute in WMA, the construction industry contributes to a more circular economy, where agricultural waste is upcycled into a valuable construction material.

Challenges and Limitations

- **Variability in Fiber Quality:** The mechanical properties of jute fibers can vary significantly depending on their origin and processing. This inconsistency can affect the performance of the asphalt mixture, making quality control a key challenge.
- **Processing Issues:** Incorporating natural fibers into asphalt requires specialized processing methods to ensure uniform distribution. Fiber clumping and inconsistent dispersion can result in suboptimal performance, highlighting the need for advanced fiber treatment and processing techniques.
- **Economic Considerations:** While jute fibers are cost-effective compared to synthetic fibers, their use in large-scale asphalt production may incur additional costs related to fiber treatment, quality control, and fiber handling.

Conclusion

The integration of **jute fibers** into **Warm Mix Asphalt** offers significant performance and environmental benefits, making it a viable solution for **sustainable road construction**. Jute fibers improve the **performance**, **durability**, and **mechanical properties** of WMA while reducing the environmental impact of asphalt production. However, challenges related to **fiber quality control**, **processing**, and **costs** need to be addressed to ensure the widespread adoption of this material in construction projects.

Future research should focus on:

- **Optimizing processing techniques** for jute fibers to ensure consistent performance.
- **Standardizing fiber quality** to minimize variability and enhance mixture consistency.
- **Long-term performance evaluations** to assess the durability and behavior of jute-modified WMA under various environmental and traffic conditions.

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