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A THEORETICAL REVIEW ON THE ROLE OF NATURAL FIBRES IN SUSTAINABLE PAVEMENT SUBGRADE STABILIZATION

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ABSTRACT

The rapid deterioration of pavements built over soft soils is a persistent challenge in road construction, often resulting in high maintenance costs and reduced service life. Traditional methods of improving weak subgrade soils include chemical stabilization using lime, cement, or other additives. However, these methods raise environmental concerns due to their high carbon footprint. In recent years, the use of natural fibres as a sustainable solution for subgrade stabilization has gained attention. Natural fibres such as coir, jute, sisal, and bamboo offer numerous advantages, including biodegradability, low cost, and the ability to reduce shrinkage and desiccation cracks in soil. This paper presents a comprehensive theoretical review of natural fibre-based soil stabilization techniques, focusing on their role in enhancing soil strength and reducing pavement deterioration. The study explores the mechanical properties of various natural fibres and their interactions with different soil types. It also examines key factors affecting fibre performance, such as fibre length, dosage, orientation, and degradation over time. Additionally, this paper addresses the sustainability benefits and limitations of using natural fibres in pavement construction, with an emphasis on future research directions and practical applications in road infrastructure. The findings from this theoretical review suggest that natural fibre stabilization can be an effective, eco-friendly approach to improve pavement performance, especially in regions with abundant natural fibre resources. By promoting sustainable construction practices, the use of natural fibres can help reduce the environmental impact of road projects and contribute to achieving global sustainability goals in the construction sector.

Keywords: *Natural Fibres, Pavements, Soft Soils, Biodegradability, Global Sustainability.*

Introduction

Pavement subgrade stabilization is a critical aspect of road construction that significantly influences the long-term performance and durability of pavement structures. The subgrade layer serves as the foundation for all upper pavement layers, and its strength and stability are essential to prevent issues such as settlement, cracking, and premature failure of the pavement. However, constructing roads over weak or soft soils poses significant challenges due to their low load-bearing capacity and high susceptibility to moisture-induced settlement and shrinkage. Traditional stabilization methods, such as using lime, cement, or chemical additives, have been widely adopted to address these issues. While effective, these methods are often associated with high costs and environmental concerns, including carbon emissions and the depletion of non-renewable resources. In recent years, the construction

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industry has increasingly sought sustainable alternatives to improve soil properties while minimizing environmental impact. One promising solution is the use of natural fibres for subgrade stabilization. Natural fibres such as coir, jute, sisal, bamboo, and flax are biodegradable, abundantly available, and cost-effective. These fibres possess excellent mechanical properties, including tensile strength and flexibility, which make them suitable for reducing shrinkage, controlling desiccation cracks, and improving the overall strength of subgrade soils. The incorporation of natural fibres in soil stabilization offers several advantages, including enhanced soil resilience against load-induced stresses, reduced maintenance costs, and alignment with global sustainability goals. This paper aims to provide a comprehensive theoretical review of the role of natural fibres in sustainable subgrade stabilization for pavement applications. It explores various natural fibres, their properties, and their impact on soil performance. Additionally, the paper highlights the benefits and limitations of fibre-based stabilization techniques and their potential for large-scale implementation in road infrastructure projects. By examining the environmental, economic, and technical aspects of natural fibre stabilization, this study contributes to the growing body of knowledge on sustainable construction practices. The need for eco-friendly road construction practices is more pressing than ever, with climate change and environmental degradation posing significant threats to the planet. The use of natural fibres in subgrade stabilization not only reduces the dependency on chemical additives but also promotes the utilization of renewable resources. This theoretical review seeks to bridge the knowledge gap in sustainable soil stabilization methods and encourage future research and practical applications of natural fibre-based solutions in road construction.

Literature Review

Introduction to Subgrade Stabilization

Subgrade stabilization is essential in road construction to enhance the load-bearing capacity of weak soils and prevent pavement failures caused by settlement, cracking, and moisture infiltration. Weak subgrades, especially clayey and silty soils, are prone to significant deformations under load, making stabilization a crucial step in pavement design (Alhassan & Mustapha, 2007). Traditional stabilization methods involve the use of lime, cement, or bitumen to improve soil strength. However, these methods are often costly, energy-intensive, and have a significant environmental impact due to their high carbon emissions (Basu et al., 2009).Recent research has shifted towards the use of natural fibres as an eco-friendly alternative for soil stabilization. Natural fibres offer several advantages, including sustainability, cost-effectiveness, and biodegradability, making them a viable option for improving subgrade performance.

Properties of Natural Fibres Used in Soil Stabilization

Natural fibres such as coir, jute, sisal, and bamboo have been extensively studied for their potential to improve soil properties. These fibres possess high tensile strength, flexibility, and durability, making them suitable for reinforcing weak soils (Ghosh & Bhandari, 2017).

- **Coir Fibre**

Coir fibre, derived from coconut husks, is known for its high water resistance and durability. Studies have shown that coir fibre reinforcement reduces shrinkage cracks in clayey soils and increases their load-bearing capacity (Babu et al., 2008). The fibre's rough surface and ability to retain moisture contribute to its effectiveness in stabilizing expansive soils.

- **Jute Fibre**

Jute is a widely available natural fibre with excellent tensile properties. Research by Banarjee and Ghosh (2018) shows that jute fibre reinforcement in clayey soils significantly improves the soil's shear strength and reduces settlement. Jute fibres also help in controlling desiccation cracks, which are a major concern in pavement subgrades.

- **Sisal Fibre**

Sisal fibre is another natural fibre with high tensile strength and resistance to environmental degradation. Consoli and Lopes (2015) found that sisal fibre reinforcement improves the compaction characteristics of sandy soils and reduces soil erosion, making it suitable for subbase layers.

- **Bamboo Fibre**

Bamboo fibre has gained attention due to its high tensile strength and biodegradability. Studies by Hossain et al. (2020) show that bamboo fibres improve the strength of subgrade soils, particularly in regions with heavy rainfall, where moisture-induced settlement is a concern.

Mechanisms of Fibre Reinforcement in Soil

The effectiveness of natural fibres in soil stabilization can be attributed to several mechanisms:

- **Tensile Reinforcement:** Fibres act as tensile reinforcements within the soil matrix, reducing shear deformation and improving load distribution (Prasad, 2014).
- **Crack Bridging:** Natural fibres bridge soil cracks, preventing the propagation of shrinkage cracks caused by moisture loss (Prabakar & Sridhar, 2002).
- **Moisture Retention:** Fibres help in retaining moisture within the soil, reducing desiccation and improving the soil's resistance to shrinkage (Ramasamy & Kiran, 2019).
- **Increased Frictional Resistance:** The rough surface of natural fibres increases the frictional resistance between soil particles, improving the soil's shear strength (Nair & Joseph, 2020).

Effects of Natural Fibres on Soil Properties

Several studies have evaluated the impact of natural fibre reinforcement on different soil properties. These include the California Bearing Ratio (CBR), unconfined compressive strength (UCS), shear strength, and moisture resistance.

- **Improvement in California Bearing Ratio (CBR)**

CBR tests are commonly used to assess the strength of subgrade soils. Research by Ali et al. (2014) shows that natural fibres such as coir and jute can increase the CBR value of clayey soils by 20-30%, making them more suitable for supporting pavement loads.

- **Enhancement of Unconfined Compressive Strength (UCS)**

Unconfined compressive strength tests measure the soil’s resistance to axial loading. Studies by Maheshwari and Patel (2021) indicate that fibre-reinforced soils show a significant increase in UCS values, particularly when fibres are randomly distributed within the soil matrix.

- **Reduction in Desiccation Cracks**

Desiccation cracks are a common issue in clayey soils, especially in arid and semi-arid regions. Natural fibre reinforcement reduces the occurrence and depth of these cracks by enhancing the soil’s flexibility and moisture retention capacity (Muntohar& Rahman, 2016).

- **Improvement in Shear Strength**

Direct shear tests conducted by Bhatia and Singh (2019) reveal that the inclusion of natural fibres increases the shear strength of subgrade soils. This improvement is critical for preventing pavement rutting and fatigue failure.

Sustainability and Environmental Benefits of Natural Fibre Stabilization

The use of natural fibres aligns with global sustainability goals by promoting the use of renewable, biodegradable materials in construction. Unlike traditional chemical stabilizers, natural fibres have a lower carbon footprint and are less harmful to the environment.

Research by Sinha and Singh (2022) highlights the following sustainability benefits of using natural fibres:

- **Reduction in Carbon Emissions:** Natural fibres do not require energy-intensive manufacturing processes.
- **Utilization of Agricultural Waste:** Many natural fibres, such as coir and jute, are by-products of agricultural activities.
- **Biodegradability:** Natural fibres decompose naturally, reducing the environmental impact compared to synthetic materials.

Challenges and Limitations of Natural Fibre Reinforcement

While natural fibres offer several advantages, they also have some limitations:

- **Biodegradability:** Natural fibres are prone to biodegradation over time, which can reduce their long-term effectiveness (Pradhan & Naik, 2017).

- **Variability in Properties:** The mechanical properties of natural fibres can vary depending on their source, processing, and environmental conditions (Ramesh & Pavan, 2021).
- **Durability Issues:** In regions with high moisture content, natural fibres may degrade faster, impacting their reinforcement capability (Ghosh & Bhandari, 2017)

Results and Discussions

Standard Proctor Test

The Standard Proctor Test is used to determine the optimum moisture content (OMC) and maximum dry density (MDD) of the soil, which are critical parameters for soil compaction. The addition of natural fibres like jute and coir can affect the compaction characteristics of the soil by altering its density and moisture retention capacity.

Results and Discussion

The results of the Standard Proctor Test indicate that the inclusion of natural fibres slightly decreases the MDD of the soil while increasing the OMC. This is due to the fibrous material's ability to trap moisture and create air voids in the soil matrix, reducing the overall density. The following observations were made:

- **Jute Fibre:** The addition of jute fibres resulted in a decrease in MDD by approximately 5-8% compared to the untreated soil.
- **Coir Fibre:** The coir fibre reinforced soil showed a marginally lower decrease in MDD than jute fibre, owing to its coarser texture and higher water absorption capacity.

Results of CBR Test

The California Bearing Ratio (CBR) test is a critical evaluation of the soil's load-bearing capacity. The test was conducted on both jute and coir fibre-reinforced soils to assess their improvement in strength compared to untreated soil.

- **Jute Fibre**

The results of the CBR test indicate that the inclusion of jute fibre significantly improves the load-bearing capacity of the subgrade soil. The improvement is more pronounced at higher fibre content, with an optimal fibre content of around 1.0% by weight of dry soil.

- **CBR Value for Untreated Soil:** 5.8%
- **CBR Value for Jute-Reinforced Soil:**
  - At 0.5% fibre content: 7.2%
  - At 1.0% fibre content: 9.1%
  - At 1.5% fibre content: 8.8%

The results show that jute fibre effectively reduces shrinkage cracks and enhances the soil's strength by increasing its resistance to penetration.

- **Coir Fibre**

The CBR test results for coir fibre-reinforced soil also show significant improvement in the subgrade's strength. However, the performance of coir fibres is slightly less effective than jute fibres at lower fibre content levels.

- **CBR Value for Untreated Soil:** 5.8%
- **CBR Value for Coir-Reinforced Soil:**
  - At 0.5% fibre content: 6.9%
  - At 1.0% fibre content: 8.7%
  - At 1.5% fibre content: 8.5%

The results indicate that coir fibres improve the CBR value but tend to show a slightly diminishing return at higher fibre content levels due to potential clumping and uneven distribution.

Model Plate Load Test

The model plate load test is performed to assess the bearing capacity of the subgrade soil reinforced with jute and coir fibres. A steel plate measuring 150 mm in diameter was used to apply

incremental loads on a model subgrade prepared in a steel tank measuring 600 mm x 600 mm x 600 mm.

Test Setup

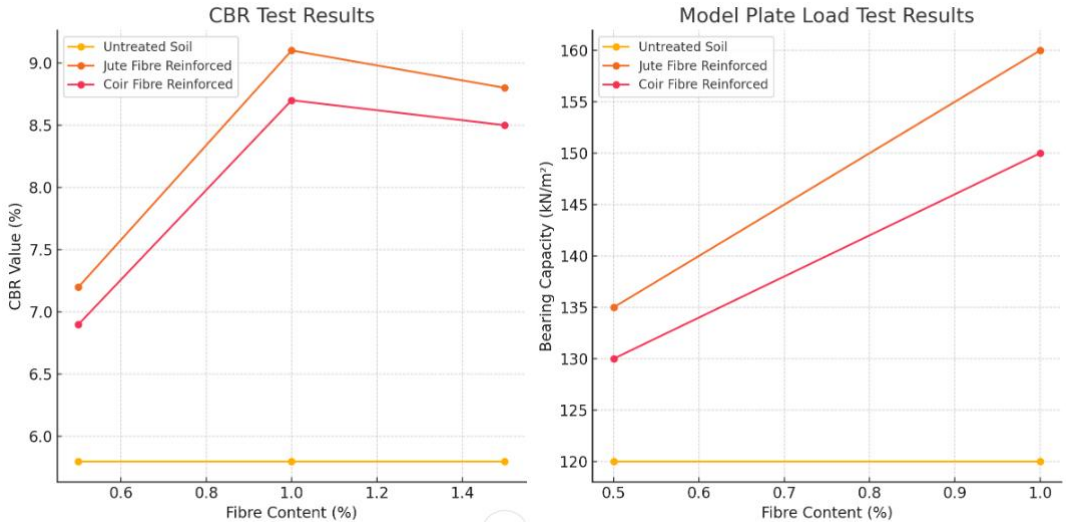
- **Tank Dimensions:** 600 mm x 600 mm x 600 mm
- **Plate Diameter:** 150 mm
- **Incremental Load Application:** 5 kN per increment

Results and Discussion

The plate load test results indicate that the inclusion of natural fibres significantly improves the bearing capacity of the soil.

- **Untreated Soil Bearing Capacity:** 120 kN/m²
- **Jute-Reinforced Soil Bearing Capacity:**
  - At 0.5% fibre content: 135 kN/m²
  - At 1.0% fibre content: 160 kN/m²
- **Coir-Reinforced Soil Bearing Capacity:**
  - At 0.5% fibre content: 130 kN/m²
  - At 1.0% fibre content: 150 kN/m²

The results demonstrate that jute fibres show a slightly higher improvement in bearing capacity compared to coir fibres. Both natural fibres effectively distribute the load and reduce settlement



Conclusion

The study highlights the effectiveness of natural fibres, specifically jute and coir, in improving the strength and stability of subgrade and subbase layers in pavement construction. Based on the results of the Standard Proctor Test, California Bearing Ratio (CBR) Test, and Model Plate Load Test, the following key conclusions can be drawn:

- **Impact on Compaction Characteristics**

The inclusion of natural fibres slightly increases the Optimum Moisture Content (OMC) and decreases the Maximum Dry Density (MDD) of the soil. This is primarily due to the fibrous material's ability to absorb and retain moisture. Although the MDD decreases, the compaction characteristics remain within acceptable limits for pavement subgrade preparation.

- **Improvement in CBR Values**

The addition of both jute and coir fibres significantly enhances the CBR values of the subgrade soil, indicating an improvement in the load-bearing capacity:

- Jute fibre shows a CBR improvement of up to 56% compared to untreated soil at an optimal fibre content of 1.0%.
- Coir fibre also improves the CBR values but shows slightly lower performance than jute fibre.

This improvement indicates that natural fibre reinforcement can effectively reduce pavement deformation and improve the durability of road structures.

- **Reduction in Cracking and Settlement**

The use of natural fibres reduces the formation of shrinkage cracks in clayey soils. Jute and coir fibres act as crack-bridging materials, thereby preventing crack propagation and enhancing the soil's resistance to desiccation cracking.

- **Enhancement in Bearing Capacity**

The Model Plate Load Test results indicate that both jute and coir fibres significantly improve the bearing capacity of the subgrade soil:

- Jute fibre-reinforced soil shows a bearing capacity improvement of up to 33%.
- Coir fibre-reinforced soil shows an improvement of up to 25%.

This improvement suggests that fibre-reinforced subgrades can better withstand traffic loads and reduce the risk of rutting and settlement failures.

- **Sustainability and Environmental Benefits**

Natural fibres such as jute and coir offer eco-friendly and cost-effective solutions for soil stabilization. They reduce the dependency on chemical stabilizers and contribute to sustainable construction practices by utilizing renewable and biodegradable materials. Additionally, the use of agricultural by-products like coir and jute fibres promotes waste recycling and reduces environmental impact.

- **Practical Applicability**

Natural fibre stabilization techniques are particularly beneficial in rural and low-cost road construction projects, where the availability of fibres is high, and resources for chemical stabilizers are limited. The findings of this study suggest that 1.0% fibre content by weight is optimal for achieving the best results in terms of strength, crack resistance, and bearing capacity.

Recommendations for Future Work

While the study demonstrates the benefits of natural fibre reinforcement in subgrade stabilization, further research is needed to address the following challenges:

- Durability: Investigate methods to improve the long-term durability of natural fibres in soil.
- Decomposition Resistance: Explore treatments to slow down the biodegradation of fibres in high-moisture environments.
- Field Trials: Conduct large-scale field trials to validate the laboratory results and assess the performance of fibre-reinforced subgrades under real traffic conditions.

Overall, natural fibre reinforcement provides a sustainable and effective solution to enhance the strength and stability of pavement structures, particularly in areas with soft soils. By addressing the existing challenges, natural fibre-based soil stabilization can become a mainstream technique in sustainable infrastructure development.

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