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Investigation of Thermo-Mechanical Behavior of Bitumen Composite Structures

Bhavna Deshmukh

Department of Physics, School of Pure and Applied sciences, Kenyatta University, Kenya

Abstract

The growing demand for sustainable, eco-friendly materials in civil engineering has prompted the exploration of natural additives in conventional bituminous binders. This study investigates the mechanical performance and thermal behavior of bitumen–Acacia sap composites, with the goal of improving the durability, workability, and environmental sustainability of flexible pavements. Acacia sap, a natural polymeric exudate, was incorporated into bitumen at varying concentrations (2%, 4%, 6%, and 8% by weight of binder). The modified binders were subjected to a series of tests, including penetration, softening point, ductility, Marshall stability, indirect tensile strength, and dynamic shear rheometer (DSR) analysis. Additionally, thermal properties were evaluated using thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC). Results indicated that the addition of Acacia sap improved stiffness and resistance to rutting at higher temperatures while enhancing tensile strength and reducing susceptibility to thermal cracking at low temperatures. Optimal performance was observed at 6% Acacia sap addition, beyond which excessive brittleness was noticed. Thermal analysis confirmed enhanced thermal stability, indicating suitability for diverse climatic conditions. The study concludes that Acacia sap is a promising renewable additive for producing sustainable bituminous composites with balanced mechanical and thermal properties.

Keywords: Bitumen modification, Acacia sap, Mechanical properties, Thermal behavior

1. Introduction

Bitumen is the most widely used binder in road construction due to its viscoelastic behavior and adhesive properties. However, conventional bitumen exhibits limitations such as susceptibility to rutting at high temperatures, brittleness at low temperatures, and oxidative aging. These shortcomings have led researchers to investigate modifiers—synthetic polymers, fibers, and natural resins—that enhance its mechanical and thermal performance.

Among natural polymers, plant-derived gums and saps are attracting attention because they are renewable, biodegradable, and inexpensive. Acacia gum (commonly known as gum arabic or Acacia sap) is a naturally occurring exudate obtained from *Acacia senegal* and *Acacia seyal*. Its unique molecular structure, comprising polysaccharides and glycoproteins, imparts binding, thickening, and film-forming properties. These characteristics make Acacia sap a potential additive for modifying bitumen.

This research explores the synergistic interaction between bitumen and Acacia sap, evaluating how its inclusion alters the mechanical strength, thermal stability, and durability of the composite. The study's significance lies in contributing to the field of sustainable pavement materials, aligning with global goals of reducing reliance on petroleum-based additives and minimizing environmental impact.

2. Literature Review

2.1 Bitumen Modification

Bitumen modification aims to enhance mechanical stability, durability, and resistance against weathering. Traditionally, polymer-modified bitumen (PMB) using styrene-butadiene-styrene (SBS) or ethylene-vinyl acetate (EVA) has been widely adopted. While these synthetic polymers significantly improve performance, they are costly and non-biodegradable. Natural alternatives, including lignin, starch, and resins, are gaining traction.

2.2 Natural Polymers in Bitumen

Plant-derived additives have demonstrated improvements in adhesion, cracking resistance, and moisture sensitivity. For instance, cashew nut shell liquid and jatropha oil have been tested as bio-modifiers. Studies on gum arabic show that its hydrophilic nature and ability to form cross-linked networks enhance viscoelasticity when blended with polymers or resins. However, research specifically focusing on Acacia sap as a sole modifier for bitumen remains scarce, thereby motivating this study.

2.3 Thermal and Mechanical Concerns in Flexible Pavements

Flexible pavements are exposed to cyclic loading and temperature fluctuations, making it essential for binders to maintain thermal stability and mechanical resilience. Bitumen should resist rutting under hot conditions, avoid cracking under cold conditions, and retain ductility over long service lives. Natural additives like Acacia sap, with their inherent polymeric nature, are hypothesized to improve both thermal and mechanical properties of the binder.

3. Materials and Methods

3.1 Materials

- **Bitumen:** VG-30 grade bitumen, commonly used in flexible pavements in tropical regions, was selected.
- **Acacia Sap:** Collected from *Acacia senegal* trees, dried, ground into powder, and sieved to 75 µm size for uniform blending.

3.2 Preparation of Bitumen–Acacia Sap Composites

The bitumen was heated to 160°C, and Acacia sap powder was added at concentrations of 2%, 4%, 6%, and 8% (by weight of bitumen). Mechanical stirring was employed to ensure homogeneous dispersion.

3.3 Testing Procedures

The following tests were performed:

- **Conventional Tests:** Penetration, softening point, and ductility.
- **Mechanical Tests:** Marshall stability and flow, indirect tensile strength (ITS).
- **Rheological Tests:** Dynamic shear rheometer (DSR) to evaluate complex modulus and phase angle.
- **Thermal Analysis:** Thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC).

4. Results and Discussion

4.1 Conventional Properties

- **Penetration:** Acacia sap addition reduced penetration values, indicating increased hardness and stiffness.
- **Softening Point:** Progressive increase observed with sap content, signifying better resistance to softening at high temperatures.
- **Ductility:** Ductility decreased slightly at higher dosages (>6%), suggesting risk of brittleness.

4.2 Marshall Stability and Flow

- Stability increased with sap addition, peaking at 6% with a 28% improvement compared to control.
- Flow values remained within permissible limits, indicating balanced stiffness and flexibility.

4.3 Indirect Tensile Strength

ITS improved by 22% at 6% addition, reflecting enhanced resistance to cracking and fatigue failure. However, 8% addition caused marginal reduction, suggesting over-stiffening.

4.4 Rheological Behavior (DSR)

- Complex modulus (G*) increased significantly, indicating improved rutting resistance.
- Phase angle (δ) decreased, highlighting transition from viscous to more elastic behavior.
- Optimum elasticity observed at 6% Acacia sap.

4.5 Thermal Behavior

- **TGA:** Bitumen–sap composites showed delayed onset of thermal degradation, with stability improving by nearly 40°C compared to neat bitumen.
- **DSC:** Composites exhibited higher glass transition temperatures (Tg), reducing low-temperature cracking potential.

4.6 Microstructural Observations

Microscopic examination revealed uniform dispersion of Acacia particles within the bitumen matrix, forming polymeric bridges that enhanced cohesion. Excessive sap (>6%) led to clustering, causing stress concentration and brittleness.

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5. Environmental and Economic Implications

Acacia sap is a naturally available, biodegradable additive, making it an eco-friendly alternative to petroleum-derived polymers. Its low cost and widespread availability in semi-arid regions support economic feasibility. Moreover, the adoption of such natural modifiers can significantly reduce the carbon footprint of road construction.

6. Conclusions

The present investigation into the thermo-mechanical behavior of bitumen composite structures demonstrates the significant influence of composite modification on both mechanical integrity and thermal stability. Bitumen, as a widely used binding material in pavement and construction applications, exhibits inherent limitations under varying temperature regimes and sustained mechanical loads. Through the incorporation of reinforcing additives, fillers, and polymeric modifiers, the mechanical stiffness, load-bearing capacity, and resistance to deformation were markedly enhanced. At the same time, improvements in thermal stability contributed to better resistance against rutting at high temperatures and reduced brittleness at low temperatures.

The results collectively highlight the dual benefit of composite reinforcement: on one hand, enhanced mechanical performance through increased tensile strength, fatigue resistance, and durability; on the other, improved thermal tolerance that ensures structural reliability across diverse climatic conditions. The synergistic effect of these modifications is crucial in extending the service life of bitumen-based structures, particularly in heavy-traffic pavements and regions subject to extreme temperature fluctuations.

The study underscores the importance of evaluating thermo-mechanical properties in an integrated manner rather than in isolation. Mechanical testing alone does not capture the complex viscoelastic responses of bitumen composites under coupled thermal and mechanical loading. By combining thermal analysis with mechanical characterization, this research establishes a more comprehensive understanding of performance, paving the way for optimized material design and application. While the investigation confirms the effectiveness of bitumen composites in improving performance, it also indicates areas for future development. Long-term aging effects, environmental durability, and large-scale field validations remain critical aspects for further study. Incorporating sustainable modifiers such as bio-based polymers, recycled aggregates, and nanomaterials could further enhance both mechanical resilience and thermal efficiency while addressing environmental concerns. Bitumen composite structures offer a promising pathway toward high-performance, durable, and climate-resilient infrastructure. The enhanced thermo-mechanical behavior not only ensures improved pavement longevity and safety but also supports broader goals of sustainable infrastructure development. Continued interdisciplinary research, integrating material science, pavement engineering, and environmental sustainability, will be vital in translating laboratory advances into real-world performance.

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