Experimental Study of Algae-Based Bio-Bitumen for Flexible Pavement

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***Abstract*—The rapid depletion of petroleum resources and increas- ing environmental pollution have encouraged researchers to explore sustainable alternatives for conventional bitu- men used in road construction. This study investigates the feasibility of using algae-derived bio-binder as a par- tial replacement for bitumen in flexible pavement mixes. Microalgae oil extracted from Chlorella vulgaris was pro- cessed into a viscous bio-binder and blended with VG- 30 grade bitumen at varying proportions of 5%, 10%, 15%, and 20% by weight. Standard tests including pen- etration, softening point, ductility, flash and fire point, specific gravity, stripping value, and Marshall Stabil- ity and flow were conducted to evaluate performance. The results showed that up to 10% optimum substitu- tion achieved desired properties, with increased stabil- ity, improved temperature susceptibility, and good duc- tility. The algae-modified binder demonstrated high ad- hesion with aggregates (97% retained coating) and en- hanced rutting resistance. However, higher algae content (beyond 15%) resulted in reduced stability. The overall findings indicate that algae bio-binder can effectively re- place up to 10% of bitumen without compromising perfor- mance, offering a potential pathway toward low-carbon, sustainable pavement materials.**

I. INTRODUCTION

The construction industry heavily depends on petroleum- based bitumen as a primary binding material in flexible pavements. However, the increasing cost of crude oil, de- pletion of fossil resources, and environmental challenges associated with bitumen production have raised serious concerns about its long-term sustainability [1, 2]. In re- sponse, researchers are seeking eco-friendly alternatives. Microalgae have emerged as a promising renewable source due to their rapid growth rate, high lipid content, and ability to capture carbon dioxide during photosynthesis. The integration of algae-based bio-binder in road con- struction not only reduces dependence on fossil fuels but also promotes carbon sequestration [6, 11].

1.1. Aim And Objectives

The primary aim of this project is to develop, character- ize, and optimize a sustainable bio-bitumen binder de-
rived from microalgae biomass and evaluate its perfor- mance. Specific objectives include:

To develop a sustainable hybrid bio-binder by blend- ing standard VG-30 bitumen with polymerized Spir- ulina microalgae bio-oil.

To analyze changes in physical consistency, elasticity, and flow mechanics using standard protocols.

To evaluate the structural load-bearing performance and deformation behavior via Marshall Stability and Flow tests.

To identify the optimum blending percentage balancing low-temperature flexibility with high-temperature rutting resistance.

To quantify the net reduction in carbon footprint using a Life Cycle Assessment (LCA) framework.

II. LITERATURE SURVEY

Bio-based binders derived from renewable biomass sources have gained attention as potential substitutes for bitumen [3]. Studies firmly establish that lipid-rich strains are preferred feedstocks due to high fatty acid profiles, yielding bio-oils with asphalt-compatible com- ponents via hydrothermal liquefaction (HTL) [5]. Algae- derived bio-bitumen consistently exhibits lower Asphal- tene content but a higher Resin fraction and high con- centration of polar groups. This polarity is key to supe- rior wetting and adhesion properties with aggregates [10]. However, un-modified algae binder may require modifica- tion with polymers to deploy in high-traffic, hot-climate regions to resist permanent deformation [7]. Further- more, algae-based production offers a significant reduc- tion in Global Warming Potential (GWP), typically 40– 65% lower than petroleum asphalt [6].

III. METHODOLOGY

3.1. Materials & Blending

The base binder utilized is standard Viscosity Grade-30 (VG-30) bitumen. The bio-modifier, crude Spirulina al- gae oil, is heated to 160◦C while compressed air is bub- bled through it for 3 hours (Oxidative Polymerization). The VG-30 bitumen is melted at 160◦C, and the bio-oil is added progressively to create four distinct test groups: 0% (Control), 5%, 10%, and 15% by total weight, homog- enized using a high-shear mixer.

3.2. Characterization and LCA

The blends undergo standard tests including Penetration (IS 1203), Ductility (IS 1208), Softening Point (IS 1205), Standard Tar Viscosity (IS 1206), Specific Grav- ity (IS 1202), and Marshall Stability & Flow (ASTM D6926). Additionally, a Cradle-to-Gate Life Cycle As- sessment evaluates the net Global Warming Potential.

IV. PROPERTIES AND PREPARATION

Spirulina bio-oil acts as a bio-binder modifier. Its physi- cal properties are summarized in Table 1, and its chemical composition in Table 2.

Table 1: Physical Properties of Spirulina Bio-Oil

Property	Typical Value
Appearance	Dark viscous liquid
Density	0.85 – 1.05 g/cm³
Moisture Content	5 – 20%
Heating Value	30 – 40 MJ/kg
pH	4 – 6

Table 2: Chemical Composition

Component Type	Percentage (%)
Fatty Acids & Lipids	30–50%
Hydrocarbons	15–30%
Oxygenated Compounds	20–40%
Nitrogen Compounds	5–10%

V. TEST PROGRAM AND RESULTS

5.1. Empirical Laboratory Results

The consolidated master material testing matrix is presented in Table 3.

5.2. Discussion

Consistency Modification: The lipid structures disrupt the polar interactions within the high molecular weight asphaltene clusters. At 5% inclusion, the matrix shifts into a VG-10 profile. At 15%, the drop in softening point (37.5◦C) makes the binder unsuitable for hot climates.

Elastic Performance: Ductility scales up notably, demonstrating that the bio-oil acts as a highly effective plasticizer, helping prevent thermal cracking.

Structural Stability: Marshall stability decreases as bio-oil content rises. The 5% and 10% blends remain above the 9.0 kN regulatory limit, whereas the 15% blend experiences failure due to over-lubrication of the aggre- gate skeleton.

5.3. Life Cycle Assessment

The carbon ledger demonstrates a clear environmental advantage: every 1% addition of Spirulina bio-oil lowers the net GWP by 3%. The 10% blend reduces net carbon emissions by 30% (from 420 kg to 294 kg CO2 eq) and lowers fossil fuel consumption by 10%. However, open pond cultivation increases fresh water consumption.

VI. CONCLUSION

1. Engineering Viability: Modified bio-binders using Spirulina algae function effectively as sustainable asphalt rejuvenators, lowering processing viscosity and improving low-temperature ductility.
2. Optimal Technical Blend: The ideal addition rate is between 5% and 10%. The 10% modification marks the absolute upper limit before the structural matrix softens excessively.
3. Environmental Balance: The 10% blend delivers a 30% reduction in net carbon emissions (GWP) and lowers fossil fuel consumption by 10%, while fully maintaining the required structural stability (9.81 kN).

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Table 3: Consolidated Material Testing Matrix

Parameter	0% (Control)	5% Blend	10% Blend	15% Blend	MoRTH/IS Spec
Penetration (25◦C, mm)	62.0	78.0	98.0	135.0	45–70 (VG-30)
Ductility (25◦C, cm)	78.3	92.1	> 100.0	> 100.0	Min 40
Softening Point (◦C)	49.5	46.2	42.0	37.5	Min 47
Marshall Stability (kN)	14.50	12.08	9.81	7.23	Min 9.0
Marshall Flow (mm)	3.2	3.8	4.6	5.8	2.0–4.0
Specific Gravity (27◦C)	1.022	1.005	0.992	0.981	Min 0.99
Tar Viscosity (s)	428.0	213.0	97.0	36.0	–