Enhancing Geotechnical and Environmental Properties of Municipal Solid Waste Fines via Biopolymer Stabilization

Characterization, Application, and Sustainability Analysis

Thesis submitted in partial fulfillment for the Award of Degree

Doctor of Philosophy

Submitted by

Abhay Kumar Verma

DEPARTMENT OF CIVIL ENGINEERING

INDIAN INSTITUTE OF TECHNOLOGY (BANARAS HINDU UNIVERSITY)

VARANASI – 221005

Roll No. 17061503 **2024**

Chapter 9

Conclusions & Future-Research Scope

This thesis presents a comprehensive study on the sustainable stabilization of Municipal Solid Waste Fines (MSWF) using biopolymers such as Xanthan Gum (XG) and Agar Gum (AG). The research integrates a depth-wise assessment of MSWF from a legacy dumpsite and evaluates the long-term durability of biopolymer-stabilized MSWF, providing valuable insights into both geotechnical and environmental aspects. Key conclusions are as follows:

1. **Depth-wise Assessment of MSWF:**

    - **Geotechnical Properties:** The study revealed that the organic content of MSWF decreases with depth, leading to more stable material at greater depths. The Unconfined Compressive Strength (UCS) of legacy waste fines (LWF) increased from 120 kPa at shallow depths to 140 kPa at 10 meters depth, indicating enhanced suitability for civil engineering applications. Specific gravity also increased from 2.21 at the surface to 2.35 at 10 meters depth, reflecting denser material compositions, such as silts and clays.

- **California Bearing Ratio (CBR):** Both soaked and unsoaked CBR values increased with depth, with soaked CBR rising from 15.3% at the surface to 17.4% at 10 meters depth. This suggests a denser soil profile at greater depths, making it more suitable for road and airfield pavements.
- **Elemental Composition and Stability:** Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray (EDX) analysis showed denser aggregation of fines and the presence of metals like Al, Mg, Ti, Fe, Nb, and Ta, with their concentrations varying by depth. The elemental composition at 10 meters depth included 48.97% O, 8.57% Al, 18.34% Si, 1.79% Ca, and 1.47% Fe, indicating the presence of heavy metals that affect material reactivity and application suitability.

2. **Effectiveness of Biopolymers:**

- **Mechanical Properties:** The highest Maximum Dry Density (MDD) was observed at 2.05 Mg/m^3 for 1.5% XG (a 12.2% increase) and 1.79 Mg/m^3 for 1% AG (a 7.8% increase). Cohesion significantly improved from 103.5 kPa (untreated) to 594.7 kPa with 1.5% XG and 613.6 kPa with 1.5% AG, reflecting an improvement of up to 492.7%. Maximum Unconfined Compressive Strength (UCS) was 3654.88 kPa for 1.5% AG after seven days, a 2419% increase from the base value of 145.12 kPa. UCS with 1.5% XG reached 3496.78 kPa, demonstrating the effectiveness of biopolymer gels in enhancing cohesion and reducing voids.
- **CBR Improvement:** Agar Gum consistently outperformed Xanthan Gum in enhancing the California Bearing Ratio (CBR) of MSWF, with a peak

value of 13.1% at 1.5% AG, making it a more effective stabilizer for improving load-bearing capacity under soaked conditions.

3. **Long-term Durability of Biopolymer-Stabilized MSWF:**

   - **Durability Findings:** The study found that AG-treated MSWF maintained near-constant cohesiveness after 14 days, while XG-treated MSWF peaked at 28 days. The internal friction angle initially decreased with increased biopolymer content up to 28 days but increased at 90 and 180 days, indicating stronger long-term interparticle bonds. XG-treated samples displayed higher ductility than AG after 180 days, while AG's shear strength rapidly increased until day 14, with XG showing significant strength gains primarily during the first 90 days. These findings suggest that biopolymer concentrations could potentially increase strength by over 450%.
   - **Structural Integrity:** Curing filled the MSWF matrix pores over time, resulting in a denser biopolymer-soil composite structure, which enhances the long-term stability of the treated material.

4. **Environmental Sustainability:**

   - **Carbon Emissions:** Lime stabilization results in 102 kg CO2e per ton of MSWF, while Xanthan Gum emits 17.76 kg CO2e, and Agar Gum is carbon-negative at -2.53 kg CO2e per ton. Despite its higher cost of ₹2073.5 per ton, Agar Gum offers potential financial benefits through carbon credits due to its carbon-negative footprint. Xanthan Gum, costing ₹516.6 per ton, effectively balances cost and environmental impact.

- **Heavy Metal Reduction:** Biopolymer treatment significantly reduced hazardous heavy metals in leachates, with elements like Cd, As, and Pb falling below detectable levels after treatment, ensuring environmental safety.

5. **Practical Applications:**
    - **Pavement Design:** The optimized pavement designs using biopolymer-treated MSWF demonstrated significant material savings and improved performance (Amena 2022). The thickness of the bituminous layer was reduced by up to 25.7%, saving 25 m^3 of material per kilometer. Maximum soaked CBR increased to 11.2% with 1.0% XG and 13.1% with 1.5% AG, further reducing the bituminous layer thickness to 138 mm and 130 mm, respectively.

6. **Economic and ESG Impact:**
    - **Cost-Effectiveness and ESG Analysis:** While Lime is cost-effective at ₹516.8 per ton, it carries significant long-term environmental costs, making it less sustainable. Agar Gum and Xanthan Gum, though more expensive, align better with sustainable development goals and present fewer governance challenges. Agar Gum, in particular, is ideal for projects prioritizing sustainability, while Lime is more suited for quick, cost-effective stabilization.

7. **Future Research Scope:**
    - **Long-term Performance:** Future studies should focus on evaluating the durability and long-term performance of biopolymer-stabilized MSWF under real-world conditions and different environment expousures.

- **Alternative Biopolymers:** There is potential for exploring other biopolymers and organic materials for waste stabilization.
- **Expanded Applications:** Additional applications for treated MSWF in various civil engineering contexts should be explored.
- **Economic Scalability:** Assessing the economic scalability and industrial adoption of biopolymer stabilization techniques is essential for broader implementation.

Overall, this research provides a solid foundation for the sustainable management of MSWF through biopolymer stabilization, offering innovative solutions that support environmental sustainability and advance the principles of a circular economy.