Development of a Laboratory-Scale Model to Evaluate Rainfall-Induced Surface Erosion Mitigation in MICP-Treated Sand

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Abstract: Microbially Induced Calcite Precipitation (MICP) has conventionally relied on Sporosarcina pasteurii for soil improvement, yet the potential of other urease-producing bacterial strains to enhance surface erosion remains largely unexplored, especially under field-simulated rainfall conditions. This study investigates the erosion behaviour and durability of Ganga River Sand (GRS) surfaces treated with three alternative ureolytic bacteria—Bacillus sp., Bacillus sphaericus, and Bacillus subtilis. Laboratory-scale GRS surfaces were prepared at 70% relative density and treated with a $CaCl_2$–urea bio-cementation solution, followed by microstructural characterization and controlled rainfall simulations replicating natural rainwater chemistry and realistic intensities. To evaluate long-term stability, additional tests were conducted using simulated acidic rainfall at a 45° slope to represent harsh weathering conditions typical of vulnerable geomorphic environments. Key parameters, including physicochemical changes, erosion rate, erosion patterns, and post-erosion surface strength, were systematically monitored. The results provide comparative insights into the performance of these bacterial strains in mitigating rainfall-induced surface erosion and demonstrate the potential of optimized MICP treatments for enhancing the resilience of sandy slopes under both natural and adverse environmental conditions.

Keywords: ***Acid rain durability; Bio-cementation; Ganga River Sand; Surface erosion; Ureolytic bacteria.***

Introduction

Soil erosion involves the detachment and transport of soil particles by natural agents such as wind, water, and rainfall, and is further accelerated by human activities like deforestation, construction, and mining (Wei et al., 2023). Heavy or prolonged rainfall often triggers erosion-induced slope and embankment failures, posing significant challenges in geotechnical engineering. Therefore, controlling soil scouring during intense rainfall events is essential for protecting embankments from failure (Sun et al., 2022a).

Microbial-chemical technologies have recently gained considerable attention in geotechnical engineering, showing highly promising results (Jha, 2022). Among them, Microbially Induced Calcite Precipitation (MICP) has emerged as an effective, modern approach for erosion control and soil improvement. This eco-friendly and cost-efficient technique uses urease-producing Bacillus species to hydrolyze urea and precipitate calcite in the presence of calcium ions (Naskar et al., 2024). The resulting calcite crystals gradually accumulate within soil pores, binding particles and improving strength and erosion resistance (Martinez et al., 2013; Taharia et al., 2024).

This study investigates the effect of natural and acid rain on MICP-treated Ganga River sand, comparing erosion resistance among Bacillus sp., B. sphaericus, and B. subtilis. Rainfall-induced erosion, physico-chemical changes, surface strength, and microstructure were evaluated to determine the most effective bacteria for enhancing GRS embankment stability.

Materials and Methodology

Ganga River sand was compacted to 70% density in trays with fibreglass-lined drainage holes. Bacterial suspensions (OD_{600} ~ 1) were applied and incubated for 24 hours, followed by urea to induce urease activity (Tarun et al., 2023). A cementation solution of urea and $CaCl_2$ was applied daily for 10 days, and trays were air-cured for 5 days. Ten years of IMD Patna rainfall data were converted to hourly intensities, with a maximum of 60 mm/hr (July 2014). Laboratory rainfall was simulated on 45°-sloped MICP-treated trays using calibrated shower heads and recorded with a high-speed camera under two conditions: natural rainwater and rainwater adjusted to pH 4.

Results and Discussion

The collected rainwater had a slightly alkaline pH (6.2– 7.5) with low salinity and turbidity, conditions that supported calcite stability but also encouraged some dissolution due to low ionic strength. Under the simulated rainfall intensity, MICP-treated GRS showed much higher surface strength and erosion resistance than untreated sand (Figure 1), owing to the formation of a protective calcite crust.

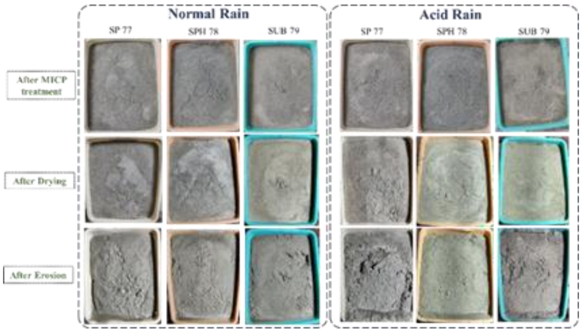

Figure 1, Sample surface characterization at different test procedure phases for a) normal rainfall, b) acid rainfall (Tarun and Jha, 2025).

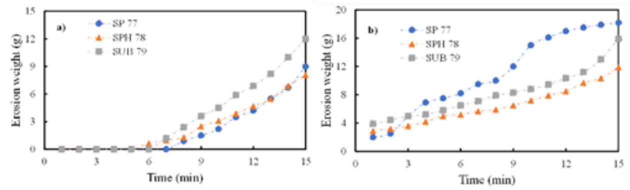

Figure 2, Weight of soil eroded versus time for different samples (a) Normal rainfall (b) Acid rainfall.

Under normal rainfall, gully erosion initiated after 6 minutes, with a peak erosion rate of 3 g/min and a total soil loss of 25 g over 900 seconds. Exposure to acidified rainwater doubled the erosion rate, resulting in 42 g of cumulative loss. Untreated samples exhibited the highest soil loss (89 g), highlighting the significant improvement in erosion resistance achieved through MICP treatment. Among the bacterial strains tested, Bacillus sphaericus produced the most stable calcite, yielding the highest surface strength and lowest erosion rate compared to Bacillus sp. and Bacillus subtilis. Surface analysis indicated that only samples with urease-producing bacteria developed effective calcite precipitation, forming interparticle bonds and increasing particle angularity, which enhanced strength and erosion resistance. However, prolonged exposure to acidic rainfall weakened the calcite structure, suggesting potential durability concerns under field conditions.

Conclusion

The study demonstrates that MICP is a sustainable, eco-friendly erosion mitigation method. Its effectiveness depends on bacterial selection, rainwater chemistry, and environmental conditions. Emphasis should be placed on protective measures and periodic maintenance, with upscaling for field validation. This approach can enhance the long-term stability and sustainability of MICP-treated surfaces.

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