

# BIO-CEMENTATION TREATMENT FOR STRENGTHENING SANDY SOILS

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**Abstract** Bio-cementation, also known as microbially induced calcite precipitation (MICP), has emerged as a sustainable and environmentally friendly ground-improvement technique for enhancing the mechanical behavior of sandy soils. This paper explores the scientific principles, microbial pathways, engineering applications, laboratory protocols, influencing parameters, and performance evaluation of bio-cemented sandy soils. The study integrates findings from recent research to evaluate the potential of MICP for increasing soil strength, reducing permeability, and improving liquefaction resistance. Sandy soils, due to their loose structure and lack of cohesion, pose challenges in foundation engineering, slope stabilization, and seismic zones. Bio-cementation introduces calcium carbonate ( $\text{CaCO}_3$ ) precipitates that bind sand grains, increasing stiffness and shear strength. This paper presents a detailed outline covering mechanisms, microbial cultures, treatment cycles, curing conditions, strength tests, durability behavior, and field implementation. The review concludes that MICP offers a cost-effective, carbon-neutral alternative to chemical grouting and cement stabilization, though challenges remain in ensuring uniform distribution, scale-up feasibility, and long-term performance. Future research should emphasize genetically optimized microbes, real-time monitoring systems, injection modeling, and hybrid bio-geochemical stabilization systems.

**Keywords:** Bio-cementation, Microbially Induced Calcite Precipitation (MICP), Sandy soils, Soil stabilization, Calcium carbonate precipitation, Ground improvement, Shear strength, Permeability, Environmental geotechnology, Ureolytic bacteria.

## 1. Introduction

Sandy soils are prevalent across coastal and inland regions but are characterized by weak inter-particle bonding, high permeability, and susceptibility to liquefaction. Traditional ground-improvement methods such as compaction, cement grouting, and chemical stabilizers are effective but contribute significantly to carbon emissions and groundwater contamination. In

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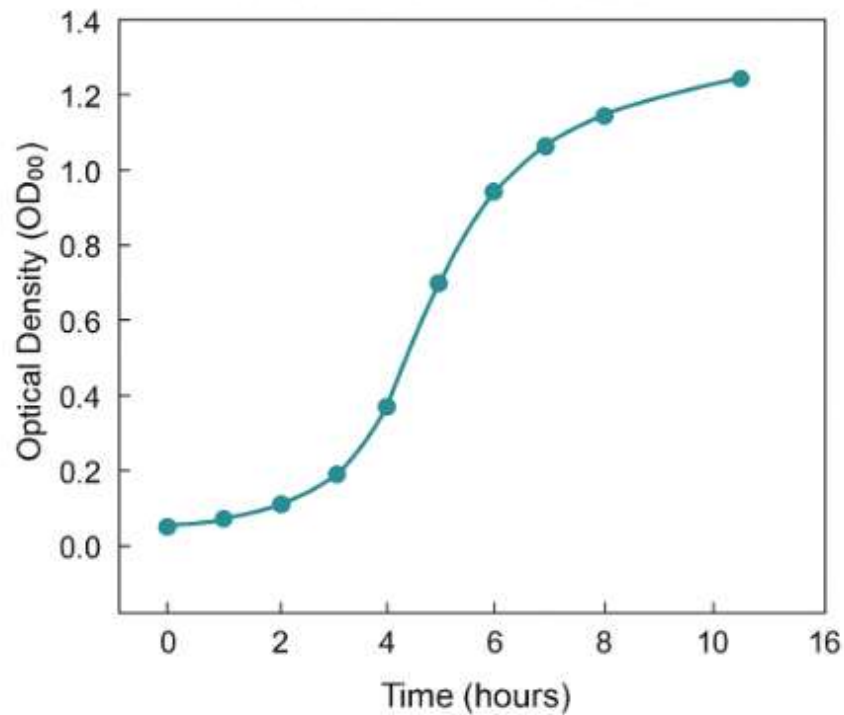
contrast, bio-cementation based on microbially induced calcite precipitation (MICP) offers a sustainable pathway where microorganisms catalyze the precipitation of  $\text{CaCO}_3$ , which acts as a biogenic binder between sand grains. This method provides not only mechanical improvement but also environmental benefits, aligning with global efforts toward green geotechnical engineering. The introduction section outlines the need for environmentally friendly soil improvement, global applications of bio-cementation, and the advantages of biochemical reactions for strengthening sandy soils.

## 2. Background and Mechanism of Bio-Cementation

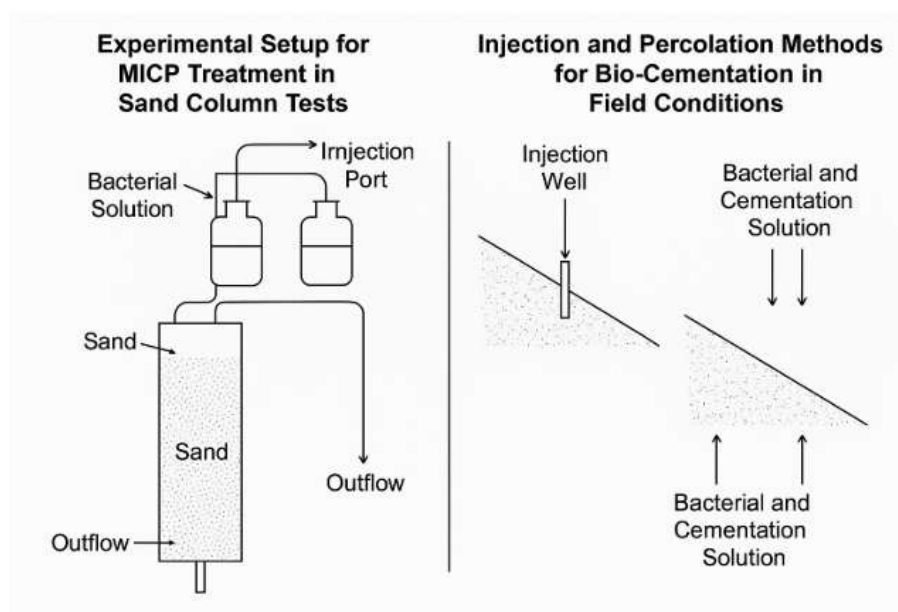
Bio-cementation relies on microbial biochemical pathways, especially ureolysis, photosynthesis, sulfate reduction, and denitrification, though ureolytic MICP remains the most widely implemented process. In ureolysis, bacteria such as *Sporosarcina pasteurii* hydrolyze urea to produce carbonate ions, which react with calcium ions to precipitate calcite. This calcite fills pore spaces and forms bonds at particle contacts, increasing soil stiffness. The mechanism involves three stages: microbial growth and attachment, biochemical conversion of nutrients, and mineral precipitation. The quality of the cementation depends on bacterial concentration, pH, calcium source, reaction rate, and injection strategy. Sandy soils are highly suitable for MICP due to their high permeability, which facilitates bacterial transport and uniform distribution of precipitates.

## 3. Literature Review on Bio-Cementation for Sandy Soils

Numerous studies have confirmed the effectiveness of MICP in improving the engineering properties of sandy soils. DeJong et al. (2010) demonstrated that  $\text{CaCO}_3$  precipitation increases the unconfined compressive strength from less than 100 kPa to more than 1 MPa in treated sands. Whiffin et al. (2007) showed that strength improvement is proportional to the calcite content, with 3–10%  $\text{CaCO}_3$  resulting in a significant increase in shear strength. Montoya and DeJong (2015) applied MICP to liquefaction mitigation and found considerable enhancement in cyclic resistance. Recently, Cheng et al. (2021) investigated field-scale MICP treatment and reported improved penetration resistance and reduced settlement. These studies collectively show that bio-cementation is a feasible alternative to chemical stabilization, but challenges remain regarding uniformity, clogging, and adaptation to field-scale hydraulic conditions.



**Figure 3.1** Growth Curve of *Sporosarcina pasteurii* Used in Bio-Cementation



**Figure 3.2** Typical Laboratory Setup for MICP Treatment in Soil Columns

#### 4. Microorganisms and Biochemical Pathways Used in Bio-Cementation

The primary microorganism used in bio-cementation is *Sporosarcina pasteurii*, valued for its high urease activity, ability to tolerate alkaline environments, and rapid growth. Other microbes, such as *Bacillus megaterium* and *Bacillus subtilis*, have also been investigated for

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MICP. The ureolytic pathway remains dominant, involving the hydrolysis of urea to ammonia and carbonate, raising the pH and enabling calcite formation. Alternative pathways such as photosynthetic MICP (using cyanobacteria), sulfate-reducing bacteria, and denitrifying bacteria offer potential for environments where urea is undesirable. Each pathway has advantages depending on pH tolerance, nutrient requirements, reaction speed, and environmental constraints.

## 5. Materials and Methods Used in Bio-Cementation Treatment

Bio-cementation experiments typically involve the preparation of sandy soil specimens, cultivation of bacteria, preparation of cementation solutions, and execution of injection cycles. Sand is sieved and cleaned to ensure uniform gradation. Bacterial cultures are grown in nutrient broth, often reaching an optical density (OD<sub>600</sub>) of 1.2–2.0. The cementation solution generally contains urea and calcium chloride, though alternatives like calcium acetate and calcium lactate are used where chloride contamination is undesirable. Specimens are treated via percolation, spraying, or injection, and are cured at controlled temperature and humidity. Evaluation requires measuring calcite content, permeability, shear strength, and microstructure using SEM, XRD, and CT scans.

## 6. Experimental Procedure for Sandy Soil Bio-Cementation

The experimental procedure follows a chronological sequence: (1) preparation of clean sand samples; (2) bacterial culture growth to achieve high urease activity; (3) injection or percolation of bacterial suspension; (4) introduction of cementation solution; (5) multiple treatment cycles; and (6) curing and mechanical testing. Treatment frequency (e.g., daily for 5–10 days) influences the final calcite content. Uniform treatment is critical because high reaction rates can clog pores, preventing deeper penetration. The curing stage allows calcite crystals to stabilize. The specimens are then subjected to unconfined compressive strength (UCS), direct shear tests, permeability tests, and microscopic analyses.

## 7. Factors Influencing the Performance of Bio-Cemented Sandy Soils

Bio-cementation is affected by several variables: bacterial cell concentration determines urease activity; calcium source affects precipitation rate; sand gradation influences flow paths; injection pressure affects distribution; curing period affects crystal growth; and environmental conditions such as pH, salinity, and temperature determine the viability of microbes. High injection rates may lead to non-uniformity due to preferential flow channels. Similarly, fine

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sand leads to rapid clogging, while very coarse sand may not retain biomass efficiently. An optimal balance between reaction speed and distribution is needed for consistent treatment across the soil matrix.

### **8. Engineering Properties of Bio-Cemented Sandy Soils**

Bio-cementation significantly improves the mechanical behavior of sandy soils. Unconfined compressive strength can increase from 50 kPa to 1–2 MPa with moderate calcite content. Direct shear tests show increased cohesion and internal friction angle. Permeability can reduce by more than an order of magnitude, making the soil more resistant to seepage. Cyclic triaxial tests indicate improved liquefaction resistance, making MICP suitable for earthquake-prone areas. Additionally, bio-cemented sand demonstrates increased stiffness, reduced settlement, and enhanced erosion resistance, making it applicable in slope stabilization, foundations, and coastal protection.

### **9. Microstructural Analysis and Calcite Morphology**

Microstructural analyses using SEM, XRD, and EDS confirm that precipitated calcite forms bridges between sand grains, creating strong inter-particle bonding. Calcite crystals typically appear as rhombohedral forms, though vaterite may be present during early stages. The distribution of calcite determines the strength uniformity, with cluster formation leading to localized stiff zones. CT scanning reveals how pore space decreases after treatment. Mineralogical studies affirm that biogenic calcite has comparable binding properties to naturally formed  $\text{CaCO}_3$ , making it suitable for long-term stabilization.

### **10. Applications of Bio-Cementation in Geotechnical Engineering**

Bio-cementation is applicable in several engineering scenarios including liquefaction mitigation, slope stability, excavation support, foundation improvement, and erosion control. In coastal engineering, MICP can reduce scour around bridge piers and offshore structures. In arid regions, bio-cementation is used for sand dune stabilization. In environmental engineering, it serves as a barrier to reduce contaminant migration. Recent pilot-scale projects demonstrate successful implementation in road subgrades, retaining structures, and low-rise building foundations.

### **11. Limitations and Challenges of Bio-Cementation**

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Despite benefits, bio-cementation faces operational challenges such as ensuring uniform treatment at large depths, technological barriers in bacterial transport, ammonium by-product management, and slow reaction times under low temperatures. Field implementation may require large nutrient supply, raising cost concerns. Long-term durability depends on environmental conditions such as acid rain and groundwater flow. Scaling up from laboratory to field requires predictive models for fluid flow, bacterial kinetics, and precipitation gradients. Regulatory concerns also exist regarding microbial introduction into soils.

## 12. Environmental Benefits and Sustainability Considerations

Bio-cementation provides substantial environmental advantages over cement or chemical grouting. It reduces carbon emissions, avoids toxic chemical use, minimizes groundwater contamination, and promotes green geotechnics. The calcite produced is stable and non-hazardous. Importantly, bio-cementation allows low-energy in-situ treatment, reducing construction disturbance. Researchers are also exploring waste-derived nutrients and genetically engineered microbes for enhanced sustainability. In future, MICP could become a major tool in carbon-neutral infrastructure development.

## 13. Future Scope and Research Opportunities

Future research should focus on improving reaction uniformity, developing low-ammonia pathways, modeling injection strategies, and integrating MICP with other stabilization techniques such as biopolymers and nano-materials. Genetic engineering presents opportunities to enhance microbial efficiency and temperature tolerance. The development of autonomous bio-cementation systems using drones or robotic injectors may transform large-scale ground improvement. More pilot-scale studies and long-term monitoring are required to validate durability under varying climatic and hydrological conditions.

## 14. Conclusion

Bio-cementation is a promising alternative to conventional soil stabilization methods, offering strength improvement, ecological benefits, reduced permeability, and enhanced resistance to deformation and liquefaction. Although laboratory studies have demonstrated significant improvements in mechanical and hydraulic behavior, field application remains challenging due to scale-dependent variables. Continued interdisciplinary research involving microbiology, materials science, and geotechnical engineering will be crucial for advancing this technology.

As global construction practices shift toward sustainability, bio-cementation has the potential to become a mainstream soil improvement technique.

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