

# Microbial-Induced Carbonate Precipitation (MICP): Bio-Cement for Sustainable Infrastructure

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## Abstract

Microbial-Induced Carbonate Precipitation (MICP) has emerged as a promising bio-mediated alternative to conventional cementitious materials that contribute substantially to global carbon emissions. The process exploits the metabolic activity of ureolytic microorganisms, particularly *Sporosarcina pasteurii*, to induce calcium carbonate precipitation within granular matrices. Resultant mineral deposition generates strong interparticle bonding, reduces permeability, and enhances compressive strength under ambient conditions. MICP also promotes autonomous crack sealing, thereby improving structural resilience and durability. This study examines the interaction between microbial activity, physicochemical process variables, and engineering performance. Unlike Portland cement production, which depends on energy-intensive calcination, MICP operates through biologically regulated mineralization pathways with substantially lower embodied energy demand. The technology therefore offers significant potential for sustainable and low-carbon infrastructure development. Several barriers continue to limit field-scale implementation. High bacterial cultivation costs, non-uniform reagent distribution, ammonium accumulation during ureolysis, and uncertain long-term durability under fluctuating environmental stress remain critical concerns. Despite these constraints, advances in microbial biotechnology and geomaterials engineering continue to strengthen the scientific and practical viability of MICP for next-generation sustainable construction systems.

**Keywords:** Microbial-Induced Carbonate Precipitation, Bio-cement, *Sporosarcina pasteurii*, Sustainable Construction, Self-healing Concrete

## 1. Introduction

The global construction industry faces escalating pressure to reduce carbon emissions generated by Portland cement production, which relies on energy-intensive limestone calcination and contributes substantially to industrial greenhouse gas release. Microbial-Induced Carbonate Precipitation (MICP) offers a biologically driven alternative through controlled biomineralization mediated by ureolytic microorganisms. Species such as *Sporosarcina pasteurii* catalyze calcium carbonate precipitation under ambient conditions, eliminating dependence on fossil-fuel-intensive kiln processing. MICP strengthens granular matrices through mineral bridging, decreases permeability, and enhances structural stability.

The technology also supports applications in soil stabilization, erosion mitigation, self-healing concrete and sustainable masonry production. Unlike conventional binders, MICP integrates microbial metabolism with low-energy material synthesis, thereby aligning with circular-economy and low-carbon infrastructure objectives. Current advances in geomicrobiology and bioengineering continue to establish MICP as a scientifically robust platform for resilient and environmentally sustainable construction systems. (Ivanov & Chu, 2008; Omoregie et al., 2020).

## 2. Scientific Basis of MICP

Ureolysis constitutes the predominant biochemical pathway governing Microbial-Induced Carbonate Precipitation (MICP). Urease-producing microorganisms, particularly *Sporosarcina pasteurii*, catalyze urea hydrolysis and generate ammonium and carbonate ions. Rapid alkalization elevates environmental pH and promotes calcium carbonate supersaturation. Carbonate ions subsequently react with dissolved calcium species to produce mineral precipitates within porous matrices. Negatively charged functional groups on bacterial cell surfaces attract calcium ions and create localized nucleation domains for crystal growth. These biologically active interfaces direct mineral deposition around soil particles and microfractures, thereby enhancing interparticle bonding and structural cohesion. Calcite commonly dominates the precipitated mineral phase because of its thermodynamic stability, dense crystal architecture, and superior mechanical performance. Environmental fluctuations, however, may also favor the formation of vaterite or aragonite polymorphs. (Stocks-Fischer et al., 1999; Whiffin et al., 2007; Dhimi et al., 2013).

**Table 1. Key Factors Influencing MICP Performance**

Criterion	Portland Cement	MICP Bio-cement
Processing temperature	~1450°C kiln	Near ambient
CO <sub>2</sub> footprint	High	Lower potential
Setting mechanism	Hydration chemistry	Biom mineralization
Best use cases	Primary structures	Repair, soil, specialty uses

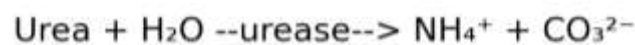
## 3. Microorganisms Used

*Sporosarcina pasteurii* remains the most effective microorganism for Microbial-Induced Carbonate Precipitation (MICP) because of its exceptional urease activity, rapid metabolic kinetics, and strong tolerance to alkaline environments generated during ureolysis. The organism sustains continuous calcium carbonate precipitation under elevated pH conditions, thereby enabling efficient bio-cementation and soil stabilization. Researchers have also investigated several *Bacillus*-related taxa and indigenous soil microorganisms for site-specific MICP applications. Native microbial communities often exhibit superior adaptation to local geochemical and environmental conditions, which enhances treatment stability and survivability. Effective microbial selection requires careful evaluation of enzymatic productivity, growth dynamics, biosafety, cultivation efficiency, and compatibility with substrate chemistry. These microbiological parameters critically determine the durability, uniformity, and field applicability of bio-cemented systems. (Burbank et al., 2012; Tsesarsky et al., 2016).

## 4. Process Parameters

The engineering efficiency of Microbial-Induced Carbonate Precipitation (MICP) depends strongly on

tightly regulated physicochemical and biological parameters. Reagent concentration, microbial distribution, injection strategy, curing duration, temperature, pH, pore geometry, and moisture availability collectively govern calcium carbonate precipitation kinetics and cementation uniformity. Rapid mineral formation near injection zones frequently induces pore blockage and restricts reagent transport into deeper regions of the substrate. Inadequate calcium availability, limited urease activity, or nutrient deficiency suppress biomineralization and weaken mechanical performance. Temperature and pH directly regulate microbial metabolism and enzymatic efficiency, whereas pore architecture controls fluid migration and crystal deposition within the soil matrix. Multi-cycle low-concentration injection strategies generally produce more homogeneous mineral distribution, stronger interparticle bonding, and superior structural performance than single high-dose treatments. Effective optimization of these coupled parameters therefore remains essential for achieving durable, field-applicable bio-cementation systems. (Zhao et al., 2014; Chou et al., 2011; Phillips et al., 2013).



Bacterial cells act as nucleation sites

**Figure 1. Biochemical Pathway of Ureolytic MICP**

## 5. Mechanical and Durability Performance

Biocemented sand exhibits substantial improvements in unconfined compressive strength, stiffness, and overall mechanical integrity following Microbial-Induced Carbonate Precipitation (MICP) treatment. Calcium carbonate deposition within pore spaces promotes dense interparticle bonding and significantly reduces hydraulic conductivity. In cementitious systems, microbially mediated mineralization initiates autonomous sealing of microcracks, thereby restricting the penetration of water, chlorides, and other aggressive chemical agents that accelerate structural deterioration. This biologically driven repair mechanism enhances durability under harsh environmental exposure and mitigates long-term degradation processes associated with conventional concrete infrastructure.

The morphology, distribution, and stability of precipitated calcite crystals critically influence the mechanical response of treated substrates. Uniform biomineralization improves load transfer efficiency across granular interfaces and strengthens resistance against cyclic stress and permeability-driven failure. Current experimental observations also indicate that MICP-treated materials exhibit improved resistance to erosion, freeze-thaw damage, and chemically aggressive environments, underscoring their potential for durable and sustainable infrastructure applications. (Mujah et al., 2019; Rong & Qian, 2012; Van Tittelboom & De Belie, 2013; Wang et al., 2014).

## 6. Sustainability Perspective

Compared with Portland cement, MICP can reduce embodied energy because it operates near ambient temperature. The method may also integrate industrial by-products as nutrient carriers or fillers. For

remote locations or repair works, on-site biological treatment can reduce transportation burdens. However, sustainability must also consider urea sourcing and ammonium management. (Gomez et al., 2018; Karthik & Rao, 2016).

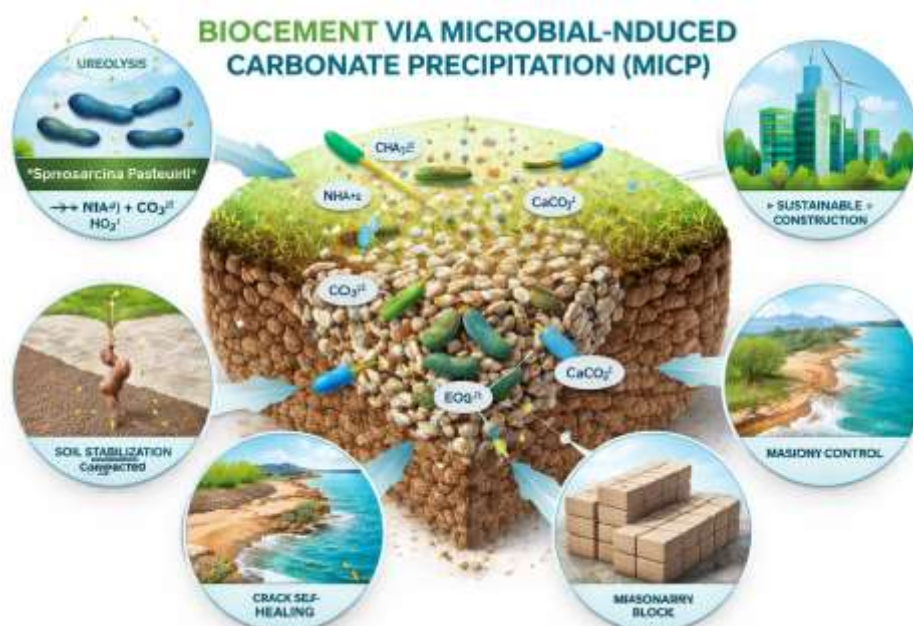
**Table 2. Comparison of Conventional Cement vs MICP**

Factor	Influence	Typical Optimization Goal
Bacterial density	Controls urease activity	Uniform high cell viability
Urea concentration	Carbonate generation	Avoid toxicity/excess ammonia
Calcium source	Crystal yield	Stable calcite precipitation
Temperature	Metabolic rate	25–35°C often favorable
Injection cycles	Distribution uniformity	Multiple low-dose cycles

### 7. Challenges and Limitations

Commercial-scale implementation of Microbial-Induced Carbonate Precipitation (MICP) continues to encounter substantial scientific, economic, and operational constraints. High costs associated with bacterial cultivation, nutrient supplementation, and large-volume reagent preparation limit industrial feasibility. Treatment kinetics also remain considerably slower than those of conventional chemical grouting systems, reducing practical efficiency during field deployment. Heterogeneous distribution of microbial suspensions and cementation solutions frequently generates non-uniform mineral precipitation, which compromises structural consistency and mechanical performance.

Ureolysis-derived ammonium accumulation presents an additional environmental concern that demands stringent management strategies to prevent ecological contamination. Long-term durability under cyclic loading, wet–dry exposure, salinity variation, and freeze–thaw stress remains insufficiently characterized. The absence of standardized design protocols, monitoring methodologies, and quality-control frameworks continues to hinder regulatory acceptance and large-scale engineering integration of MICP-based construction technologies. (Jiang & Soga, 2017; Omoregie et al., 2020).

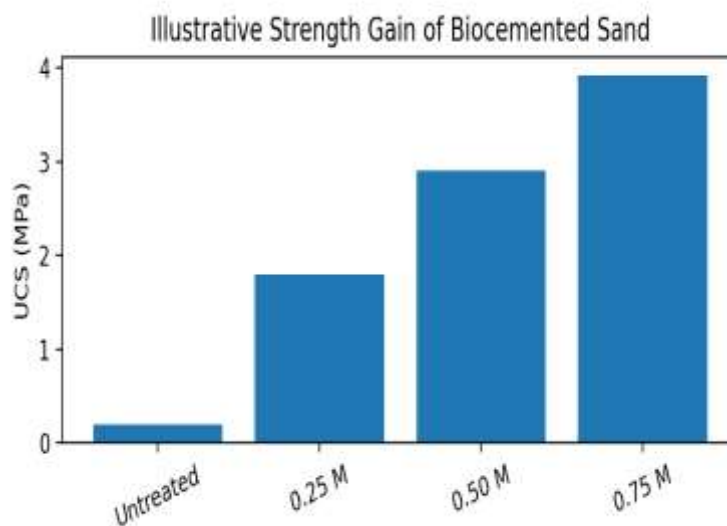


**Figure 2. Illustrative Strength Gain with Treatment Intensity**

## 8. Future Directions

Current investigations into Microbial-Induced Carbonate Precipitation (MICP) increasingly prioritize sustainable biomineralization strategies beyond conventional ureolytic systems. Researchers now explore non-ureolytic metabolic pathways to reduce ammonium generation and improve environmental compatibility. Genetically optimized microbial strains demonstrate enhanced enzymatic efficiency, controlled mineral precipitation, and improved durability under variable field conditions. Recycled calcium substrates derived from industrial by-products also offer economically viable and resource-efficient alternatives for large-scale bio-cementation processes.

Advanced digital monitoring systems and automated treatment controls continue to improve spatial precision, reagent distribution, and process reproducibility during field implementation. Hybrid composites integrating MICP with fiber-reinforced or geopolymer matrices exhibit superior mechanical resilience, autonomous crack-healing capacity, and reduced carbon intensity. These multidisciplinary developments collectively strengthen the potential of MICP as a next-generation platform for adaptive, low-carbon, and biologically engineered infrastructure systems. (Achal & Mukherjee, 2015; Gomez et al., 2018).



## 9. Conclusion

Microbial-Induced Carbonate Precipitation (MICP) has evolved from a laboratory-scale biomineralization concept into a scientifically credible technology for sustainable construction and geotechnical engineering. The process converts microbial metabolic activity into stable calcium carbonate mineral bonding, thereby improving soil strength, reducing permeability, sealing structural cracks, and generating bio-based construction materials with reduced carbon intensity. Unlike conventional cementitious systems, MICP operates through biologically regulated mineralization under ambient conditions, significantly lowering energy demand and environmental impact. Its integration with green infrastructure strategies highlights the growing importance of microbial technologies in resilient and low-carbon construction systems. (Ivanov & Chu, 2008; DeJong et al., 2006).

## References

1. Achal, V., & Mukherjee, A. (2015). A review of microbial precipitation for sustainable construction design. *Frontiers in Microbiology*, 6, 396.

2. Anbu, P., Kang, C. H., Shin, Y. J., & So, J. S. (2016). Formations of calcium carbonate minerals by bacteria and its multiple applications. *SpringerPlus*, 5(1), 250.
3. Burbank, M. B., Weaver, T. J., Williams, B. C., & Crawford, R. L. (2012). Ureolytic microbial-induced calcium carbonate precipitation. *Geomicrobiology Journal*, 29(4), 387–395.
4. Chou, C. W., Seagren, E. A., Aydilek, A. H., & Lai, M. (2011). Biocalcification of sand through ureolysis. *Journal of Geotechnical and Geoenvironmental Engineering*, 137(12), 1179–1189.
5. DeJong, J. T., Fritzges, M. B., & Nüsslein, K. (2006). Microbially induced cementation to control sand response to undrained shear. *Journal of Geotechnical and Geoenvironmental Engineering*, 132(11), 1381–1392.
6. Dhami, N. K., Reddy, M. S., & Mukherjee, A. (2013). Biomineralization of calcium carbonate polymorphs by bacterial strains. *Journal of Microbiology and Biotechnology*, 23(5), 707–714.
7. Gomez, M. G., Graddy, C. M., DeJong, J. T., & Nelson, D. C. (2018). Biogeochemical changes during microbial-induced calcium carbonate precipitation. *Geotextiles and Geomembranes*, 46(1), 23–36.
8. Ivanov, V., & Chu, J. (2008). Applications of microorganisms to geotechnical engineering for bioclogging and biocementation of soil. *Reviews in Environmental Science and Bio/Technology*, 7(2), 139–153.
9. Jiang, N. J., & Soga, K. (2017). The use of microbial-induced calcite precipitation in civil engineering. *Frontiers in Built Environment*, 3, 41.
10. Karthik, S., & Rao, K. S. (2016). Bio-cementation as a sustainable technique for soil improvement. *Indian Geotechnical Journal*, 46(4), 415–422.
11. Mujah, D., Cheng, L., & Shahin, M. A. (2019). Microstructural and mechanical characteristics of biocemented sand. *Crystals*, 9(11), 541.
12. Omoregie, A. I., et al. (2020). Integrating biotechnology into construction engineering. *Biotechnology Reports*, 27, e00508.
13. Phillips, A. J., et al. (2013). Engineered applications of ureolytic microbial calcium carbonate precipitation. *Environmental Science & Technology*, 47(24), 14209–14217.
14. Rong, H., & Qian, C. X. (2012). Recovery of microstructure and mechanical properties of self-healing concrete. *Construction and Building Materials*, 34, 67–72.
15. Stocks-Fischer, S., Galinat, J. K., & Bang, S. S. (1999). Microbiological precipitation of CaCO<sub>3</sub>. *Soil Biology and Biochemistry*, 31(11), 1563–1571.
16. Tsesarsky, M., Gat, D., & Ronen, Z. (2016). Biological aspects of microbial-induced calcite precipitation. *Environmental Geotechnics*, 5(2), 69–78.
17. Van Tittelboom, K., & De Belie, N. (2013). Self-healing in cementitious materials—A review. *Materials*, 6(6), 2182–2217.
18. Wang, J. Y., et al. (2014). Use of silica gel or polyurethane as a carrier for bacteria in self-healing concrete. *Construction and Building Materials*, 54, 192–199.
19. Whiffin, V. S., van Paassen, L. A., & Harkes, M. P. (2007). Microbial carbonate precipitation as a soil improvement technique. *Geomicrobiology Journal*, 24(5), 417–423.
20. Zhao, Q., et al. (2014). Factors affecting the strength of biocemented sand. *Journal of Geotechnical and Geoenvironmental Engineering*, 140(8), 04014038.