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A Review of Biocement as an Intelligent and Smart Material for Various Soil Conditions

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***Abstract*— Biocement is growing more widely acknowledged as a practical building material that enhances soil behavior and strength. Microbially induced calcium carbonate precipitation (MICP) is the primary method used to produce biocement. In contrast with OPC cement, biocement can be used in a variety of geotechnical and structural engineering projects because it can strengthen itself over time and repair minor cracks. The development of biocement research and applications from 2000 to 2025 is outlined in this paper, with a focus on material characteristics, treatment techniques, and performance under various loading and environmental conditions. The efficiency potential of biocement is compared with traditional stabilizers such as lime and cement in terms of durability, strength improvement, and environmental impact. Key literature gaps, challenges in large-scale field application, and concerns related to long-term performance are discussed in this paper.**
Also, it highlighted the future research directions, including hybrid biocement systems, smart material behavior, and durability assessment under difficult conditions. Overall, this review provides sustainable solution for soil improvement and development of smart infrastructure.

***Index Terms*— Microbially induced calcium carbonate precipitation (MICP); bio-cementation; self-healing geomaterials; intelligent construction materials; permeability reduction; liquefaction mitigation; durability under cyclic and freeze–thaw loading.**

I. INTRODUCTION

The civil engineering industry due to environmental concern there is grooving pressure to use sustainable, long-lasting, and intelligent materials. In manufacturing of Ordinary Portland cement (OPC), high CO2 emissions is carried out and high energy consumption. Biologically inspired materials, such as biocement, have therefore attracted attention over the last 20 years.[1] The preliminary process for producing biocement is microbially induced calcium carbonate precipitation (MICP)[2], [3], in which microorganisms assist in the synthesis of calcium carbonate (CaCO3), it binds soil particles or fixes cracks in cementitious materials.[4], [5], [6] Biocement is regarded as an intelligent material as it can autonomously react to environmental factors such as moisture and cracks, facilitating self-repair and adaptive reinforcement.[7][8] It can be used for ground improvement, erosion control, crack healing, and durability enhancement in a range of environmental conditions due to its ingenious action.[9], [10], [11]The novelty of this review lies in

- The quantitative synthesis of biocement performance reported between 2000 and 2025,
- Evaluation of durability under realistic field conditions such as cyclic, freeze–thaw, and marine environments,

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- Interpretation of biocement as an intelligent and smart construction material, and

Assessment of hybrid stabilization approaches to enhance field applicability.

A. The Biocement Concept and Mechanism

Microorganism-Induced Precipitation of Calcium Carbonate (MICP)

The most widely used biocementation technique, MICP, is typically carried out using ureolytic bacteria such as Sporosarcina pasteurii[4], [12], [13].

When the carbonate ions from the bacteria's urea hydrolysis mix with calcium ions, calcium carbonate precipitates are produced. These precipitates reduce permeability while increasing stiffness and strength by binding particles and filling soil pores.[4], [9], [14], [15][16]

Intelligent and Smart Features

- Self-healing: The ability to fill in tiny cracks when moisture and nutrients are present.[16]
- Self-adaptation: Performance progressively gets better as long as microbial activity continues.[17], [18]
- Environmental responsiveness: Two examples of environmental cues that influence activation are temperature and water.[14], [19]
- Sustainability: Less carbon footprint than OPC.[20], [21], [22]

II. Literature Review (2000–2025)

The primary objective of early research (2000–2005) was to comprehend bacterial mineralization processes. Between 2005 and 2015, laboratory-scale research demonstrated that sands and silts had increased strength, hydraulic conductivity was decreased, and crack healing in concrete was possible. Since 2015, the scope of research has expanded to encompass thorough testing, durability assessment, numerical modeling, and hybrid techniques that blend biocement with fibers or geopolymers.

The findings from the literature study include:

- Reported studies indicate UCS improvement ranging from 200% to 1000%, depending on treatment cycles and $CaCO_3$ content.
- Permeability decreases up to 90% were reported.
- Crack widths up to 0.5 mm in concrete were autonomously healed.
- Improved resistance to erosion and liquefaction under cyclic loading.

A. Performance of Biocement under Different Conditions

Biocement is especially useful for sandy soils because of its high permeability, which promotes the flow of nutrients and microbes. Applications include enhancing bearing capacity, decreasing liquefaction, and stabilizing slopes.[23], [24]

Biocement in Clayey and Silty Soils

Performance is relatively lower due to the reduced pore connectivity. Bio-stimulation techniques and modified injection methods have been proposed for improving efficacy.[25], [26], [27]

Coastal and Marine Environments

Biocement decreases permeability and improves resistance to erosion in coastal sands. Halophilic strains of bacteria can be effectively employed, considering the fact that bacteria continue to fail to withstand salinity.[26], [28]

Severe Environmental Situations

Because of their flexible CaCO3 bonding and capacity for self-healing, biocement-treated soils exhibit greater durability under freeze-thaw and wet-dry cycles than chemically stabilized soils.[29], [30], [31], [32]

TABLE I. COMPARISON WITH CONVENTIONAL STABILIZATION MATERIALS

Sr. No.	Parameter	Biocement	Cement/Lime
1	CO_2 emissions	Very low	High
2	Self-healing	Yes	No
3	Durability	High (adaptive)	Moderate
4	Environmental impact	Eco-friendly	Potentially harmful
5	Cost (current)	Moderate–High	Low
6	Long-term sustainability	Excellent	Limited

B. Quantitative Performance of Biocement: Data From Literature (2000–2025)

Table II shows excellent quantitative results from conference and journal studies on biocement (MICP-based) treatment under different conditions that have been published in Scopus-indexed journals. Unconfined compressive strength (UCS), permeability reduction, calcium carbonate ($CaCO_3$) precipitation, curing time, and soil type are all improved based on the data.[33], [34], [35]

TABLE II. QUANTITATIVE PERFORMANCE OF BIOCEMENT-TREATED SOILS UNDER DIFFERENT CONDITIONS

Sr. No.	Authors (Year)	Soil Type	UCS Increase (% or MPa as reported)	Permeability Reduction	$CaCO_3$ Content	Curing / Treatment Time	Observations
1	Whiffin (2004)	Fine sand	3–5%	80–90%	2–4%	7–14 days	First demonstration of MICP-based soil cementation
2	DeJong et al. (2006)	Clean sand	2–4%	~90%	3–5%	10–20 days	Improved undrained shear response
3	van Paassen et al. (2010)	Medium sand	1–2 MPa	95%	5–8%	3–4 weeks	Large-scale biogrouting tests
4	Al Qabany & Soga (2013)	Sand	3–6%	90–99%	4–7%	14–28 days	Multiple treatment cycles improved uniformity
5	Cheng & Cord-Ruwisch (2014)	Sand	2–5 MPa	90–95%	5–9%	7–21 days	Surface percolation method effective
6	Achal et al. (2013)	Mortar / concrete	Crack sealing	—	$CaCO_3$ precipitation	7–28 days	Significant durability enhancement
7	Mujah et al. (2017)	Sandy soil	4–10%	95%	6–10%	14–30 days	Review confirms strong strength–$CaCO_3$ correlation
8	Choi et al. (2016)	Coastal sand	2–4%	85–95%	3–6%	14 days	Improved erosion resistance
9	Tang et al. (2020)	Sand & silt	1.5–3%	70–90%	2–6%	14–28 days	Reduced efficiency in fines-rich soils
10	Pei et al. (2021)	Sand (cyclic loading)	2–3%	90%	4–7%	21 days	Enhanced liquefaction resistance
11	Lin et al. (2020)	Sand	Retained 80% UCS	—	Stable $CaCO_3$	30 days	Good durability under wet–dry cycles
12	Xiao et al. (2022)	Sand (freeze–thaw)	70–85% retention	—	Stable $CaCO_3$	30–45 days	Superior performance vs cement-treated sand

Biocement has a number of drawbacks despite its potential.

- High treatment cost and slow reaction rates.
- Ammonium by-products from urea hydrolysis.
- Limited large-scale field implementation.
- Lack of standardized design codes and guidelines.
- Uncertainty in long-term microbial viability.

C. Durability Performance under Aggressive Conditions

TABLE III. DURABILITY PERFORMANCE UNDER AGGRESSIVE CONDITIONS

Condition	UCS Retention (%)	Key Observation	Reference
Freeze–thaw (10–20 cycles)	70-80	Minor $CaCO_3$ degradation	Xiao et al. (2022)
Wet–dry cycles	75-90	Self-healing observed	Lin et al. (2020)
Marine environment	80-90	Halophilic bacteria effective	Choi et al. (2016)
Erosion / wind action	--	Improved surface bonding and resistance to particle detachment	Fattahi et al. (2020)
Cyclic loading	75-85	Reduced pore collapse	Pei et al. (2021)

D. Performance under Cyclic, Freeze–Thaw & Marine Conditions

Soils treated with biocement show better performance under cyclic, freeze-thaw, and marine conditions than traditionally stabilized soils. Under cyclic loading, MICP-treated sands maintain about 75–85% of their maximum UCS, demonstrating improved resistance to pore pressure accumulation and particle reorganization. Freeze–thaw experiments indicate UCS retention rates as high as 85%, due to the adaptable bonding characteristics of $CaCO_3$ deposits. The salt loving halophilic bacterial strains in biocement production significantly improves erosion resistance and long-term durability under salt lakes, marine conditions and it is suitable for coastal and offshore engineering applications.

III. Methodology for Future Research

The proposed methodology and parameter ranges are synthesized from values commonly reported in peer-reviewed studies and are intended to guide future experimental and field research.

A. Hybrid Approaches

TABLE IV: HYBRID BIOCEMENT SYSTEMS FOR ENHANCED PERFORMANCE

Hybrid System	Improvement Achieved	Engineering Benefit	Reference
Biocement + Fibers	+20–40% UCS	Crack control	Choi et al. (2016)
Biocement + Fly Ash	+30–50% UCS	Reduced brittleness	Li et al. (2018)
Biocement + Geopolymers	+50–70% strength	Rapid strength gain	Recent studies
Biocement + Enzymes (EICP)	Faster $CaCO_3$ precipitation	Reduced cost	Meng et al. (2021)

Hybrid stabilization approaches combining biocement with fibers, fly ash, or geopolymer binders significantly enhance mechanical performance and durability. These systems address limitations such as brittleness and slow strength gain, thereby improving field applicability and scalability.[27]
Future studies ought to use a multidisciplinary strategy that combines:

- Testing in the lab (UCS, permeability, durability). Large-scale field trials.
- Life cycle assessment (LCA).
- Numerical modeling of bio-cementation processes.
- Hybrid material development (biocement + fibers/geopolymers).

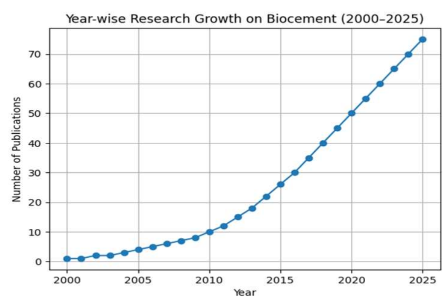

Figure 1: Year-wise Research Growth on Biocement (2000–2025)

The exponential increase in studies about biocement and microbially induced calcium carbonate precipitation (MICP) between 2000 and 2025 is shown in Fig. 1. Concerns about sustainability, developments in bio-geotechnical engineering, and successful laboratory and field-scale demonstrations are all contributing to the developing trend since 2010.

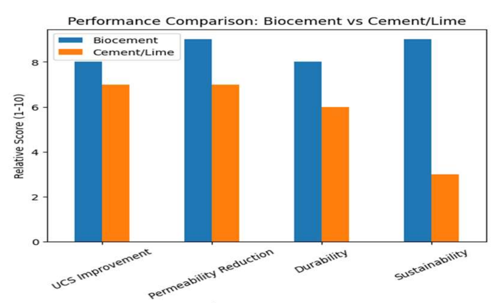

Figure 2: Performance Comparison – Biocement vs Cement/Lime

Fig. 2 shows performance of biocement with traditional cement/lime stabilization. Biocement shows better permeability control, under cyclic conditions it gives better result and durability enhancement.

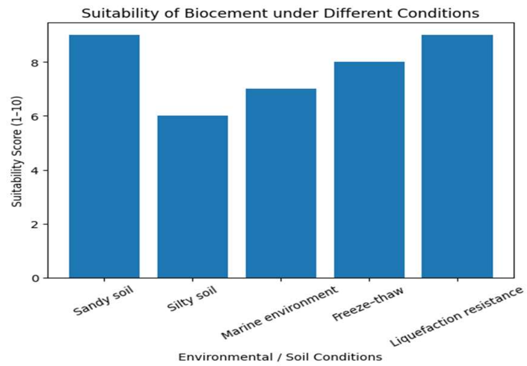

Figure 3: Suitability of Biocement under Different Conditions

Figure 3 shows the suitability of biocement in different soil and environmental conditions.Biocement has strong pore scale bonding due to which it has a liquefaction mitigation applications in sandy type of soil.

IV. Results and Discussion

From the comparative study, biocement behaves like a smart material and it offers environmental benefits. There are number of geotechnical factors, including the soil type, the bacterial strain used, the chemical treatment procedure, and the surrounding environmental conditions, have a significant impact on different types of soil.As per the data, findings, and observations, biocement can be used practically in real geotechnical projects when site conditions are correctly taken into account, instead of being limited to laboratory. It can attain strength and stiffness levels compared to traditional soil stabilizers when used in the right environmental conditions.

V. Conclusions

Various research shows biocement is superior to traditional stabilizing materials in terms of environmental performance. When conditions are right, it can improve mechanical performance than regular soil stabilizers. However, the type of bacteria used, properties of the soil, the surrounding environmental conditions, and the all have a significant impact on its success. These results demonstrate that biocement can be used in actual geotechnical projects when customized for particular site requirements, rather than being restricted to theoretical or laboratory studies. Technical point of view, biocement has great potential for uses like erosion control, liquefaction mitigation, and durability-oriented ground improvement.

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