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Biocementation via Microbially Induced Calcite Precipitation (MICP): A Sustainable Approach to Eco-Friendly Soil Stabilization

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***Abstract*—Microbially induced calcite precipitation (MICP) is a biological method for improving ground in which ureolytic microorganisms, often Sporosarcina pasteurii, break down urea. This reaction produces carbonate species that combine with calcium ions to form calcium carbonate ($CaCO_3$) in the soil pores. The calcite coats grains and forms bridges at points of contact, potentially increasing strength and stiffness while reducing permeability and erosion. This review considers MICP as an alternative to conventional cement- and lime-based stabilization, whose production can require substantial energy and generate carbon dioxide emissions. It outlines the underlying chemistry, related biocementation methods, laboratory and field procedures, tests for treated soil, factors affecting performance, applications, indicative laboratory costs and comparison with conventional techniques. The literature identifies several possible benefits, including a lower environmental burden in some applications and the ability to treat selected zones of existing ground. However, uneven precipitation, ammonia generation, treatment time, chemical demand and limited field-scale evidence remain important concerns. MICP is therefore most suitable at present for targeted and specialised applications. Further optimisation, durability assessment and well-monitored field trials are needed before it can be adopted more widely.**

***Keywords*—Biocementation, Calcium carbonate, Enzyme-induced calcite precipitation, Erosion control, Ground improvement, Microbially induced calcite precipitation, Soil stabilization, *Sporosarcina pasteurii*, Urease**

I. Introduction

Weak, loose and highly permeable soils can create problems for civil engineering works. Depending on the site and loading, they may undergo excessive settlement, lose shear strength beneath foundations or slopes, erode under flowing water or wind, or become less stable during earthquake shaking. Ground improvement is used to address these risks. Cement, lime and other additives are common choices, but their production and use can consume considerable energy and contribute to carbon dioxide emissions [1], [3].

Biocementation is being studied as an alternative that uses biological activity to form a binding mineral within the soil. One of the best-known approaches is microbially induced calcite precipitation (MICP) [8], [9]. Microorganisms that produce urease are introduced into the soil; the enzyme breaks down urea and creates carbonate species. These react with available calcium ions to form calcium carbonate crystals. When the crystals develop around grain surfaces and contacts, they can strengthen the connections between particles and reduce the open pore space.

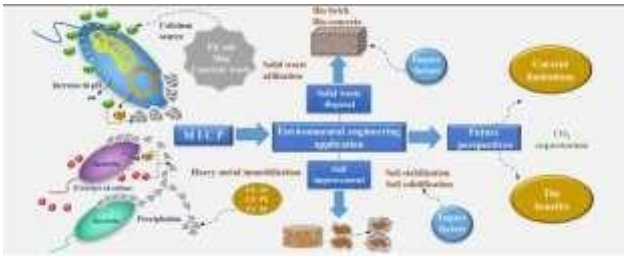


Figure 1. Overview of microbially induced calcite precipitation (MICP), its environmental engineering applications, impact factors and future perspectives.

Since MICP forms its binding mineral within the soil under relatively mild conditions, researchers have examined its use in soil stabilization, erosion reduction, bearing-capacity improvement, liquefaction mitigation, crack sealing and permeability control [2], [4], [6]. Its performance is not automatic, however. It depends on the microorganisms, nutrient supply, urea and calcium concentrations, temperature, pH, soil properties and the way calcite is distributed. These variables need to be controlled if the treatment is to produce consistent results.

This paper brings together the seminar material and the published studies cited in it to provide an overview of biocementation for civil engineering readers. It explains the basic mechanism, describes laboratory and field application procedures, reviews the properties used to assess treated soil, and considers the method's practical benefits and limitations. It also identifies issues that require further investigation before the technique can be used more widely.

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II. Need For The Study And Objectives

Conventional ground improvement often relies on cement, lime or other chemical additives. Although these materials can improve soil performance, their environmental effects make it worthwhile to investigate alternatives. MICP uses biological activity to improve the engineering behaviour of soil and may reduce reliance on cement-based treatment. Before its suitability can be judged for a project, the process, application methods, benefits and limitations need to be understood.

The objectives of the study are:

- To understand the mechanism of biocementation and the role of microorganisms in inducing calcite precipitation within soil pores.
- To assess how calcite formation can improve soil bearing capacity, strength, stiffness and stability.
- To examine how precipitation reduces the void spaces between soil particles and hence soil permeability, and how it increases resistance to erosion.
- To identify the treatment parameters, such as bacterial concentration, calcium source, chemical concentration and curing duration, that influence effectiveness.
- To review applications of biocementation in geotechnical engineering, including soil stabilization, foundation improvement, slope protection and erosion control.
- To evaluate environmental benefits, cost, practical limitations and sustainability in comparison with cement and lime stabilization.

III. Literature Review

Research on MICP has expanded from the chemistry of calcite formation to its performance in engineering applications and the challenges of moving from laboratory tests to field use. Recent reviews discuss the mechanism and prospects for field-scale deployment [1], treatment methods and soil properties [3], and applications in soil stabilization [2], low-cohesive soils [4], unsaturated soils [10] and erosion control [6], [7]. Other work examines ways to make MICP more environmentally efficient, particularly by addressing ammonia production [5].

Table I brings together studies discussed in the seminar. Their topics include the use of S. pasteurii in sandy, silty and clayey soils; treatment of cadmium-contaminated soil; the relationship between urease activity and calcite formation; and the durability of treated specimens exposed to repeated wetting and drying in seawater. The studies also highlight recurring practical concerns, including bacterial transport, uniformity of treatment, long-term performance and field implementation.

Cheng and Cord-Ruwisch [11], for example, investigated a percolation-based method intended to improve the distribution of calcite through soil.

TABLE I
Summary of Studies Presented in the Seminar

Researcher and year	Focus / key finding
Jumbo-Flores et al. (2026)	Use of *Sporosarcina pasteurii* for improving sandy, silty and clayey soils.
Wang et al. (2025)	*S. pasteurii*-based MICP for solidification of cadmium-contaminated soil.
Lapierre and Huber (2024)	Urease activity directly affects urea hydrolysis and therefore calcium carbonate precipitation.
Rawat and Satyam (2024)	Treated specimens subjected to repeated wetting–drying cycles under seawater conditions.
Fu et al. (2023)	MICP improves soil strength; treatment uniformity, bacterial transport, long-term performance and field implementation are major challenges.
Cheng and Cord-Ruwisch (2012) [11]	Improved MICP treatment approach; uniform calcite distribution in soil investigated.

Overall, the studies point to three broad conclusions. The urease-driven process can be reproduced under laboratory conditions, but the degree of improvement varies with soil type, calcite content and the location of the precipitate. Achieving a similar distribution in the field is more difficult because bacteria and treatment solutions do not necessarily travel evenly through natural ground [1], [3], [11].

IV. Ground Improvement Methods

Ground improvement is used when the natural soil cannot provide the required support or resist the environmental conditions expected at a site. Methods are commonly grouped according to how they improve the ground:

- *Mechanical methods:* compaction, dynamic compaction and vibro-compaction, which densify the soil.
- *Grouting methods:* cement grouting, chemical grouting and jet grouting, which fill pores or create cemented zones.
- *Reinforcement methods:* geotextiles, geogrids and soil nails, which add tensile resistance.
- *Drainage methods:* prefabricated vertical drains (PVD) and sand drains, which accelerate consolidation.
- *Chemical stabilization:* lime, cement and fly-ash stabilization, which alter soil properties through chemical reaction.
- *Inclusion methods:* stone columns, sand columns and lime piles, which introduce stiffer elements into the ground.

International Journal of Recent Development in Engineering and Technology
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- *Biological methods:* MICP, sulphate reduction and denitrification, which use microbial activity to change the soil.



Figure 2. Common ground-improvement techniques, from mechanical methods to biocementation (MICP), and the conditions in which they are applied.

Biocementation is of interest because it can form calcium carbonate directly within soil pores rather than relying entirely on manufactured binders. The mineral acts as a bond between neighbouring grains. Unlike methods that require densification equipment or mixing large amounts of cement into the ground, MICP solutions can potentially be delivered through the existing pore network. This offers a way to treat selected areas with limited excavation, although the practicality depends on the soil and the delivery method [2], [3].

V. Fundamentals Of Biocementation

A. Main Components

Ureolytic MICP requires three main components:

- Microorganisms. Urease-producing bacteria, including Sporosarcina pasteurii, help break down urea and create conditions that favour calcium carbonate precipitation.
- Urea and a calcium source. Urea is the material acted on by urease. Calcium chloride ($CaCl_2$) is one commonly used source of the calcium ions needed to form calcium carbonate.
- Soil and water. The soil provides the pore space and grain surfaces where calcite can form. Water supports microbial activity and carries the treatment solutions through the ground.

B. The Biocementation Process

Biocementation uses microorganisms to encourage mineral formation between soil particles. In MICP, the principal binding mineral is calcite. First, bacteria are introduced and attach to grain surfaces. A solution containing urea and calcium is then supplied. Urease breaks down the urea, increasing alkalinity and producing carbonate species. Calcium ions react with these species, and calcium carbonate forms on grain surfaces and around points of contact. Repeating the treatment can increase the amount of precipitate and strengthen the particle bonds [8].

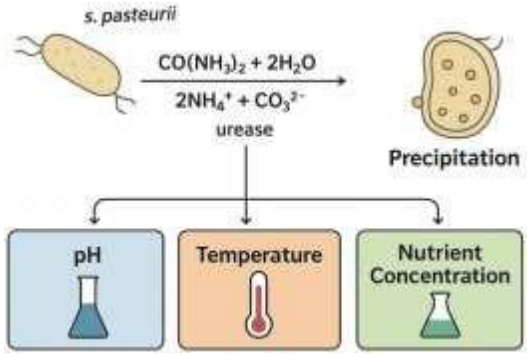


Figure 3. Ureolytic mechanism of MICP: urease from *S. pasteurii* hydrolyses urea, and pH, temperature and nutrient concentration influence the reaction.

Calcite formation can change several soil properties. Bonds between grains help loose soil resist movement, while crystals occupying part of the pore space can restrict water flow. The treatment may also make particles less likely to be detached by flowing water. The extent of each benefit depends not only on the quantity of calcite but also on where it forms in relation to the contacts between grains [4], [8].

C. Types and Mechanisms of Biocementation

Three related approaches are recognised.

- Microbially induced calcite precipitation (MICP). This widely studied method uses microorganisms to promote calcium carbonate formation. In the ureolytic form, bacteria produce urease, which catalyses urea hydrolysis. The resulting chemical conditions allow carbonate species to react with calcium ions and precipitate as calcite.

International Journal of Recent Development in Engineering and Technology
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- Enzyme-induced calcite precipitation (EICP). EICP uses urease directly rather than introducing living bacterial cells into the soil. It is being investigated as an alternative where bacterial transport or survival may limit the effectiveness of MICP [7].
- Biologically induced mineral precipitation. Other microbial processes can change local chemical conditions and encourage minerals to form. The mineral produced depends on the biological pathway and the ions present. These approaches have been explored for ground improvement, contaminant immobilisation and environmental remediation.

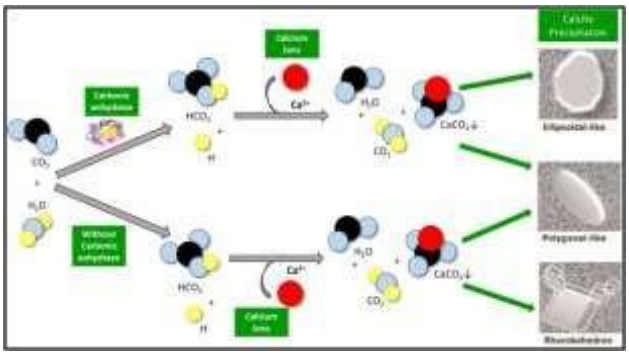


Figure 4. Role of carbonic anhydrase in carbonate formation and the resulting calcite crystal forms (ellipsoidal, polygonal and rhombohedral).

D. Carbonic Anhydrase and Crystal Morphology

Carbonic anhydrase accelerates the reversible conversion of carbon dioxide and water into bicarbonate. In some bacteria, it may work alongside urease and increase the supply of bicarbonate and carbonate; it has also been investigated as a separate route to calcium carbonate formation. As illustrated in Fig. 4, calcium carbonate can form with or without this enzyme, and the crystals may have ellipsoidal, polygonal or rhombohedral shapes. Crystal shape and placement affect how well the precipitate occupies pores and attaches to soil grains, influencing the resulting cementation [3], [8].

E. Chemical Reactions Involved in MICP

Ureolytic MICP involves a sequence of chemical reactions. First, bacterial urease catalyses the breakdown of urea, producing ammonia and carbon dioxide:

$$CO(NH_2)_2 + H_2O \rightarrow 2NH_3 + CO_2 \qquad (1)$$

Ammonia reacts with water to form ammonium and hydroxide ions. The hydroxide raises the pH of the solution:

$$NH_3 + H_2O \rightleftharpoons NH_4^+ + OH^- \qquad (2)$$

Carbon dioxide dissolves in water and forms carbonic acid, which can then dissociate to bicarbonate:

$$CO_2 + H_2O \rightleftharpoons H_2CO_3 \qquad (3)$$

$$H_2CO_3 \rightleftharpoons HCO_3^- + H^+ \qquad (4)$$

Bicarbonate can dissociate further to form carbonate. The rise in pH caused by urea hydrolysis favours the presence of carbonate ions:

$$HCO_3^- \rightleftharpoons CO_3^{2-} + H^+ \qquad (5)$$

In the final step, calcium ions supplied by a reagent such as calcium chloride react with carbonate ions to form solid calcium carbonate:

$$Ca^{2+} + CO_3^{2-} \rightarrow CaCO_3 \downarrow \qquad (6)$$

The bacteria do not provide the mineral directly. Instead, their activity creates alkaline conditions and carbonate species around the soil grains, allowing calcium carbonate to precipitate. Reaction (2) also explains why ammonium is produced when urea is used, making by-product management an important environmental consideration [5].

VI. Microorganisms Used In Biocementation

Different microorganisms can promote carbonate precipitation. They are often described as ureolytic or non-ureolytic according to whether urea hydrolysis is part of the process. Table II lists examples included in the seminar.

TABLE II
Examples of Microorganisms Used in Biocementation

Microorganism	Type	Category
Sporosarcina pasteurii	Bacteria	Ureolytic
Bacillus sphaericus	Bacteria	Ureolytic
Pseudomonas spp.	Bacteria	Non-ureolytic
Aspergillus niger	Fungi	Non-ureolytic

Sporosarcina pasteurii is frequently selected for laboratory MICP because it produces urease efficiently. The enzyme speeds up urea hydrolysis, helping calcium carbonate to form when calcium ions are available [8], [9]. Ureolytic bacteria can give effective and relatively predictable results, but the process produces ammonia. Some non-ureolytic organisms, including certain Pseudomonas species and fungi such as Aspergillus niger, are being studied for alternative pathways that may reduce this concern [5]. When selecting an organism, researchers need to consider its activity, tolerance of the soil environment, safety and ability to move through and attach to soil pores.

Figure 5 summarises the main stages of ureolytic biocementation. Urease-producing bacteria promote urea breakdown, which increases alkalinity and makes carbonate available.

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When calcium is present, calcium carbonate precipitates and bonds neighbouring soil grains, potentially improving the soil's engineering properties.

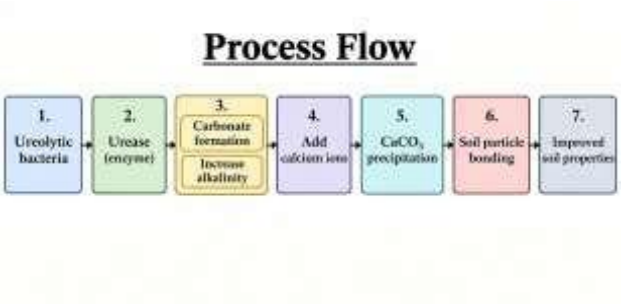


Figure 5. Process flow of MICP: ureolytic bacteria, urease, carbonate formation, addition of calcium, $CaCO_3$ precipitation, particle bonding and improved soil properties.

VII. Methodology And Experimental Procedure

A. Materials Required

A laboratory study of MICP requires soil, microorganisms, chemical solutions and suitable laboratory equipment. The main materials are listed below.

- Ureolytic bacteria: Sporosarcina pasteurii is commonly used because it produces the urease enzyme needed for the reaction.
- Urea solution: provides the substrate for urease. Its breakdown produces dissolved inorganic carbon species and ammonia.
- Calcium chloride solution: supplies calcium ions that combine with carbonate to form calcium carbonate within the soil pores.
- Water and bacterial growth medium: water is used to prepare the suspensions and solutions, while the growth medium supplies nutrients for bacterial growth and activity.

B. Working Principle

The working principle follows the reactions described earlier. Ureolytic bacteria are introduced into the soil, where their urease breaks down urea. This produces ammonia and dissolved inorganic carbon and raises alkalinity. If calcium ions are available and the chemical conditions are suitable, calcium carbonate precipitates on grain surfaces and within the pores. The sequence is illustrated in Fig. 6.

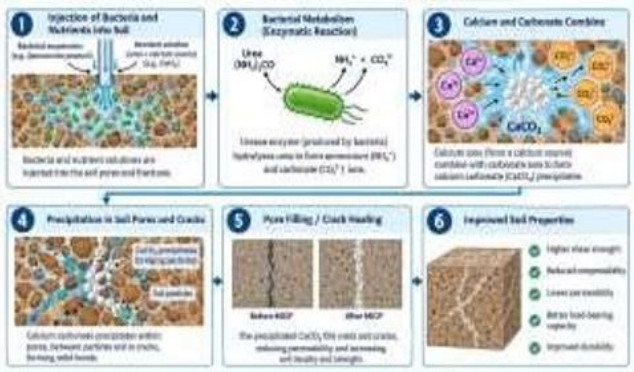


Figure 6. Step-by-step biological and chemical process of MICP, from injection of bacteria and nutrients to improved soil properties.

C. Laboratory Procedure

The laboratory procedure can be organised into the following stages, shown schematically in Fig. 7.

- Collection and preparation of soil samples. Collect soil from the selected site and determine its physical characteristics. Dry it if necessary, then sieve it to remove unwanted particles and impurities.
- Preparation of bacterial culture and cementation solution. Grow a suitable ureolytic culture, such as S. pasteurii, in an appropriate medium. Prepare the cementation solution separately using urea and a calcium source, such as calcium chloride, at the selected concentrations.
- Treatment of soil samples. Apply the bacterial suspension so that microorganisms enter the soil pores. Add the cementation solution using a suitable mixing or injection method. Bacterial activity then promotes calcium carbonate precipitation.
- Curing. Keep the specimens under controlled conditions for the selected curing period. This allows crystals to develop and form bonds between particles. Use the same curing conditions for each specimen so that the results can be compared reliably.
- Untreated control samples. Prepare a separate set of specimens without bacterial or cementation treatment. Test both sets and compare their strength, permeability and other relevant engineering properties.

International Journal of Recent Development in Engineering and Technology
Website: www.ijrdet.com (ISSN 2347-6435 (Online) Volume 15, Issue 10, October 2026)

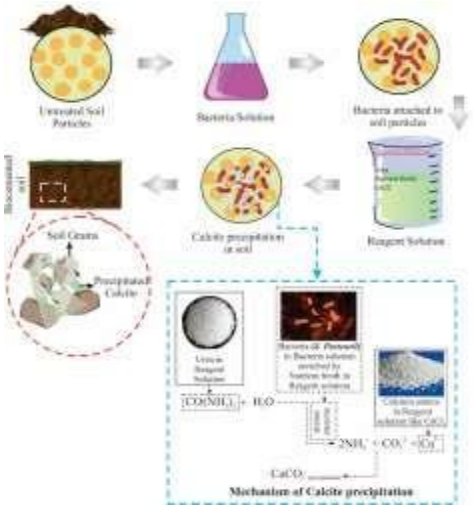


Figure 7. Schematic illustration of the MICP process: untreated soil, bacteria attachment, reagent solution, calcite precipitation and biocemented soil.

D. Field Construction Procedure

Field treatment follows the same biological and chemical principles as laboratory work, but it must account for actual site conditions. The procedure described in the seminar is summarised below.

- *Site investigation:* determine soil type, density, permeability, groundwater level and groundwater flow.
- *Site preparation:* prepare the treatment area and install injection pipes or wells to the depth required by the site investigation and project objectives.
- *Introduction of bacteria:* deliver a suitable urease-producing bacterial suspension through the planned injection points.
- *Bacterial attachment:* allow time for the bacteria to spread and attach to soil grains; the procedure described here allows approximately 6–24 hours.
- *Injection of cementation solution:* introduce a solution containing urea and a calcium source, commonly calcium chloride.
- *Calcite formation:* bacterial activity breaks down urea and creates conditions in which calcium carbonate can form.
- *Bonding of soil particles:* the precipitated crystals occupy pore spaces and connect adjacent grains, which can increase strength and stiffness.
- *Repeated treatment:* carry out additional injection cycles as needed. The number and spacing of cycles depend on the soil, site conditions and target improvement.
- *Curing:* allow the treated ground to cure for approximately 3–7 days so that precipitation and bonding can continue.
- *Testing and quality control:* assess the treated soil using suitable laboratory and field tests, as described in the following section.

Allowing bacteria to attach before injecting the cementation solution is an important part of the process. This pause helps retain cells in the target zone instead of allowing them to wash away with the flowing solution [11].

VIII. Delivery Methods And Treatment Strategies

MICP performance depends on both the reaction chemistry and the way bacteria and reagents are distributed through the soil. The delivery method affects where calcite forms, how evenly it is spread and how much of the solution is lost.

A. Bioaugmentation and Biostimulation

The literature describes two ways to establish ureolytic activity in soil. Bioaugmentation involves growing a selected strain, such as S. pasteurii, and injecting it into the ground. This can provide strong, relatively predictable activity, but the culture must be prepared and the introduced bacteria must survive and spread. Biostimulation instead supplies nutrients and urea to encourage ureolytic microorganisms already present in the soil. This may suit local conditions and avoids adding an external strain, although the level of activity is less predictable because it depends on the native microbial community [1], [3].

B. Mixing, Injection and Surface Percolation

MICP solutions can be delivered in several ways. In mix-and-compact treatment, the bacterial suspension and cementation solution are mixed with soil before it is compacted into specimens or layers. This approach is convenient for laboratory studies but requires the soil to be excavated and remixed. Injection treatment delivers bacteria and reagents through pipes or wells into the ground in place. Surface percolation applies the solutions to the ground surface and allows them to move down through the soil; it can be useful for shallow treatment, including erosion control. Cheng and Cord-Ruwisch [11] investigated surface percolation as a way to cement soil in place and improve calcite distribution.

International Journal of Recent Development in Engineering and Technology
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C. Staged Treatment

One treatment cycle may not produce enough bonding, so applications are often carried out in stages. Bacteria are introduced first and given time to attach to the grains; the cementation solution is then supplied and the process may be repeated until the target improvement is reached. Staging can reduce excessive precipitation near an injection point, allow fresh solution to replace spent reagent, and make it easier to monitor progress. The trade-off is a longer treatment period and greater chemical use.

TABLE III
MICP AND EICP COMPARED

Aspect	MICP	EICP
Active agent	Living ureolytic bacteria	Urease enzyme (no living cells)
Urea hydrolysis	Catalysed by bacterial urease	Catalysed by supplied urease
Transport in soil	Limited by cell size; cells must attach	Enzyme is smaller and may move more easily
Survival issues	Cells must survive in the soil	Not applicable, but the enzyme may degrade
Main by-product	Ammonia / ammonium	Ammonia / ammonium

Both MICP and EICP rely on urea hydrolysis and therefore can generate ammonia. EICP avoids the need to grow and transport living cells, which may help where bacterial movement or survival is a concern. However, the enzyme still has to be supplied and its activity may decline over time [7]. The choice between the methods depends on site conditions, available expertise and the relevant requirements for introducing biological materials into the ground.

IX. Testing, Results And Analysis

Testing is needed both before and after treatment. Initial tests describe the soil and help determine a suitable procedure; follow-up tests show whether the treatment has changed its engineering properties. Results from treated specimens should be compared with untreated controls and reported clearly in tables or graphs. Table IV summarises the tests used in the study and their purpose.

TABLE IV
LABORATORY TESTS AND THEIR INFLUENCE ON MICP EVALUATION

Test	Necessity	Influence on MICP
Grain size analysis	Determines particle size.	Affects bacterial movement and $CaCO_3$ distribution.
Specific gravity	Determines particle density.	Helps assess soil density and voids.
Proctor compaction	Determines OMC and MDD.	Controls moisture and bacterial distribution.
Permeability test	Measures water flow.	Shows pore filling by $CaCO_3$ (permeability).
UCS test	Measures soil strength.	Shows strength improvement after MICP (bearing capacity, stiffness).
Direct shear test	Measures shear strength.	Shows improvement in stability (bearing capacity).
$CaCO_3$ content	Measures precipitated $CaCO_3$.	Indicates the effectiveness of MICP.
pH test	Measures soil or solution pH.	Indicates conditions favourable for $CaCO_3$ precipitation.
SEM analysis	Observes microstructure.	Shows $CaCO_3$ crystals and particle bonding.
XRD analysis	Identifies minerals.	Confirms calcite / $CaCO_3$ formation.

The tests can be grouped by what they tell us. Grain-size, specific-gravity and Proctor compaction tests describe the soil and help assess whether bacteria and solutions can move through it. Permeability, unconfined compressive strength and direct shear tests measure changes in water flow and mechanical performance. Calcium carbonate content, pH, SEM and XRD help confirm that precipitation occurred and show the amount, mineral identity and arrangement of the calcite.

A useful way to interpret the results is to compare strength and permeability with the measured calcium carbonate content. Strength and stiffness often rise as more calcite forms, while permeability tends to fall. The relationship is not fixed, because calcite at grain contacts usually contributes more to bonding than crystals that coat surfaces or fill pores away from those contacts [3], [4]. This is why SEM observations and XRD results can usefully support the engineering test data.

X. Engineering Behaviour Of Biocemented Soil

The aim of MICP treatment is to change how the soil behaves under loading and water flow. Research reviews report several possible effects [2]–[4], but the amount of improvement depends on the soil, the quantity and distribution of calcite, and the treatment conditions. The effects should therefore be evaluated for each soil rather than assumed to be the same in every case.

International Journal of Recent Development in Engineering and Technology
Website: www.ijrdet.com (ISSN 2347-6435 (Online) Volume 15, Issue 10, October 2026)

A. Strength and Stiffness

Calcite at grain contacts acts as a binder. It creates additional connections between particles, which can increase stiffness and give granular soil a stronger bonded response under load. This may improve bearing capacity and the stability of foundations and slopes. Unconfined compressive strength and shear strength tests are commonly used to assess the change (Table IV). The result depends on where the calcite forms: bonds at particle contacts are generally more useful than deposits located away from them.

B. Permeability and Pore Structure

As calcite develops within the pore space, it can narrow the flow paths and reduce the connectivity between pores. Water then moves through the soil less easily, which may be useful for seepage control in slopes and embankments. However, excessive precipitation near an injection point can block the pores and prevent solution from reaching more distant parts of the treatment zone. This is one reason staged delivery is often considered.

C. Erosion Resistance

When calcite binds loose grains together, flowing water and wind have more difficulty detaching and transporting the particles. Reviews of MICP and EICP for erosion control [6], [7] identify potential uses on slopes, embankments, riverbanks and coastal ground, especially where solutions can be sprayed or allowed to percolate through the surface. The treated crust may be thin, so its performance under repeated wetting and drying, waves and abrasion still needs careful assessment.

D. Liquefaction Mitigation

During earthquake shaking, pore-water pressure can rise in loose saturated sand and reduce contact between grains, leading to loss of strength. Cementing some of the grain contacts may help limit this loss, which is why MICP has been proposed as a possible way to reduce liquefaction susceptibility. It may be worth investigating beneath existing structures where conventional densification methods are difficult to apply [1], [3].

E. Durability

Calcite can dissolve or change in acidic conditions, so durability cannot be assumed from short-term strength results alone. The treated soil needs to be assessed under the conditions it may experience in service, including wetting and drying, freezing, salt exposure and groundwater flow. Studies of specimens exposed to repeated wetting–drying cycles in seawater address part of this issue, but long-term durability remains an important research gap [1], [3].

XI. Soil Suitability and Design Considerations

Soils do not all respond to MICP in the same way. Bacteria need pore spaces large enough to move through and attach to grains, while the soil must retain the treatment solution long enough for precipitation to take place. Table V gives a general indication of how different soil types may respond.

TABLE V
General Suitability of Soil Types for MICP

Soil type	General suitability	Main consideration
Clean sands	Generally suitable	Pores allow bacteria and solutions to pass; widely used in studies.
Gravels	Possible	Solutions may drain too quickly; retention of bacteria and reagents is difficult.
Silty soils	Possible with care	Reduced pore size restricts movement; uniformity is difficult to obtain.
Clays	Difficult	Very small pores restrict bacteria; mixing methods are usually needed.

Several practical points should guide the design of an MICP treatment.

- Characterise the soil first. Grain size, density, permeability and groundwater conditions help determine whether injection or surface percolation is suitable and whether the solution is likely to remain in the target zone.
- Define the required outcome. The target—such as higher strength, lower permeability or improved erosion resistance—together with the depth and area of treatment, affects how many cycles may be needed.
- Optimise concentrations in the laboratory. Test bacterial density, urea and calcium concentrations, and flow rate using the actual site soil before planning field treatment [1].
- Account for groundwater movement. Strong flow may transport bacteria and reagents away before enough calcite forms. Flow management or adjustments to the reaction conditions may therefore be necessary.
- Plan for by-products. Collection, monitoring and appropriate treatment of ammonium-containing effluent should be included in the design from the beginning [5].

A practical design should begin with laboratory tests on soil from the site. The findings can then be used to choose the treatment mixture and number of cycles. Before extending the method across the full area, the proposed procedure should be checked in a trial zone and verified with suitable field tests.

International Journal of Recent Development in Engineering and Technology
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XII. Monitoring, Quality Control And Safety

Monitoring is particularly important because MICP depends on biological and chemical reactions. During treatment, pH, electrical conductivity and the concentrations of urea, calcium and ammonium in injected and recovered solutions can help show whether urea is being hydrolysed and calcium is being consumed. A decrease in calcium and an increase in ammonium in the recovered solution may indicate that the reaction is proceeding. After treatment, calcite content, strength and permeability tests are used to assess the outcome. Where possible, non-destructive measurements such as wave velocity can provide additional information. Untreated comparison zones are useful for accounting for natural variation.

Safety and environmental controls are also necessary. Strains used in biocementation, including S. pasteurii, are generally regarded as non-pathogenic, but microorganisms must still be handled using good laboratory practice and in line with local biosafety requirements. Urea and calcium chloride should be handled with normal chemical precautions. Ammonia may cause odour and irritation, and solutions containing ammonium should not be discharged untreated into groundwater or surface water. These controls should be included in the planning and cost of field applications [5].

XIII. Illustrative Laboratory Test Plan

Table VIII presents an example test matrix for a laboratory study using sandy soil. The treatment-cycle counts and curing periods are illustrative planning choices, not experimental findings from this paper. Actual values should be selected through preliminary trials using the soil being investigated.

TABLE VIII
Illustrative Test Matrix for a Laboratory MICP Study

Specimen set	Treatment	Tests
Control	No bacteria, no cementation solution	Grain size, specific gravity, compaction, permeability, UCS, direct shear
Low treatment	Few treatment cycles, standard curing	$CaCO_3$ content, pH, permeability, UCS
Medium treatment	More cycles, same curing	$CaCO_3$ content, pH, permeability, UCS, direct shear
High treatment	Many cycles, same curing	All tests; SEM and XRD on selected specimens

This test plan helps answer three practical questions: how much the treated soil changes relative to the control, whether additional treatment cycles lead to worthwhile improvement, and how the measured performance relates to calcite content.

Using duplicate or triplicate specimens in each group helps reveal variability, which is expected in biological processes. Soil preparation, density, bacterial concentration, solution composition and curing conditions should otherwise be kept consistent so that the effect of treatment level can be compared fairly.

XIV. Factors Affecting MICP

The effectiveness of biocementation depends on a set of interacting factors, grouped in Fig. 8 into matrix factors (carbon source, nitrogen source, trace elements), the viable bacterial population, and external factors (pH, temperature, dissolved oxygen).

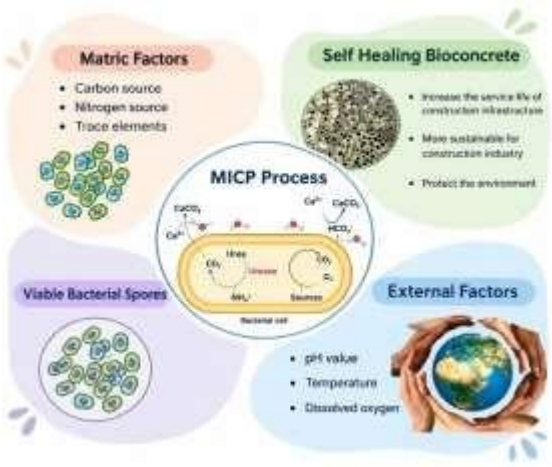


Figure 8. Key factors of MICP, grouped as matrix factors, viable bacterial spores and external factors, and links to applications.

- Soil characteristics. Grain size, porosity, permeability and mineral composition affect how bacteria and treatment solutions move through the ground. Fine-grained soils can restrict their movement, while highly permeable soils may allow solutions to drain away before enough calcite forms [4].
- Bacterial activity and amount. The concentration and activity of the microorganisms affect the rate of precipitation. Active bacteria can promote greater $CaCO_3$ formation, while poor growth or a lack of nutrients may limit the reaction.
- pH. Bacterial activity and carbonate availability depend on pH. Urea hydrolysis raises pH, helping create conditions that favour calcite precipitation.
- Temperature. Temperature influences bacterial growth and enzyme activity. Conditions outside a suitable range can slow the process and reduce treatment effectiveness.

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- Calcium and urea concentration. These concentrations influence both the rate and quantity of precipitation. Too little reagent limits calcite formation, while excessive concentrations increase costs and may leave residual chemicals. Laboratory trials are needed to select suitable levels.
- Treatment time and curing. Longer treatment can allow additional $CaCO_3$ to form, but repeated applications and extended curing increase the overall project duration and chemical demand.
- Bacterial spread and flow rate. The bacteria need to reach the intended treatment zone. Flow rate affects how far the suspension and reagents travel; uneven distribution can lead to patchy cementation [11].
- Environmental conditions. Moisture helps move the treatment solution, but rapid groundwater flow may carry bacteria and chemicals away before precipitation occurs.
- Chemical and water quality. Impurities or unsuitable solution chemistry may affect microbial activity and calcite formation. Excess reagent and leftover solution can also alter soil chemistry and create risks for groundwater.
- Treatment management. Consistent application, routine monitoring and responsible handling of residual solutions and ammonia-containing waste are essential for safe, effective treatment.

These factors influence one another. For example, a high urea concentration may cause a rapid pH rise and encourage calcite to form close to the injection point. The resulting deposits can block pores and restrict treatment at greater depths. A slower flow may give the reaction more time, but it can be impractical when treating large soil volumes. A workable design therefore balances reagent concentration, flow rate and the number of treatment cycles for the soil in question.

XV. Applications Of MICP

Published studies and proposed uses of biocementation cover several areas [1], [2], [6]:

- Soil stabilization: can improve the strength and stiffness of weak soils.
- Erosion control: can help protect slopes, embankments and shorelines from erosion caused by water or wind [6], [7].
- Permeability reduction: calcite occupies pore space and can reduce seepage through soil.
- Foundation and pavement improvement: may improve the support provided by weak soil beneath foundations and roads.
- Slope stabilization: bonding between particles can increase resistance to soil movement.
- Liquefaction mitigation: cementation in loose saturated sands may reduce susceptibility to liquefaction.
- Crack remediation: may be used to help seal cracks in cementitious materials.
- Environmental applications: may immobilise certain contaminants, including heavy metals, and allow some waste materials to be considered as calcium sources.

For near-term use, surface erosion control, localised ground improvement and some crack-sealing applications appear more practical because the treatment area can be limited and delivery can be controlled. Treating large volumes of soil at depth is more complex and remains largely within research and pilot work [1].

XVI. Cost Analysis and Practical Feasibility

A. Materials and Equipment Cost

MICP costs depend on the bacterial culture, reagents, laboratory facilities, equipment and delivery procedure. Table VI provides indicative cost ranges in Indian rupees for the main consumables used in a laboratory-scale study.

TABLE VI
Estimated Materials and Equipment Costs (Laboratory Scale)

Sl. No.	Material / equipment	Estimated cost (Rs)
1	Soil sample	200–500
2	*Sporosarcina pasteurii* culture	2,100–6,300
3	Urea	100–250
4	Calcium chloride ($CaCl_2$)	300–800
5	Bacterial growth medium	500–1,500
6	Distilled water	100–250

The listed amounts cover consumable materials only. They do not include laboratory equipment, testing charges, labour, repeat treatment cycles or waste management, which can add substantially to the total. For field projects, repeated use of urea and calcium solutions may become a major cost because large volumes of soil require larger quantities of reagent [2], [5].

B. Comparison with Conventional Methods

Cement and lime stabilization are established construction methods, and their costs depend on material quantities, transport, mixing, labour and site conditions. MICP has different requirements: a bacterial culture, cementation chemicals, a way to deliver them through the soil, and monitoring of the reactions. The main differences between the approaches are summarised in Table VII.

International Journal of Recent Development in Engineering and Technology
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TABLE VII
MICP VERSUS CONVENTIONAL METHODS

Parameter	MICP	Conventional methods
Principle	Microbial $CaCO_3$ precipitation	Compaction, cement / lime, grouting
Soil improvement	Increases strength and stiffness	Increases strength and stiffness
Environmental impact	Lower potential impact	Material consumption
Material used	Bacteria + urea + calcium source	Cement, lime, chemicals, aggregates
Energy requirement	Potentially lower energy	Higher
Application	More suitable for targeted treatment	Well established for large-scale projects
Limitations	Uniformity, cost	Higher carbon footprint in cement-based stabilization

Both MICP and conventional methods can improve strength and stiffness, but they suit different situations. MICP may reduce reliance on cement and could require less energy in some applications; its main challenges include treatment uniformity and chemical cost. Cement and lime methods have established procedures and are often more straightforward for large projects. MICP is therefore better viewed as a complementary option for selected cases where localised treatment and minimal disturbance are valuable.

C. Feasibility for Small-Scale Applications

MICP may be practical for laboratory research, demonstration trials, localised ground improvement and some erosion-control work. Suitability depends on the available materials, facilities, technical experience and the performance target. Small-scale studies are easier to manage when:

- ready access to bacterial cultures, urea, calcium chloride and consumables;
- use of existing laboratory equipment, which reduces extra investment;
- a small treatment volume, so that the process can be evaluated before larger use;
- ease of monitoring of treatment conditions and of measuring changes in properties; and
- easier control of solution concentration, treatment frequency, curing period and environmental conditions.

XVII. ADVANTAGES

- It may offer environmental benefits compared with cement- or lime-based stabilization by reducing reliance on cement in suitable applications [1].
- Calcite bonds between soil grains can improve strength and stiffness.
- Calcite filling part of the pore space can lower permeability.
- It may help control erosion and reduce liquefaction susceptibility.
- Solutions can be delivered to selected zones of existing ground, potentially avoiding major excavation and unnecessary material use.
- The process can operate under relatively mild temperature and pressure conditions compared with cement manufacture.

XVIII. LIMITATIONS AND CHALLENGES

- Non-uniform precipitation. Bacteria and reagents may not distribute evenly, so the treated ground can have inconsistent strength and permeability.
- Treatment time. Bacterial activity, precipitation and curing take time. Several applications may be needed, making the process slower than some conventional options.
- Chemical demand and cost. Reagents, culture preparation, repeated treatment, testing and waste handling add to the cost, particularly at larger scales.
- Dependence on soil type. Particle size, porosity, permeability and mineral composition all influence how well the treatment works.
- Ammonia generation. Urea hydrolysis produces ammonia, which must be managed to protect soil and groundwater quality.
- Sensitivity to conditions. Changes in pH and temperature can affect bacterial and enzyme activity.
- Limited field validation. Long-term durability and performance at field scale still need further evidence [1], [3].

XIX. ENVIRONMENTAL IMPACT

The environmental benefits of MICP are possible, but they depend on how the treatment is designed and managed. Replacing some cement or lime use may reduce associated energy demand and carbon emissions, and the process can operate under relatively mild conditions [1], [5]. However, a fair assessment must also account for reagent production, water and energy use, treatment efficiency and the handling of by-products.

Ammonia is a key concern. Urea hydrolysis produces ammonia and ammonium, as shown in reaction (2). If residual chemicals and ammonia are not controlled, they may affect soil quality or groundwater. Suitable monitoring and collection and treatment of leftover solutions are therefore essential.

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Proposed ways to improve the environmental profile include exploring non-ureolytic pathways, using alternative calcium sources such as industrial wastes, and improving reagent delivery to reduce excess chemical use [5]. Sustainability should be assessed across the full treatment process, not simply by noting that cement is not used.

XX. Scaling Up from Laboratory to Field

Moving from a small laboratory specimen to treatment in the field introduces several additional challenges [1], [3]. The main issues are outlined below.

- Heterogeneity. Natural soil varies in grain size, density and permeability. Solutions tend to follow easier flow paths, so some areas may receive more reagent than others.
- Reagent volume. Larger treatment zones and repeated cycles require more urea, calcium chloride, nutrients and water. This increases material costs, transport needs and the amount of residual solution that must be managed.
- Reaction time and flow. Solutions must travel far enough to reach the target area but remain in contact with bacteria long enough for the reaction to occur.
- Environmental control. Field temperature, groundwater chemistry and flow vary and cannot be controlled as closely as laboratory conditions. These changes may reduce bacterial activity or carry reagents away.
- Verification. Field samples represent only a small portion of the treated ground, making it harder to confirm that improvement is uniform throughout the full treatment zone.

These challenges help explain why many field applications focus on specific tasks, such as surface erosion control or treatment around existing infrastructure, rather than stabilising large soil volumes. The literature recommends monitored field trials [1], [3], [11]. A cautious development path is to move from laboratory testing to small pilot areas and then to larger trials, checking distribution, performance and cost at each stage.

XXI. Case Studies

Field use of MICP is still developing, but the examples below illustrate the range of settings in which it has been investigated.

- Netherlands (2010). MICP was used in work associated with installing a gas pipeline by horizontal directional drilling (HDD), providing an example of the technique being explored in an infrastructure setting.
- North Carolina, USA (2018–2021). Biocementation was investigated for a coastal highway slope exposed to wave and storm action, an application linked to the erosion-control research [6], [7].
- Kerala, India. Work has mainly involved research and experiments, including studies of native bacteria from coastal areas for $CaCO_3$ precipitation and possible use in soil stabilization and coastal erosion control.

These examples are based on the seminar material and are indicative rather than a substitute for detailed project reports. A common feature is that field applications target a defined problem—such as slope erosion or ground near a pipeline—rather than the treatment of a large soil mass. Locally isolated bacteria are also of interest because they may be better adapted to regional soil and climate conditions.

XXII. Discussion

The literature gives a clear explanation of the MICP reaction, but the level of improvement varies between soils and treatment methods. Urease breaks down urea, alkalinity increases, carbonate becomes available and calcium carbonate precipitates. Studies report improvements in strength, stiffness and permeability, although the size of the change depends on soil conditions, calcite quantity and its distribution [3], [4].

Three issues appear repeatedly. The first is uniformity: rapid precipitation can block pores near an injection point and leave other parts of the soil under-treated. Better control of percolation, injection rate and treatment stages is therefore important [11]. The second is the environmental trade-off. MICP reduces dependence on cement, but the ureolytic process still uses chemicals and produces ammonia, so by-products must be managed properly [5]. The third is scale. Laboratory specimens are easy to control, whereas field soils are variable; results from a small test cannot simply be assumed to apply across an entire site [1].

At present, small and targeted applications appear more feasible than treatment of large soil volumes, where repeated reagent use and its associated costs must be justified. MICP should not be considered a universal substitute for cement or lime.

It is better treated as an additional option for cases such as erosion control, local strengthening and permeability reduction, where the ability to treat existing ground with limited disturbance may be useful.

The overall findings of the seminar are consistent with the reviewed literature: MICP can bond soil grains, increase strength and stiffness, and reduce permeability and erosion. Its wider use is constrained by uneven treatment, ammonia generation, cost and uncertainty about long-term performance [1], [3], [5]. Alongside the underlying chemistry, practical issues—such as the cost of consumables in Table VI and the staged field procedure—matter when deciding whether the method is realistic for a student laboratory or a local ground-improvement problem.

XXIII. Future Scope

- Use of non-ureolytic bacteria and other pathways to reduce ammonia problems [5].
- Large-scale application of MICP for soil improvement, supported by field trials under actual site conditions.
- Determination of the optimum amounts of bacteria and nutrients, together with pH, temperature, chemical dosage and curing period.
- Improved distribution of $CaCO_3$ throughout the soil, through advanced injection methods and controlled solution delivery.
- Study of long-term durability and environmental safety, including repeated wetting and drying, groundwater flow and mechanical loading.
- Use of advanced monitoring and modelling for better control of treatment.
- Identification of alternative bacterial strains, including native strains, and environmentally friendly calcium sources to improve sustainability.
- Development of standard procedures, design guidance and quality-control criteria so that MICP can be specified and verified on projects.

XXIV. Conclusion

Microbially induced calcite precipitation is a promising biological method for improving soil. In the ureolytic process, bacteria break down urea and create alkaline conditions in which calcium carbonate forms. The resulting calcite can connect soil particles, potentially improving strength, stiffness and stability while reducing permeability and erosion. Since the treatment solution can be introduced into existing ground, selected areas may be improved without extensive excavation.

Compared with conventional cement-based stabilization, MICP may offer environmental advantages in suitable applications.

Its performance nevertheless depends on soil properties, bacterial activity, reagent concentrations and site conditions. Uneven calcite distribution, ammonia production, treatment duration, cost and long-term durability remain important limitations. For now, the technique appears most appropriate for targeted and specialised uses, including erosion control and localised soil improvement.

Further progress will depend on improving the distribution of reagents, developing pathways that reduce ammonia-related impacts, selecting suitable treatment conditions, and establishing durability through monitored field trials. These steps are needed before MICP can be adopted more broadly in civil engineering practice.

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Figure note: Figures 1–8 are adapted from the author's seminar report and presentation and are schematic illustrations of the process, not experimental micrographs.