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Overview of MICP Geotechnical Engineering Applications and Development Prospects

Xiaoqiang Wang, Xiaoqing Yuan*

College of Construction Engineering, Jilin University, Changchun 130026, China
**Correspondence Author, yuanxiaoqing@jlu.edu.cn*

Abstract: ***This study examines the research directions and potential of geotechnical engineering applications utilizing MICP. Due to the effective application of this technology in various geological reconstruction and engineering projects, coupled with the controllable and universal microbial induction process, it serves as an alternative green technology to a significant degree. Current research indicates that the urea hydrolysis reaction is extensively utilized due to its high efficiency and ease of control, yet its by-product ammonia may pose environmental pressures; meanwhile, the sulfate reduction reaction encounters issues related to the generation of toxic gases. In comparison, although iron reduction and denitrifying bacteria are more environmentally friendly, there remains room for improvement in sedimentation efficiency and gas production control. At the practical application level, MICP has been employed in soil remediation, soil reinforcement, and pollution control, demonstrating notable engineering value. However, technical challenges arise, including limited improvement effects on fine-grained soil, significant discrepancies between laboratory research outcomes and actual environmental adaptability, as well as research difficulties stemming from the complexity of microbial behavior. Nevertheless, MICP holds potential in achieving the carbon peak goal, thanks to its environmental friendliness, low energy consumption, and high efficiency. Through innovative approaches such as multi-material composite improvement, the technical adaptability and application effectiveness can be further enhanced. Future research should integrate interdisciplinary strengths to optimize bacterial selection and process design, thereby promoting the widespread application of MICP in geotechnical engineering.***

1. Introduction

With the rapid development of society and economy, the number of engineering facilities has increased continuously, accompanied by various geo-engineering problems such as slope instability, sand liquefaction, soil contamination, erosion, and solid waste disposal. In response to these issues, scholars have conducted extensive research across multiple domains, including rock, soil, underground, and aquatic environments. Traditional remediation methods primarily include physical reinforcement (e.g., compaction, preloading, replacement, drainage, and support) and chemical stabilization (e.g., adding cement, lime, fly ash, and polymers). However, these methods often suffer from drawbacks such as labor-intensive processes, prolonged project timelines, high energy consumption, and significant environmental pollution. In recent years, with the promotion of environmental-friendly policies and sustainable development concepts (e.g., "green waters and lush mountains"), there has been a surge in research aimed at developing eco-friendly technologies across various fields. Therefore, it is imperative to thoroughly analyze the limitations of traditional methods and explore innovative solutions that balance engineering demands, reduce costs, and minimize environmental impacts. Traditional improvement techniques primarily address isolated issues related to structures and environments, focusing on their individual characteristics while often neglecting the interconnections and interactions between them.

In recent years, scientists have discovered that large bacterial communities can induce calcium carbonate precipitation through various mechanisms or pathways. Among these, microbial-induced carbonate precipitation (MICP) has played a critical role in natural systems such as caves, soils, and sediments (Castanier et al., 2000). Additionally, studies have shown that microorganisms can generate diverse important carbonate minerals in natural systems (Zhu and Dittrich, 2016). Based on these findings, many researchers have proposed using naturally occurring mineralizing microbes for eco-friendly soil improvement. The core of this technology lies in shifting traditional application concepts: instead of viewing rocks and soils as inert systems composed solely of particles and pores, they are regarded as living ecosystems capable of interacting with their surroundings and altering their properties in response to external stimuli.

MICP is a technology that utilizes the mineralization properties of microbes to induce calcium carbonate deposition. This technique can effectively address multiple engineering issues, with the most notable benefits including enhanced soil engineering properties, slope stabilization, erosion resistance, and damage repair. Importantly, MICP extends beyond conventional improvement methods that merely stimulate or utilize indigenous bacteria; it also involves introducing large quantities of local mineralizing microbes to achieve more efficient outcomes. To date, MICP has successfully completed the conceptual verification stage in most fields, with its technical readiness level continuously improving and demonstrating promising application prospects.

This study focuses on microbial solidification technology, integrating existing research findings and literature. Based on different types of MICP reaction mechanisms, it systematically reviews the application history, development potential, and current technical challenges in geo-engineering fields, followed by a comprehensive summary and evaluation.

2. MICP Geotechnique Application

Through a search in Web of Science, the keyword "MICP" yielded 2,809 articles, while "microbial cementation" resulted in 991 relevant publications. This highlights the significant academic engagement in MICP research. Moreover, any discussion of MICP (Microbial Induced Carbonate Precipitation) inherently revolves around the critical role of microbes. The utilization and study of microbes can be traced back to prehistoric times. Humans accumulated extensive knowledge about microbial behaviors and their effects through production activities and daily life, ultimately applying this understanding to improve living conditions and quality. These include traditional practices such as winemaking, vinegar production, bread fermentation, pickling of sauerkraut and other vegetables, salt curing, and the creation of preserved fruits—examples where humans have effectively harnessed microbial activity in food processing. In agricultural practices, techniques such as composting, manure fermentation, green manuring, and intercropping legumes with other crops reflect humanity's ability to regulate microbial activity in the soil—demonstrating effective management of microbial life cycles. As human civilization advanced, microbes found another critical application in the medical field. In the 11th century, China developed variolation—a precursor to vaccination—while Edward Jenner successfully used cowpox to prevent smallpox in 1796, eventually resolving this age-old global health challenge. Additionally, in the late 17th century, Dutch scientist Antony van Leeuwenhoek observed bacterial individuals under his homemade microscope, marking humanity's first direct encounter with these microorganisms—our unseen yet deeply connected neighbors. In essence, the study and application of microbes have been intertwined with the long history of human civilization development.

In their studies on MICP (Microbial Induced Carbonate Precipitation), scientists have discovered that diverse bacterial populations in natural ecosystems can induce carbonate precipitation through various mechanisms, particularly in alkaline environments rich in Ca^{2+} ions (Ehrlich, 1998). Furthermore, Alluding to this, Boquet et al. as early as 1973 noted that calcium carbonate formation is a characteristic shared by almost all bacteria under suitable conditions. Subsequently, Douglas and Beveridge discovered that under neutral pH conditions, bacterial cell surfaces are rich in carboxyl, phosphoryl, and amino functional groups. These groups impart an unevenly distributed negative charge to the cell surface. This characteristic provides favorable adsorption sites for positively charged cations such as Ca^{2+} and Mg^{2+}, thereby facilitating the nucleation process. Notably, ion-exchange reactions occurring around the cell membrane further promote calcium carbonate precipitation (Douglas and Beveridge, 1998).

Further research has shown that bio-mineralization is a complex process involving four main categories of microorganisms: phototrophic organisms (including cyanobacteria and algae), sulfate-reducing bacteria (SRB, which reduce sulfate to hydrogen sulfide via dissimilatory pathways), microbes utilizing organic acids, and organisms participating in the nitrogen cycle. These bio-mineralization processes encompass a variety of reaction types, including urea hydrolysis, denitrification, iron reduction, and sulfate reduction. It is important to note that different types of bio-mineralization reactions require specific microbial strains and environmental conditions, leading to variations in the resulting mineral products. In this study, we classify and discuss these reactions based on their types and explore their current research and applications in geo-engineering fields.

2.1 Urea Hydrolysis Microbial

The urea hydrolysis-based MICP technique is the most well-known method. It works by introducing or stimulating urea-hydrolyzing bacteria and providing a solution containing urea and calcium ions. The bacteria produce urease, which is adsorbed and fixed on pre-formed gel materials. Urea is then hydrolyzed into ammonium ions and calcium carbonate precipitate, while the consumption of protons leads to an increase in pH levels. In this environment, the precipitation reaction of calcium carbonate can be expressed as:

$$CO(NH_2)_2 + H_2O \xrightarrow{\text{urease}} CO_3^{2-} + NH_3 \tag{1}$$

$$NH_3 + H_2O \rightarrow NH_4^+ + OH^- \tag{2}$$

$$Ca^{2+} + CO_3^{2-} \rightarrow CaCO_3 \tag{3}$$

The reaction has a Gibbs free energy of -27kJ/mol, which is self-driven. However, its progress level is lower compared to the other reaction types. Despite this, it is widely used and studied in research due to its high efficiency, ease of control, simple product formation, and no requirement for additional nutrients to sustain bacterial activity over time.

The commonly used strains of urease-producing bacteria in research include Bacillus anthracis, Bacillus megasporium, Spherical bacillus, Bacterium salmnellae and Clostridium perfringens. These bacteria exhibit varying urease enzyme activities under identical conditions, leading to differences in calcium carbonate production over a certain period. Due to its excellent performance, the use of these strains has significantly enriched rock engineering and geotechnical applications. Since the 20th century, researchers have utilized selectivity bonding agents extensively in oil, geological, and civil engineering fields. Fractures in rocks, particularly those found in oil reservoirs, can be effectively sealed by microbial activity, enhancing oil recovery rates (Jack, 1991).

Following this, studies have applied this technology to coarse-grained soils with relatively large pore diameters. The results indicate that the technology modifies soil behavior (including hydraulic conductivity, dispersion and strength), promotes weathering and aging, and alters its physical-chemical properties. Chou et al., utilizing Sporosarcina pasteurii, successfully improved the mechanical properties of coarse-grained soils through carbonate mineral precipitation and filling, which slightly increases friction angle and strength due to attached bacteria (Chou Chiung-Wen et al., 2011). Tian et al. investigated how different biosolutions affect MICP and soil stabilization in sand. Their research found that higher initial urease concentrations in raw bacterial solutions may reduce enzyme levels when using fresh cultures, while also noting the cost-effectiveness of raw bacterial solutions due to their lower costs and potential negative impacts on human health from byproducts (Avramenko et al., 2024).

To further validate this, Avramenko’s team combined Limosilactobacillus sp. with fish bone extract (FBS) to significantly enhance the mechanical properties of sand, achieving a conversion of diphosphate calcium (DCPD) to hydroxyl apatite via pH and calcium ion concentration control.

The high void ratio, high strength, low density, and susceptibility to disintegration in water make residual granites commonly found in infrastructure construction highly challenging. An et al. employed biological bonding techniques to enhance soil strength and compaction, achieving soil stabilization through carbonate mineral precipitation and incorporation mechanisms (An et al., 2023). The hydraulic properties of modified residual granite have been studied to mitigate rainfall-induced landslides (Tian et al., 2020; Feng et al., 2024; Hao et al., 2023; Luo et al., 2024).

However, in the application of soil stabilization and improvement for fine-grained soils, conventional grouting techniques are limited due to smaller void volume and lower permeability. Recent studies have revealed that microbial suspensions exhibit strong interactions with clay minerals, making MICP technology an effective method for improving the geotechnical properties of cohesive soils (Yuan et al., 2024). For instance, Liu et al. successfully repaired soil damage under cyclic wet-dry conditions using MICP and identified mechanisms behind soil drying and cracking (Liu et al., 2020).

Wind-deposited silt-clay soils, such as loess, often suffer from structural looseness due to their high porosity and sensitivity to water. By precipitating calcium carbonate crystals, MICP can effectively bridge particles, enhance skeleton strength, and reduce the risk of collapse (Chen et al., 2024, 2023; Sun et al., 2021).

Furthermore, MICP technology is widely applied in environmental geotechnics. By encapsulating pollutants and heavy metal ions within calcium carbonate crystals or carbonate lattices and regulating pH to maintain stable conditions, this method achieves long-term fixation efficiency (Kumar et al., 2023).

2.2 Denitrification Microbial

This process involves microbial activities that reduce nitrate to nitrogen gas and oxidize organic carbon to inorganic carbon, leading to an increase in environmental pH value. When calcium salts are introduced, the inorganic carbon reacts with dissolved calcium ions, precipitating as calcium carbonate minerals. This mechanism is referred to as Microbial-Induced Desaturation and Precipitation (MIDP). O'Donnell et al. described this method in two phases: first, gas production causes soil desaturation (O'Donnell et al., 2017b); second, precipitated calcium carbonate fills and strengthens the soil structure (O'Donnell et al., 2017a). With acetate as an electron donor, the metabolic denitrification process can be expressed as follows:

$$CH_3COO^- + 1.6NO^- + 2.6H^+ \xrightarrow{\text{microbial}} 2CO_2 + 0.8N_2 + 2.8H_2O \qquad (4)$$

The Gibbs free energy of this reaction is -785 kJ/mol, exhibiting the highest reaction degree among four types of reactions. However, due to the slow growth rate and longer cultivation period of these denitrifying bacteria, their culture cost is relatively high. Additionally, a main drawback of the denitrification pathway is its lower calcium carbonate precipitation efficiency. Nevertheless, unlike urea - hydrolyzing bacteria, denitrifying bacteria can grow and function under anaerobic conditions, making long-term in-situ field remediation possible. Furthermore, the gas production associated with this process can desaturate the soil, leading to significant research interest in its potential to mitigate soil liquefaction (O'Donnell et al., 2019; Uba et al., 2018).

In terms of soil improvement, Vinh P Pham et al. investigated the process of carbonate precipitation induced by denitrifying bacteria and its potential as a soil reinforcement method. Moreover, due to methane production in the denitrification MICP system, Hamdan N et al. and Pham et al. proposed its potential for energy applications (Hamdan et al., 2017; Pham et al., 2018).

2.3 Iron Reduction Microbial

The iron reduction reaction is a biomineralization process mediated by iron-reducing bacteria. Its core mechanism involves the use of organic acids, produced from the anaerobic decomposition of sugars, as electron donors (Lovley, 1991). During this process, hydrogen ions are continually consumed as insoluble trivalent iron compounds are reduced to dissolvable divalent iron ions. These divalent iron ions subsequently become unstable and prone to oxidation under biochemical reactions, leading to the formation of iron hydroxides or carbonates.

In summary, iron-reducing bacteria utilize their unique metabolic pathways to convert insoluble trivalent iron into soluble divalent iron, which is then further oxidized to compounds with soil-improving effects. This process can be represented as:

$$C_6H_{12}O_6 + 24Fe(III) + 48H^+ \xrightarrow{\text{microbial}} 6CO_2 + 24Fe(II) + 30H_2O \qquad (5)$$

$$CH_3COO^- + 8Fe(OH)_3 + 6HCO_3^- + 7\,H^+ \rightarrow 8FeCO_3 + 20H_2O \qquad (6)$$

These products play a significant role in soil improvement by stabilizing soil particles, enhancing mechanical properties, reducing permeability, and improving resistance to liquefaction (Chu and Ivanov, 2014; Roh et al., 2006)

2.4 Sulfate-reducing Microbial

Sulfate-reducing bacteria are typical anaerobic microorganisms widely distributed in natural environments such as soil and seawater. Under anoxic conditions, they utilize organic acids as electron donors to convert sulfate into other compounds. Specifically, in oxygen-deprived environments, SRB reduce sulfate to produce hydrogen sulfide and carbon dioxide (Castanier et al., 1999). This process increases the pH of the solution, providing favorable conditions for the formation of insoluble cementing substances. During this process, generated sulfides react with metal cations such as iron, while carbonate ions react with calcium ions to form insoluble cementing products. The general reaction mechanism is represented as follows:

$$2(CH_2O) + SO_4^{2-} \xrightarrow{\text{microbial}} HS^- + HCO_3^- + CO_2 + H_2O \quad (7)$$

$$Ca^{2+} + HCO_3^- + OH^- \rightarrow CaCO_3 + H_2O \quad (8)$$

The Gibbs free energy of this reaction is -57 kJ/mol. However, the low solubility of sulfate for the required oxidizing substrates and the production of toxic gases (e.g., hydrogen sulfide) during the sulfate reduction process pose potential risks to the environment and human health.

3. MICP Development Prospects

3.1 Challenges

While the scope of MICP research in geotechnical engineering is broad, it primarily focuses on improving coarse-grained soils. For fine-grained soil improvement, challenges arise from clay mineral composition and soil permeability issues, often leading to poor modification outcomes and complex processes. Furthermore, most studies are confined to laboratory settings, where microbes are significantly influenced by environmental factors such as soil properties, seasonal changes, and geographical conditions. Current theoretical research tends to emphasize efficiency while overestimating the technology's adaptability to various environments and neglecting its potential impacts on ecosystems and structures. Although large-scale applications include Liu's work on reinforcing South China Sea reefs and Van's grouting reinforcement projects, other land types lack substantial application cases.

Regarding the microbial strains used in MICP applications, urea-hydrolyzing reactions are more efficient and easier to control compared to other types. However, they produce ammonia as a byproduct, which can exert environmental pressure during large-scale modifications. Similarly, sulfate-reducing reactions generate hydrogen sulfide, a toxic gas. While iron-reducing and denitrifying bacteria are more environmentally friendly, they face challenges such as low calcium carbonate precipitation efficiency and difficulties in controlling gas production.

Microbial research presents significant challenges due to the complex and variable nature of bacterial behavior. Traditional geotechnical engineering struggles to improve MICP technology at the mechanistic level, making interdisciplinary collaboration crucial for advancing microbial applications. Additionally, microbes have long been subject to mixed evaluations, attracting considerable public attention. Therefore, rigorous methodologies and advanced technical requirements are essential when exploring new microbial strains. In conclusion, this paper identifies the aforementioned three challenges as critical areas requiring improvement in the application of MICP within geotechnical engineering.

3.2 Opportunities

Despite these challenges, MICP remains a highly promising and significant improvement technology with advantages such as environmental friendliness, low energy consumption, and high efficiency. In the context of global efforts to achieve carbon peaking and neutrality, MICP's carbon fixation mechanism provides strong support, significantly reducing energy consumption and greenhouse gas emissions associated with concrete structures.

Additionally, multi-material composite modification represents a key direction for addressing MICP research challenges. By incorporating suitable materials such as tailings, fibers, and porous media, improvements can be achieved across multiple aspects including strength, fixation rates, and environmental secondary pollution, all while maintaining cost control and significantly enhancing modification outcomes.

Compared to modifying and researching microorganisms themselves, this method demands lower technical complexity and research costs, while demonstrating more pronounced improvement effects. Therefore, MICP is also an enhanced technology with remarkable adaptability. Compared to modifying and researching microorganisms themselves, this method demands lower technical complexity and research costs, while demonstrating more pronounced improvement effects. Therefore, MICP is also an enhanced technology with remarkable adaptability.

4. Conclusion

MICP is an environmentally friendly, low-energy consumption, and efficient geotechnical improvement technology that exhibits significant potential in engineering applications. However, its large-scale promotion still faces multiple challenges. Firstly, existing research mostly focuses on improving coarse-grained soil, while the application in fine-grained soil often results in poor outcomes and complex processes due to limitations in clay mineral composition and permeability. Secondly, laboratory research often overlooks the adaptability of microorganisms in real-world environments and their sensitivity to external conditions, leading to a disconnect between theory and practice. Additionally, although Professor Liu has successfully implemented large-scale applications in projects such as the reinforcement of islands and reefs in the South China Sea, further exploration is needed for large-scale promotion in other scenarios. From the perspective of bacterial species, the urea hydrolysis reaction is efficient and easily controllable, yet the by-product ammonia may exert pressure on the environment. Although sulfate reduction reactions can produce cementation products, the release of toxic gases (such as hydrogen sulfide) increases environmental risks. In contrast, iron-reducing and denitrifying bacteria are more environmentally friendly, but they face challenges such as low calcium carbonate precipitation efficiency and difficulties in controlling gas production.

The complexity of microbial research poses challenges for technological advancement. Bacterial behavior is unpredictable and variable, limiting the ability of traditional geotechnical engineering to make breakthroughs at the mechanistic level. Although interdisciplinary collaboration offers new avenues for breakthroughs, the development of new bacterial strains requires overcoming technical and public opinion pressures, demanding high standards in both theory and practice. Nevertheless, the advantages of MICP cannot be overlooked: its carbon fixation mechanism aligns with low-carbon objectives, significantly reducing energy consumption and greenhouse gas emissions in concrete structures; Multi-material composites (such as tailings, fibers, etc.) offer a new direction for enhancing technical adaptability and effectiveness. By optimizing strain selection and process design, improved outcomes can be achieved while controlling costs.

Future research should harness interdisciplinary strengths to explore more efficient and environmentally friendly bacterial strains and composite improvement techniques. Additionally, emphasis should be placed on the practical adaptability and environmental friendliness of the technology, minimizing the ecological impact of by-products, and conducting in-depth research on microbial behavior mechanisms. Only by striking a balance between technological innovation and practical application can MICP successfully transition from the laboratory to engineering practice, becoming a valuable technology in the field of geotechnical engineering.

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