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A Review of Factors Affecting the Efficiency of Geomaterial Treatment Using the MICP Technique

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ABSTRACT

Microbial-induced carbonate precipitation (MICP) is a fast-evolving technology for cementing sandy soils, improving ground, repairing concrete cracks, and remediating contaminated land. The current work thoroughly reviews various factors that can impact the effect of the MICP technology on geomaterials. These factors include the type and strain of the microbes, concentration of bacterial solution, cementation solution composition and concentration, environmental factors (temperature, pH level, and oxygen dissolved), and soil properties. It was found that the type and strain of bacteria, concentration of bacterial suspension, pH value, temperature, and the reaction solution properties are the most affecting factors in controlling the characteristics of the produced calcium carbonate, which in turn affects the degree of bonding between geomaterials particles. For an optimal implementation of the MICP in soils treatment, it appeared that for the most commonly used bacterial strains a temperature between 20 and 40 °C, a pH between 6.5 and 9.5, and a cementation solution concentration of 0.5 mol/L, are typically recommended.

1. Introduction

Soil improvement with the MICP technology is considered a simple, more environmentally friendly alternative to traditional chemical soil stabilization technologies. Unlike conventional chemical grouting, this method uses bacterial and cementation solutions with lower viscosity, making it easier to infiltrate into thicker and deeper geotechnical materials. This makes it an effective solution for challenging geomaterials (Ivanov et al., 2014).The mechanism of ureolysis-based MICP is that urease-producing bacteria can absorb Ca^{2+} on the cell surface from the surrounding environment (Fig 1). At the same time, urea can be decomposed into CO_3^{2-}, HCO_3^{-}, and NH_4^{+} by

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urease secreted from the cell. When Ca^{2+} binds to CO_3^{2-}, a large number of calcium carbonate crystals can be formed on the cell surface (DeJong, Fritzges & Nüsslein, 2006):

$$Ca^{2+} + cell \longrightarrow cell - Ca^{2+} \quad (1)$$

$$NH_2 - CO - NH_2 + 2H_2O \longrightarrow 2NH^{4+} + CO_3^{2-} \quad (2)$$

$$CO_3^{2-} + cell - Ca^{2+} \longrightarrow cell - CaCO_3 \quad (3)$$

Fig. 1 Schematic diagram illustrating how calcium carbonate precipitation is induced by urease-producing bacteria (Fu et al., 2023)

The precipitated crystals in bio-cemented soil can have two primary functions; bonding at particle contacts and coating on particle surface(Choi et al., 2020). According to Cheng et al. (2014), coating and bridging usually coexist after MICP treatment, as shown in Fig 2.

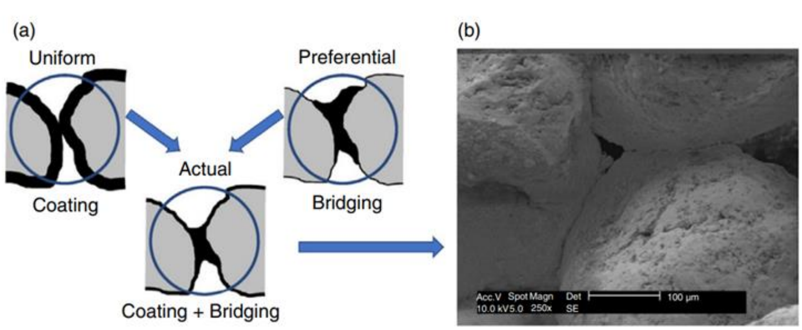


Fig. 2 The pattern of CaCO3 distribution within the soil matrix (Cheng et al., 2014).

2. Factors influencing the efficiency of geomaterials treatment with the MICP technique

2.1. Bacterial strain and concentration

While Sporosarcina pasteurii (also known as S. pasteurii) has been widely used for MICP, researchers have explored other bacterial strains as potential alternatives. Studies have indicated that using different amount of bacterial solution can result in varying reaction rates and differences in the size, polymorph, and morphology of $CaCO_3$ crystals formed during the process (Jiang et al., 2022; Hadi & Saeed, 2022), as shown in Fig 3.

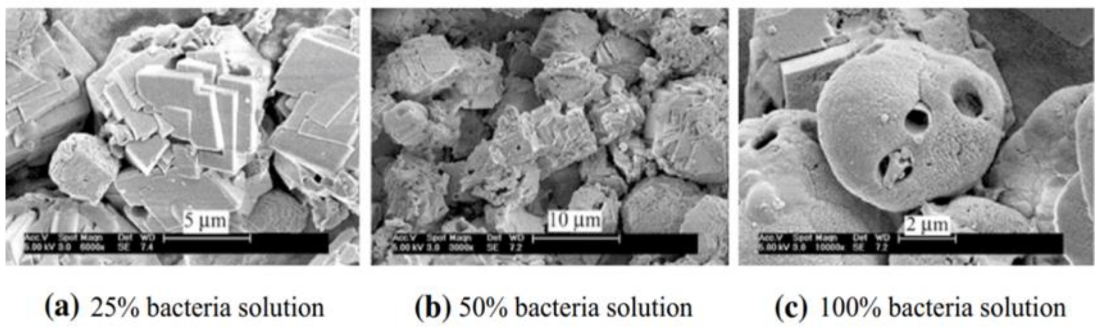


Fig. 3 Calcium carbonate crystal appearance of different concentrations of bacteria solution (Cheng et al., 2007)

Some early studies suggested that the strain type selection can influence the polymorph and morphology of precipitated calcium carbonate crystals. Dhami et al. (2013) isolated five strains from calcareous soils and observed significant morphological differences in the precipitated crystals. Similar results can be found in Chang et al. (2017), as shown in Fig 4.

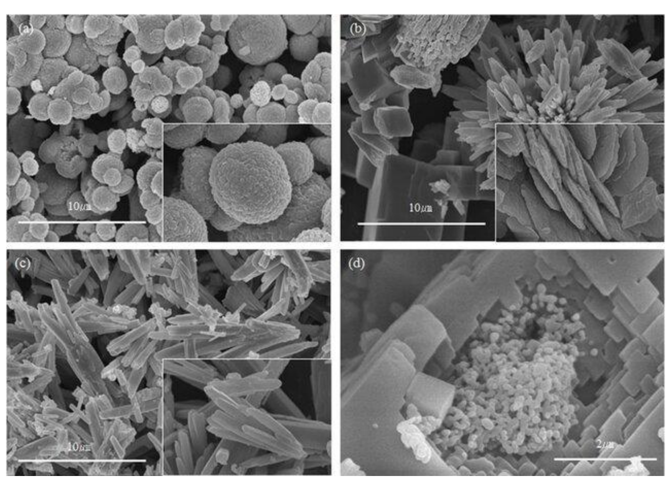


Fig. 4 SEM images of calcium carbonate: (a) vaterite as spherical- shaped, (b) calcite as cubic-shaped and aragonite as rosette-shaped, and (c) needle-like aragonite. (d) calcite around to vaterite as planar arrays (Chang et al., 2017).

Most studies indicate that S. pasteurii has higher urease activity than other strains, justifying its extensive use in previous research(Jiang et al., 2022; Kalantary and Kahani, 2019). Bacillus megaterium (B. megaterium), another gram-positive strain that is commonly found in soil, has been discovered to have a similar level of urease activity as S. pasteurii and is capable of creating spores, which withstands a wider range of temperatures than S. pasteurii (Dhami et al., 2013; Li et al., 2016).

The concentration of bacteria is another critical factor determining urease activity and the ureolysis rate (Jiang et al., 2022). It is easy to understand that urease production for the reaction increases when more bacteria are present. Soon et al. (2014) researched Bacillus megaspores and their ability to induce calcium carbonate in tropical residual soil. Their study showed that an increase in the concentration of bacterial solution resulted in a significant increase in calcium carbonate content, CCC, in the soil. This, in turn, improved the soil's strength and reduced its permeability. Similarly, (Zhao et al., 2014) improved quartz sand through a bacterial solution with varying OD_{600} of 0.3, 0.6, 0.9, 1.2, and 1.5 concentrations. They showed that as the concentration of bacteria increased, so did the urease activity, CCC, and UCS of the cemented samples. A concentration of 1.5 OD_{600} resulted in a CCC of about 14% and a compressive strength of 2.22 MPa. According to Jin et al. (2022), there is a correlation between the concentration of bacterial solution and $CaCO_3$ content. This is shown in Fig 5.

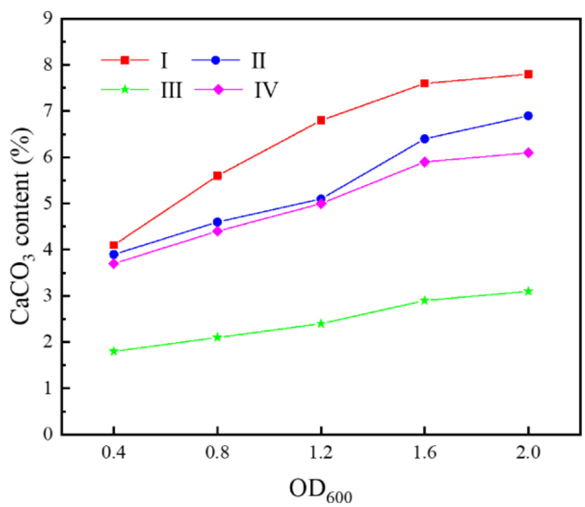


Fig. 5 Relationship between bacterial solution concentration and $CaCO_3$ content in each region (Jin et al., 2022)

Whiffin (2004) expressed the value of urease activity by measuring the conductivity variation of urea solution in (mS/cm/min). He developed the following empirical formula:

$$\boldsymbol{Urease\ hydrolysis\ (mM) = Conductivity\ variation * 11.1} \quad (4)$$

Collee (1996), Achal et al. (2009), and Aryal (2022) tested a bacterial isolate for the presence of the urease enzyme. They visually inspected the Petri dish containing urea agar and observed a change in color from yellow to pink, indicating a change in pH due to the presence of the enzyme. The amount of hydrolyzing enzyme and the accumulation of ammonia were responsible for this change.

2.2. Reagents composition and concentration

To perform MICP treatment, two reagents are typically used: urea and a soluble calcium salt. In most previous studies, the basic reagents solution, i.e., urea and a calcium source, are mixed together, and occasionally nutrient is included. As a result, much of the research exploring the reagent composition has focused on the formation of different types of calcium carbonate crystals (Gorospe et al., 2013). In the work of (Zhang et al.,2015), sand samples treated with calcium acetate presented higher UCS and aragonite was the dominant form, whereas similar samples formed calcite as the dominant polymorph when samples treated with calcium nitrate.

Various calcium salts have been observed to produce different crystal morphologies, and calcium carbonate polymorphs in spite of the bacterial strain used (Jiang et al., 2022; Achal and Pan, 2014). However, the mechanisms underlying this process still need to be explored. Calcium chloride is the conventional calcium source in the MICP treatment. However, due to its high cost and potential environmental impact, researchers have been exploring cheaper and more sustainable methods to produce soluble calcium. Natural and recycled sources such as, seawater (Cheng et al., 2014) have been used to produce calcium for MICP, limestone (S. et al. et al., 2017), calcareous sand (Liu et al., 2018) dolerite (Casas et al., 2019), eggshells, oyster and scallop shells (Liang et al., 2020). Many of which have exposed alike or as better results in strengthening soil compared to calcium chloride.

Many studies have investigated the effect of reagent concentration and found an ideal concentration range for the best strengthening outcome in a given experimental setting. However, this range may change with variations in other variables. Phang et al.(2022) indicated that the increase in concentration of reagent from 0.25 to 0.5 mol/L leads to increase the UCS of treated soil. However, increasing that concentration to 1 mol/L led to a decline in UCS to the value for the uncemented state. Mahawish et al. (2019) found that 1 mol/L reagent concentration was the most effective on MICP-treated coarse soil compared to 0.75 and 1.5 mol/L.

Low concentrations of reagents can lead to poor performance in cementation development due to inadequate reagent supply and low calcium carbonate precipitation (Fig 6). However, the adverse results of high concentrations are more complex. It is likely that high concentrations of reagents can demoralize bacterial urease activity.

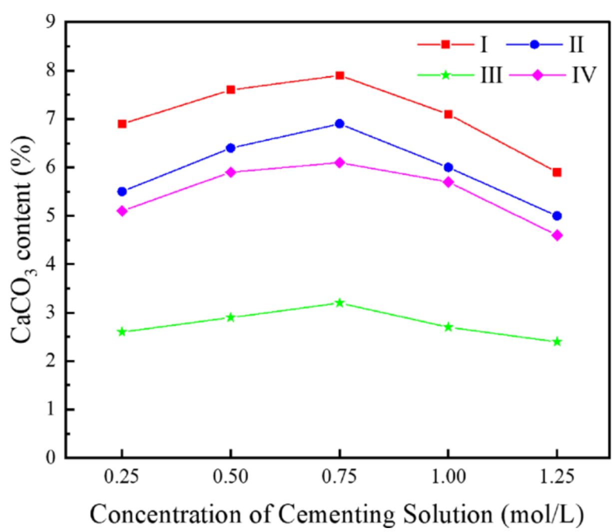
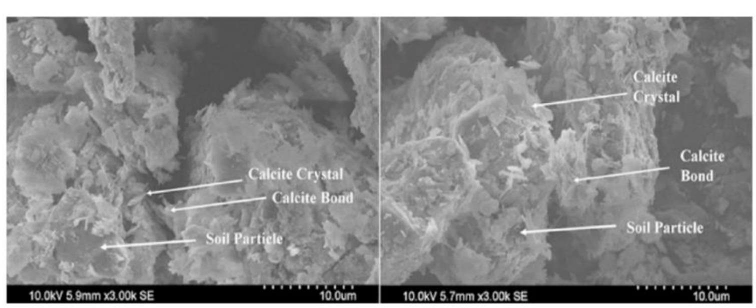


Fig. 6 Relationship between cementing solution concentration and CaCO3 content by immersion treatment method (Jin et al., 2022)

Soon et al. (2014) showed that when using B. megaterium, calcium carbonate precipitated less densely at the concentration of 0.25 mol/L than at 0.5 mol/L, (Fig 7).



(a) 0.25mol/L **(b)**0.5mol/L

Fig. 7 Distribution of calcium carbonate under altered concentrations (Soon et al., 2014)

2.3. Environmental factors

During MICP treatment, environmental conditions affect bacterial activity, precipitation kinetics, and $CaCO_3$ crystal production and properties. The impacts of temperature and pH are briefly discussed below.

- **Impact of temperature**. It is essential to consider the impact of temperature when using MICP for soil strengthening in geotechnical applications. While most experimental studies have been achieved at a constant temperature of around 20°C, it is crucial to remember that field temperatures vary greatly depending on season, location, and depth. It is generally agreed upon that the growth and activity of bacterial strains are affected by temperatures ranging from 0-30°C (Omoregie et al., 2017). For instance, both S. pasteurii and B. megaterium gradually increased urease activity when the temperature rose from 15° to 30°C (Sun et al., 2019).
- **Impact of pH**. The pH level has several complex effects on soil strengthening through the MICP method (Soon et al., 2014). Adding to the complexity, MICP involves many pH adjustment processes, such as the generation and volatilization of ammonia, dissolution and degassing of carbon dioxide, and precipitating calcium carbonate. This, in turn, can alter the calcium carbonate precipitation and production rate. Whiffin (2004) found that the highest urease activity can be achieved with pH values ranging between 6.5 and 8 (Fig 8).

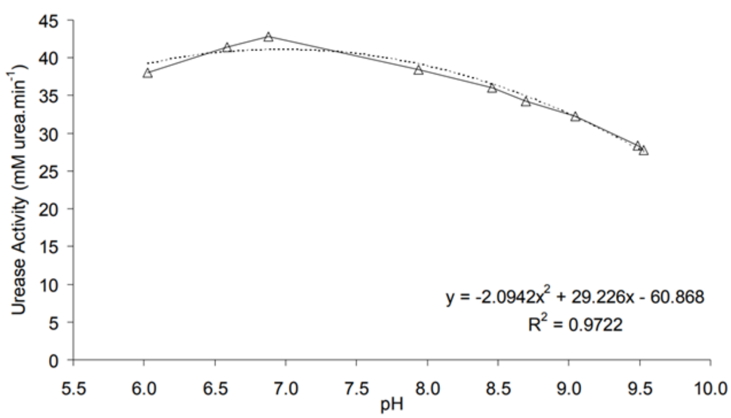


Fig. 8 Effect of pH on the urease activity between 6.5-9.5 (Whiffin, 2004)

2.4. Treatment methods for MICP

Introducing bacterial and cementation solutions into the soil is crucial for MICP-based soil strengthening. This process significantly impacts the soil's final properties and determines how closely laboratory samples resemble treated soils in the field. Three methods have consistently been used for this process by numerous researchers, namely; immersion, mixing, and injection, where each method has specific implementation procedures.

- **The immersing method.** It is one of the commonly used treatment methods for soils improvement with the MICP (Wen et al., 2019; Jin et al., 2022). This method was successfully implemented to improve the properties of contaminated soil through bioremediation (Hadi & Saeed, 2022). This method is considered advantageous for forming larger CaCO3 crystal particles. However, immersion may be unsuitable for certain improvements such as protecting historic buildings (Liu et al., 2020).
- **The mixing method.** In this method, the bacterial solution and cementation solution is directly blended with the problematic soil before molding the sample (Osinubi et al., 2019). This method is commonly used for fine soils, which has relatively low permeability and difficult penetration of the treatment solutions (Bu et al., 2022). The main advantage of the mixing method is that it gives uniform distribution of treatment solution through the soil structure, which leads to a homogeneous bond between the soil grains (Pacheco et al., 2022). Nevertheless, several disadvantages make this method less favored on the field, including; i. practical difficulties in mixing a bulky soil volume with

treatment solutions. ii. The mechanical blending process causes soils to have different geotechnical properties than natural soils and may change their stress history (Mujah et al., 2017).

- **The injection method.** It is commonly implemented in lab experiments. This method involves pumping bacterial and cementation solutions through the soil sample (Salman, Karkush & Karim, 2022). Generally, bacterial solution and cementation solution were mixed together and then injected. However, this causes quick blockage at the injection point and significant heterogeneity in the soil fabric.

3. Summary

In this study, the most influencing factors controlling the efficiency of the MICP treatment were thoroughly reviewed. The main conclusions are summarized below.

- The type and strains of the used microbes. Bacillus or Sporosarcina pasteurii appeared as the main strain used in MICP treatment for geotechnical applications. Other commonly used strain is Bacillus Megaterium.
- The constituents and concentration of cementation solution. These factors appeared to have a significant effect on the formation, size and amount of precipitated calcium carbonate crystals. Calcium chloride is the most commonly used calcium source in the MICP treatment.
- Temperature. The optimum temperature for MICP appears to be between 20 and 40 °C.
- The pH value has no clear effect on the crystalline form of calcium carbonate precipitation by bacteria. However, it has a certain effect on the crystalline appearance.
- Injection and immersion are the most widely used methods for MICP implementation. The most widely applied on-site method is the injection method due to the low viscosity of the reagents and their good penetration into geomaterials cracks and voids.

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