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Factors Influencing the Effectiveness of MICP in Dispersive Soil Improvement: A Review

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Abstract: ***Microbially Induced Calcite Precipitation (MICP) technology has demonstrated significant potential in the improvement and stabilization of dispersive soils due to its environmental friendliness, efficiency, and cost-effectiveness. Dispersive soils, characterized by high exchangeable sodium ion content, are prone to dispersion upon contact with water, leading to severe soil erosion and structural instability. Traditional improvement methods, such as the use of chemical additives and industrial by-products, are often associated with environmental pollution and high costs. MICP, through the catalytic activity of urease in bacteria, generates calcium carbonate precipitates, which enhance the cementation between soil particles, thereby improving the soil's mechanical strength and stability. This review summarizes the key factors influencing MICP effectiveness, including the pH and concentration of the cementation solution, as well as curing time, and systematically evaluates how these factors impact the dispersivity and strength of dispersive soils. Studies show that optimal conditions for soil improvement are a pH range of 7-8, a cementation solution concentration of 1.0 mol/L, and a curing time between 7 and 14 days. Furthermore, there is a positive correlation between calcium carbonate content and soil strength; however, excessive calcium carbonate precipitation can increase soil brittleness, potentially leading to performance degradation. Through a systematic analysis of the mechanisms underlying these factors, this paper proposes methods to optimize MICP technology for soil stabilization, emphasizing the importance of further research on the interactions between these factors and their long-term effects to enhance the application efficiency and sustainability of MICP in practical engineering.***

Keywords: Microbially induced calcium carbonate precipitation, Dispersive soil, Geotechnical engineering, Cementing solution concentration, Curing time, Influencing factors**.**

1. Introduction

Dispersive soil is a type of soil characterized by specific physical and chemical properties, typically exhibiting high levels of exchangeable sodium ions (Nagy et al., 2016). This composition makes it susceptible to disaggregation into primary particles when subjected to water flow, resulting in a range of engineering problems. Due to its weak erosion resistance, dispersive soil often causes phenomena such as gully erosion and piping when in contact with water, which compromise the stability and load-bearing capacity of infrastructure (Fan Henghui et al., 2019). The dispersive nature of this soil type makes it prone to safety hazards in various engineering applications, especially in hydraulic and civil engineering projects (Abbaslou et al., 2020; Bell F.G. & Maud R.R., 1994; Elges H., 1985; Umesh et al., 2011). For example, in the mid-20th century, some soils in North American hydraulic irrigation projects exhibited dispersive behavior upon contact with water, posing significant challenges to engineering stability (Petry et al., 1974; Cole et al., 1960; Jiahuan Qian et al., 1981; Jeff et al., 2003; Rui et al., 2019; Vakili et al., 2018b).

To address the improvement of dispersive soils, traditional methods often involve the use of chemical reagents (e.g., alum, aluminum sulfate) and industrial byproducts (e.g., fly ash, cement, lime) (Mahamaya et al., 2021; Umesha, T.S. et al., 2009; Vakili et al., 2013; Yuan et al., 2021; Zhao et al., 2023). While these methods alleviate the dispersive nature of the soil to some extent, most chemical additives contribute to environmental pollution and incur high costs (Chen et al., 2015; DeJong et al., 2010; Vakili et al., 2018a, 2017). Therefore, identifying an environmentally friendly, cost-effective, and efficient soil improvement technique has become a research priority.

Recently, Microbially Induced Calcite Precipitation (MICP) has attracted widespread attention due to its environmental friendliness, cost-effectiveness, and practicality (Mujah et al., 2021; Omoregie A.I. et al., 2017; Tang Chaosheng et al., 2021; Wang et al., 2022). MICP is a natural mineralization process that involves introducing microorganisms into the soil. The bacteria secrete urease to catalyze the hydrolysis of urea, which alters the pH of the soil, produces carbonate ions, and reacts with calcium ions to form calcium carbonate precipitates. These precipitates fill the gaps between soil particles, thereby enhancing the strength and stability of the soil (Dejong et al., 2013; Mahawish et al., 2019; Wu et al., 2021; Xiao et al., 2022). MICP has been shown to effectively improve the mechanical properties of sands and has significant effects on clay and dispersive soils (Jiang and Soga, 2017). Studies have demonstrated that MICP can substantially increase the compressive strength, reduce permeability, and improve load-bearing capacity and wind erosion resistance of soils (Riveros G.A. and Sadrekarimi A, 2020; Sara Ghalandarzadeh et al., 2024; Wu et al., 2021).

Although MICP technology shows great potential for soil improvement, its effectiveness is constrained by various factors due to the complex biochemical reactions involved. For instance, factors such as the pH, concentration of the cementation solution, and curing time significantly influence the amount and distribution of calcium carbonate precipitates, which in turn affect the soil's mechanical properties (Al Qabany et al., 2012; Yin Liyang et al., 2019). Thus, further research is needed to explore the mechanisms underlying the effects of these factors on MICP performance and to enhance its application in practical engineering.

Current research is largely focused on the analysis of individual factors, with a lack of systematic evaluation of the interactions between different factors. Additionally, many studies are limited to short-term performance tests, with long-term effects receiving insufficient attention (Tang Chaosheng et al., 2021). This review aims to systematically assess the influence mechanisms of factors such as pH, cementation solution concentration, and curing time on MICP improvement of dispersive soils and to explore how these factors can be optimized to enhance the improvement effect. Furthermore, this paper will discuss future research directions for MICP technology and propose feasible engineering application recommendations.

2. The Current Research Status of Microbially Induced Calcite Precipitation (MICP) Technology.

Biotechnology has been widely applied in environmental monitoring, control, and soil remediation. In geotechnical engineering, most soil improvement techniques involve significant energy consumption during material production and on-site construction, while also posing potential environmental risks, such as excessive carbon dioxide emissions and toxic chemicals. To address this ecological issue, some researchers have shifted their focus to sustainable, biologically derived alternatives, aiming to achieve soil improvement with minimal carbon emissions. Mitchell et al. (2005) first proposed the use of microorganisms as catalysts for biogeotechnical reinforcement. Since then, numerous studies have made significant advancements in the field of geotechnical engineering.2.1 The mechanism of MICP.

Microbially Induced Calcite Precipitation (MICP) is a biologically driven calcium carbonate precipitation technique, which involves two mechanisms: biological control and biologically induced $CaCO_3$ precipitation. Bacteriol et al. (2007) presented an example of biological control mineralization, demonstrating through strain selection, mutation insertion, transcription, and validation that Bacillus subtilis can achieve $CaCO_3$ precipitation at the molecular level. On the other hand, in the biologically induced mechanism, the production of $CaCO_3$ depends, to some extent, on environmental conditions. Among the MICP processes reported in the literature, Bacillus pasteurii is the most commonly used bacterium due to its high environmental adaptability, ability to grow under varying temperatures and pH levels, and its high urease activity. This bacterium can rapidly synthesize urea and amino acids, promoting carbonate precipitation (Dhami et al., 2017). Researchers prefer using urea hydrolysis for $CaCO_3$ precipitation because the method is straightforward, easy to control, and can achieve up to 90% chemical conversion efficiency of $CaCO_3$ precipitation within 24 hours.

2.2 Research Status of Microbially Induced Calcium Carbonate Precipitation (MICP) in the Engineering Field

Microbially Induced Calcite Precipitation (MICP) has demonstrated significant potential in geotechnical engineering applications. In practical engineering, in-situ treatment is commonly used, where microorganisms and suitable growth media are directly applied to the surface of the soil or structure requiring reinforcement, promoting calcium carbonate precipitation to enhance soil stability. In laboratory tests, ex-situ treatment is typically employed, using microbial precipitation of calcium carbonate to improve the stiffness, strength, and reduce the permeability of the soil.

Soil stiffness, also known as the modulus of elasticity (E), is an indicator of soil deformation. Montoya [57] noted that the stiffness of sand treated with MICP increases with the amount of $CaCO_3$ precipitation. (Cheng L et al., 2017) applied MICP grouting to treat sand and residual soils, demonstrating that the treated soil exhibited higher elastic modulus.

Shear strength, which measures a material's resistance to shear forces, depends on the soil's shear strength parameters. (Duraisamy et al., 2012) used flexural elements to track the degree of microbial cementation in sand, establishing a relationship between shear wave velocity and cementation. Their results indicated that the increase in shear strength of biocemented soil was largely attributed to an increase in soil cohesion, with little effect on the internal friction angle. In contrast, (Chou et al., 2011) observed a significant increase in the internal friction angle of sand treated with MICP, while cohesion only showed a slight increase. Furthermore, the peak strength of microbial-treated soil was higher than that of untreated or other treatment methods in direct shear tests. (Cheng et al., 2012) highlighted that, under lower saturation levels, the precipitation of $CaCO_3$ crystals contributed more to the improvement of soil cohesion than to the friction angle. Additionally, because calcium carbonate crystals can fill soil pores, both cohesion and friction angle increase when higher levels of $CaCO_3$ precipitation are present, regardless of saturation.

Unconfined compressive strength (UCS) is a simple and widely used test for determining soil strength. Many studies have discussed this parameter (Cheng L et al., 2012). Under different MICP treatments, the highest and lowest UCS values were 34 MPa and 150 kPa, respectively. Van Paassen et al. (2009) revealed an exponential relationship between the $CaCO_3$ content produced in biocemented soil and the UCS value, noting that, although the amount of $CaCO_3$ precipitation is the same, the mechanical strength of MICP-treated soil is heavily influenced by the effective precipitation mechanism of $CaCO_3$. The use of Bacillus pasteurii to reinforce expansive soil and investigate its mechanical properties showed that MICP treatment resulted in an increase in UCS.

In summary, dispersive soils are highly susceptible to erosion upon contact with water. While chemical additives can effectively improve the dispersive properties of soils, they often lead to environmental pollution. Therefore, the application of MICP for the improvement of dispersive soils is of great significance.

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Shear strength is the ability of a material to resist shear forces, and it depends on the soil's shear strength parameters. (Duraisamy et al., 2012) used bending elements to track the degree of microbial cementation in sand, establishing a relationship between shear wave velocity and cementation. Their results found that the increase in shear strength of biocemented soil was largely attributed to the increase in soil cohesion, while the effect on the internal friction angle was minimal. In contrast, (Chou et al., 2011) pointed out that almost all sand treated with MICP exhibited a significant increase in the internal friction angle, while the increase in soil cohesion was modest. Additionally, the peak strength of microbial-treated soil in direct shear tests was higher than that of untreated or other treatment methods. MICP treatment significantly increased the shear strength of microbial-treated soil compared to untreated soil. (Cheng et al., 2012) indicated that, under lower saturation levels, the precipitation of $CaCO_3$ crystals contributed more to improving soil cohesion than the friction angle. Furthermore, since calcium carbonate crystals can fill soil pores, both cohesion and the friction angle increased with higher levels of $CaCO_3$ precipitation, regardless of saturation.

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In summary, dispersive soils are highly susceptible to erosion when exposed to water. Although chemical additives can effectively improve the dispersive properties of soil, they often result in environmental pollution. Therefore, applying MICP for the improvement of dispersive soils is of significant importance.

3. The Influencing Factors of MICP

Microbially Induced Calcite Precipitation (MICP) has demonstrated extensive potential for soil improvement. Commonly used bacterial strains include species from the Bacillus genus and Sporosarcina pasteurii. The mineralization process induced by these microorganisms in the soil is influenced by various factors, particularly the physicochemical properties of the soil, microbial activity, the pH and concentration of the cementation solution, as well as curing time. Understanding how these factors affect the application of MICP technology is crucial for improving soil enhancement efficiency, increasing soil resistance to erosion, and enhancing soil strength. This section will explore the impact of these factors on the effectiveness of MICP for improving dispersive soils and summarize the key mechanisms identified in current research.

3.1 The Influence of Soil Properties on the Effect of Microbially Induced Calcite Precipitation (MICP)

The basic physical and chemical properties of soil are critical factors influencing the effectiveness of Microbially Induced Calcite Precipitation (MICP). Soil properties such as particle size distribution, liquid limit, plasticity index, and the type and content of exchangeable ions in the soil all affect the success of MICP treatment. For instance, finer soils, such as clay, typically have a larger specific surface area, which provides more reactive sites, thereby enhancing the effectiveness of MICP. In contrast, sandy soils, due to their larger particles and smaller surface area, may not experience as significant an improvement from MICP treatment as clay soils (Riveros & Sadrekarimi, 2020).

Additionally, exchangeable ions such as sodium ions (Na^+) in the soil significantly impact the MICP treatment. Higher concentrations of sodium ions tend to increase soil dispersivity and reduce the cementation between soil particles. Therefore, it is important to consider the effect of sodium ions during the treatment process and adjust the reaction conditions of MICP accordingly to minimize soil dispersivity (Riveros G A and Sadrekarimi A, 2020). 3.2 Bacterial concentration and its enzyme activity

3.2 The Preparation Process of the Culture Medium

Strict control of each step during the preparation of the culture medium is essential to ensure the viability of the microbial strains. The precise formulation of nutritional components directly impacts microbial metabolic efficiency. A deficiency or imbalance of carbon sources, nitrogen sources, vitamins, and other essential substances can lead to stagnation or even death of the microbial cells. Therefore, accurate measurement and dissolution processes are crucial to maintaining nutritional balance. pH regulation significantly affects enzyme activity and membrane permeability (Hammes and Verstraete, 2002). Different microbial strains exhibit notable variations in their tolerance to pH levels (e.g., bacteria thrive in neutral environments, while fungi prefer slightly acidic conditions), making it necessary to use precise instruments to monitor and adjust pH before and after sterilization. Sterile techniques are critical to prevent contamination by unwanted microorganisms. Proper handling of raw materials, sterilization of equipment, and operation under laminar flow hoods must adhere to strict protocols (as shown in Figure 1) to prevent interference from competing microbes. Additionally, the agar concentration and dissolution temperature determine the solidification state of the culture medium, while the uniformity of stirring affects the even distribution of nutrients. Fluctuations in these physical parameters can result in abnormal colony morphology or differences in growth rates. In summary, standardized procedures for culture medium preparation are essential to maintaining strain viability and ensuring the reliability of experimental data.

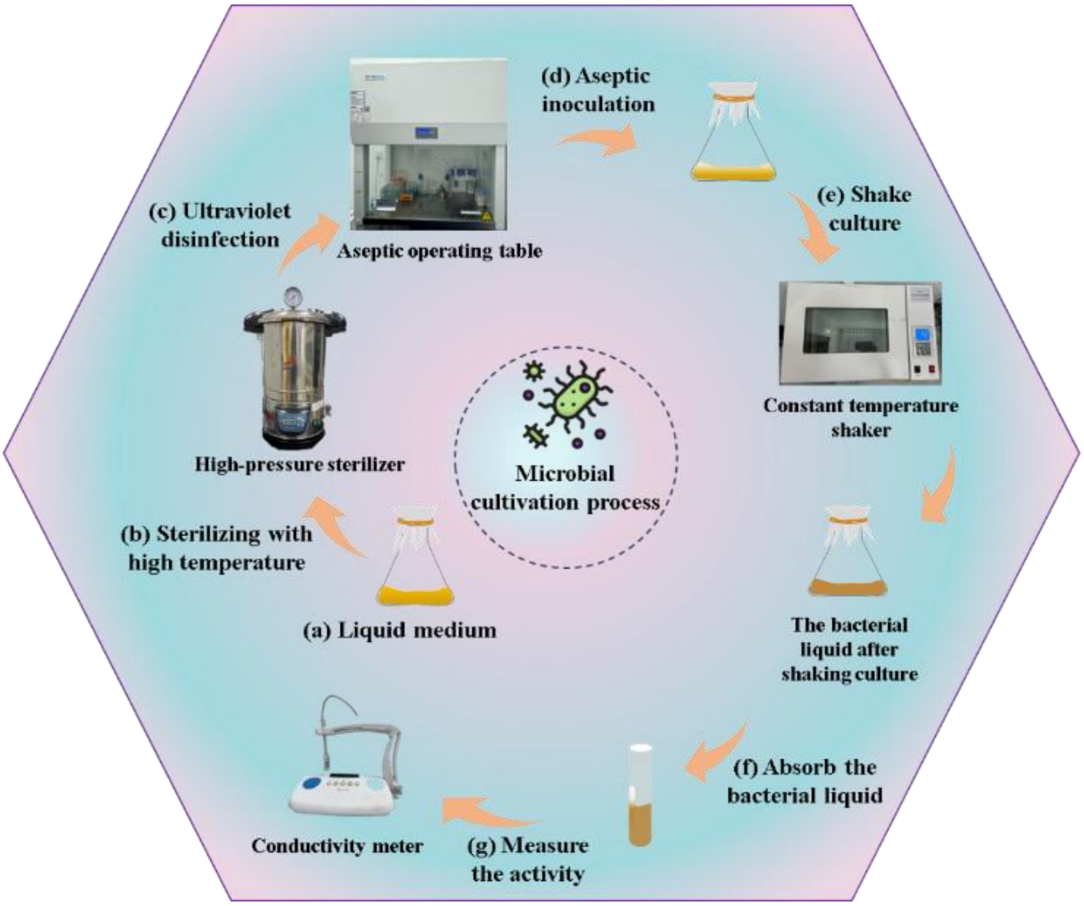

Figure 1: The preparation process of bacterial liquid

3.2.1 Bacterial culture time

The concentration of microorganisms and their enzyme activity are key factors influencing the effectiveness of Microbially Induced Calcite Precipitation (MICP) in soil improvement. During MICP, urease plays a crucial role in catalyzing the hydrolysis of urea, which produces carbonate ions (CO_3^{2-}). These ions then react with calcium ions (Ca^{2+}) in the soil or with calcium ions provided by the cementation solution (urea and calcium chloride in a 1:1 ratio) to form calcium carbonate precipitates (WU Yang et al., 2017), thereby enhancing the structural stability of the soil (Dickson and Koohmaraie, 1989; Ng et al., 2012; Okwadha and Li, 2010). Therefore, it is essential to maintain high and stable urease activity when extracting and utilizing microorganisms for soil improvement.

3.3 Cementation Solution

3.3.1 pH value of the cementation solution

The pH, concentration, and calcium source (e.g., calcium chloride) of the cementation solution play a crucial role in the effectiveness of Microbially Induced Calcite Precipitation (MICP). The pH of the cementation solution affects both the microbial growth environment and the activity of urease, thereby influencing calcium carbonate formation. For example, lower pH values may inhibit microbial activity, reducing calcium carbonate production, while higher pH values favor urea hydrolysis and promote the generation of carbonate ions (Ha mmes & Verstraete, 2002). Given that bacteria are sensitive to environmental pH, as the pH increases from 6 to 7 and 8, the efficiency of urea decomposition by bacteria improves. This enhances the ability of calcium ions to reduce the repulsive effects of negative charges in the soil, thus weakening the electrostatic repulsion between soil particles and facilitating particle aggregation. This, in turn, effectively improves the soil's aggregate structure and reduces its dispersivity. Furthermore, the increased concentration of carbonate ions leads to greater calcium carbonate precipitation, cementing the soil particles and further decreasing soil dispersivity. Experimental results show that at a pH of 7 or 8, the changes in soil dispersivity and sodium ion exchange capacity are particularly significant. In conclusion, experiments demonstrate that MICP is most effective when the pH is 7 or 8.

3.3.2 Concentration of cementing fluid

The concentration of the cementation solution (Cocr) significantly affects the effectiveness of Microbially Induced Calcite Precipitation (MICP) in improving dispersive soils. An optimal concentration of the cementation solution provides sufficient calcium ions and carbonate ions to promote calcium carbonate formation. However, excessively high concentrations can lead to ion imbalance, inhibiting microbial activity and reducing the improvement effect, or causing minimal changes in the improvement effect as concentration increases (Burbank et al., 2013). Based on existing studies, a cementation solution concentration of 1.0 mol/L is considered optimal for MICP treatment of soils (Meng and Li, 2019).

The Exchangeable Sodium Percentage (ESP) decreases as Cocr increases, indicating that the concentration of the reaction solution influences the ESP trend. The ESP of untreated soil is consistent with that of non-dispersive soils. When treated with Cocr 0.5, the soil exhibits transitional characteristics. However, at Cocr 1.0, the ESP decreases, and the soil transitions from dispersive to non-dispersive. As Cocr increases from 1.0 to 2.0, the change in ESP is approximately 1% (Yuan et al., 2024). This can be attributed to two factors: first, the microbial mineralization process facilitates the cementation of soil particles; and second, the divalent calcium ions (Ca^{2+}) have smaller hydration shells and diffuse double layers compared to monovalent sodium ions (Na^{+}), leading to stronger flocculation.

At lower concentrations of the reaction solution, only a moderate amount of carbonate ions is produced through urea hydrolysis. In contrast, at an optimal concentration of Cocr, the cations produced are adsorbed onto soil particles, promoting rapid calcium carbonate precipitation. Simultaneously, the exchange of calcium and sodium ions proceeds steadily, reducing the thickness of the diffuse double layer and increasing the attractive forces between particles, which reduces dispersivity. At high concentrations of calcium ions, excessive ammonium ions produced by urea hydrolysis can elevate the concentration of ammonium in the soil. This can affect the soil's pH, thereby influencing its chemical properties. Additionally, high concentrations of ammonium ions and calcium ions can impair urease activity, thereby inhibiting the mineralization process and reducing changes in soil dispersivity and ESP. Experimental results indicate that a Cocr concentration of 1.0 is most effective in improving soil dispersivity and ESP.

3.4 Curing Time and Its Influence on the Effect of Microbially Induced Calcite Precipitation (MICP)

Curing time is another critical factor influencing the effectiveness of Microbially Induced Calcite Precipitation (MICP) in soil improvement. Short-term curing, such as 7 days, can significantly enhance soil compressive strength and resistance to erosion (Yuan et al., 2024). As the curing time increases, the amount of calcium carbonate precipitation gradually stabilizes, but the improvement effect on the soil tends to plateau (Cui et al., 2017; Lv et al., 2023). In the early stages, microbial activity is high, leading to rapid calcium carbonate precipitation, which effectively strengthens the soil.

However, with prolonged curing, the improvement effect becomes more stable due to the saturation effect of calcium carbonate precipitation, and microbial activity gradually decreases (Teng et al., 2021). Therefore, short-term curing (7 days) provides the most significant enhancement in soil stability, while extended curing may lead to further changes in the soil structure, such as uneven calcium carbonate precipitation (Sun et al., 2021).

3.5 The Interactions Among Factors and Their Comprehensive Influences

The interactions between various factors also play a crucial role in the effectiveness of Microbially Induced Calcite Precipitation (MICP). Factors such as pH, cementation solution concentration, microbial activity, and curing time are intricately interrelated, and together, they determine the ultimate outcome of MICP treatment. For example, an appropriate pH and cementation solution concentration can promote calcium carbonate formation, while curing time dictates the amount of calcium carbonate precipitation and the improvement in soil strength (Shan et al., 2022). Therefore, optimizing the combination of these factors is key to enhancing the effectiveness of MICP technology.

4. Effects of Different Influencing Factors on Dispersive Soil

4.1 The Influence of pH on the Dispersibility and Strength of Soil

The pH is a key factor influencing the effectiveness of Microbially Induced Calcite Precipitation (MICP) for soil improvement. As shown in Figure 6, it not only regulates microbial growth and urease activity but also directly affects calcium carbonate precipitation by altering the concentrations of carbonate ions and calcium ions in the soil. This, in turn, influences the dispersivity and mechanical properties of the soil. MICP treatment results in significant variations in soil improvement depending on the pH. The impact of pH on soil dispersivity primarily stems from its regulation of microbial and urease activity. Experimental results show that at lower pH levels (e.g., pH = 6), bacterial urease activity is weak, reducing the generation of carbonate ions from urea hydrolysis and resulting in limited improvement in soil dispersivity. At pH = 6, MICP-treated soil still exhibits high dispersivity after being soaked in water, with a dispersivity rating of 3.

As the pH increases, microbial urease activity enhances, leading to a greater production of carbonate ions and promoting calcium carbonate precipitation (Wang et al., 2023). At pH = 7, soil dispersivity significantly decreases, with a reduction in the dispersivity rating to 2, and at pH = 8, the soil almost becomes non-dispersive. This indicates that higher pH levels lead to more pronounced improvement in soil dispersivity and stronger cementation of soil particles.

In addition to its impact on soil dispersivity, pH also significantly affects the mechanical strength of the soil. Experimental data show that pH changes have a major influence on unconfined compressive strength (UCS) (Atashgahi et al., 2020). As shown in Figure 7, at pH = 6, while there is some improvement in soil dispersivity, the amount of calcium carbonate precipitation is low, and the soil’s strength enhancement is limited. As the pH increases to 7 and 8, the amount of calcium carbonate produced increases, significantly enhancing the cementation between soil particles and thereby improving the compressive strength.

At pH = 8, the precipitation of calcium carbonate is at its highest, leading to the strongest bonding between soil particles, and thus the maximum compressive strength is achieved. However, when the pH is too high, although the amount of calcium carbonate increases, excessive precipitation can lead to increased brittleness, negatively impacting the soil's compressive strength. This suggests that a moderate increase in pH during MICP treatment helps to improve soil mechanical strength, but excessively high pH levels may cause detrimental structural changes.

The mechanism by which pH affects MICP improvement primarily involves its impact on microbial activity and carbonate ion production. At lower pH levels, microbial urease activity is suppressed, leading to a lower concentration of carbonate ions and less calcium carbonate production (Wu et al., 2021). The amount and distribution of calcium carbonate precipitation in this process determine the bonding strength between soil particles, affecting both soil dispersivity and compressive strength.

As the pH increases, urease activity increases, carbonate ion concentration rises, and more calcium carbonate precipitates, filling the pores between soil particles and enhancing the bond between them. At this point, soil dispersivity decreases, and compressive strength increases (Zhang et al., 2020). However, excessively high pH levels may lead to uneven calcium carbonate crystal formation, which can affect the overall strength of the soil. Specifically, when pH exceeds 8, excessive calcium carbonate precipitation may cause localized stress concentrations, reducing the compressive strength of the soil (Wang et al., 2023).

4.2 The Influence of the Concentration of the Cementing Solution on the Dispersibility and Strength of Soil

The concentration of the cementation solution (Cocr) is another key factor influencing the effectiveness of Microbially Induced Calcite Precipitation (MICP) in soil improvement. During MICP, carbonate ions produced by urea hydrolysis react with calcium ions to form calcium carbonate precipitates, which promote the cementation of soil particles, improving soil dispersivity and mechanical strength. The concentration of the cementation solution directly affects the rate of calcium carbonate formation and the amount of precipitation, thus influencing the overall improvement effect. Therefore, studying the impact of cementation solution concentration on MICP effectiveness is of great importance.

In MICP treatment, cementation solution concentration has a significant effect on soil dispersivity. Experimental results show that lower concentrations (e.g., 0.5 mol/L) are insufficient to generate adequate calcium carbonate precipitation, leading to poor improvement in soil dispersivity (Shi Zhiyong et al., 2020). At a concentration of 0.5 mol/L, the soil still exhibits strong dispersivity after being soaked in water, with a dispersivity rating of 4. As the cementation solution concentration increases, soil dispersivity gradually decreases. Notably, at a concentration of 1.0 mol/L, the soil transitions to non-dispersive, with the dispersivity rating dropping to 1, showing significant improvement.

At concentrations of 1.5 mol/L and 2.0 mol/L, soil dispersivity increases again, with dispersivity ratings of 3 and 2, respectively (Wang Xi, 2023). This change suggests that excessively high cementation solution concentrations may result in uneven calcium carbonate precipitation, affecting the bonding strength between soil particles and thus increasing dispersivity again. According to experimental results, the optimal cementation solution concentration is 1.0 mol/L, which significantly improves soil dispersivity in a short period.

Cementation solution concentration also significantly affects soil mechanical strength (Yuan et al., 2024). At low concentrations (e.g., 0.5 mol/L), the amount of calcium carbonate precipitation is limited, resulting in low unconfined compressive strength (UCS) for the soil samples. As the concentration increases, the amount of calcium carbonate precipitation increases, leading to enhanced soil strength. At a concentration of 1.0 mol/L, the compressive strength reaches its peak, indicated by a high UCS, and the failure mode shifts from bulging failure to failure along the maximum shear plane. However, as the cementation solution concentration increases further (e.g., 1.5 mol/L and 2.0 mol/L), the compressive strength begins to decrease. This is due to the fact that, under high concentration conditions, excessive calcium carbonate precipitation may lead to uneven crystal formation, which reduces the bonding strength between soil particles and lowers the overall strength (Wu et al., 2021). Moreover, excessively high concentrations may inhibit microbial activity, decreasing urease activity and thereby reducing calcium carbonate production (Burbank et al., 2013). Therefore, moderate control of cementation solution concentration is crucial for improving the mechanical properties of the soil.

The mechanism by which cementation solution concentration affects soil dispersivity and strength is primarily linked to the amount of calcium carbonate generated and the bonding between soil particles. At lower concentrations, the amount of calcium carbonate precipitation is insufficient, failing to effectively bond soil particles, leading to poor improvements in soil dispersivity and strength. At optimal concentrations (e.g., 1.0 mol/L), the carbonate ions produced from urea hydrolysis combine with calcium ions to form abundant calcium carbonate precipitation, which fills the pores between soil particles and strengthens the bond between them. This effectively reduces soil dispersivity and enhances strength. However, at excessively high concentrations, uneven precipitation of calcium carbonate may occur, destabilizing the deposition and weakening the cementation between soil particles, ultimately reducing soil strength (Atashgahi et al., 2020). Furthermore, excessively high concentrations may inhibit microbial growth, decrease urease activity, and reduce calcium carbonate precipitation, thereby impairing the improvement effect on the soil.

4.3 The Influence of Curing Time on the Dispersibility and Strength of Soil

Curing time is a key factor influencing the effectiveness of Microbially Induced Calcite Precipitation (MICP) for soil improvement. As curing time increases, the amount of calcium carbonate precipitation gradually increases, thereby enhancing soil mechanical strength and stability. However, excessively long curing times may lead to a saturation of improvement effects, or even have adverse impacts. Therefore, understanding the specific effects of curing time on soil dispersivity and mechanical strength is crucial for optimizing the application of MICP technology.

Curing time has a significant impact on soil dispersivity during the MICP process. Experimental results show that, as curing time extends, soil dispersivity gradually decreases (Cheng et al., 2017). During short-term curing (e.g., 7 days), calcium carbonate precipitation increases, and the cementation between soil particles strengthens, effectively suppressing dispersivity. After 7 days of curing, the soil transitions from dispersive to non-dispersive. However, when curing time exceeds 14 days, changes in dispersivity become minimal, and there may even be a slight increase in dispersivity. This could be due to the instability of calcium carbonate precipitation over extended curing periods, which affects the bonding between soil particles. Therefore, the effect of curing time on soil dispersivity is stage-dependent: short-term curing (e.g., 7 days) produces more significant effects, while long-term curing may lead to diminished results.

Curing time also plays an important role in improving soil strength (Yuan et al., 2024). During short-term curing (e.g., 7 days), the rate of calcium carbonate formation is high, leading to a significant increase in soil unconfined compressive strength (UCS). After 7 days of curing, soil compressive strength reaches its peak, indicating that calcium carbonate precipitation has sufficiently filled the voids between soil particles, enhancing the overall strength of the soil. However, with longer curing times, although calcium carbonate continues to precipitate, the rate of increase in compressive strength slows down and may even stabilize. During the 14-day and 28-day curing periods, the rate of calcium carbonate formation slows, and microbial activity begins to decline, leading to a reduced increase in soil strength. This suggests that although longer curing times can increase calcium carbonate precipitation, their contribution to soil strength becomes less significant. Therefore, a curing time of 7 to 14 days is considered optimal for MICP in soil improvement.

The mechanism by which curing time affects soil dispersivity and strength is primarily linked to the amount of calcium carbonate precipitation and changes in microbial activity. During short-term curing, the rate of calcium carbonate precipitation is high, rapidly filling the pores between soil particles and enhancing soil structural stability, which effectively reduces dispersivity and increases compressive strength. As curing time extends, the rate of calcium carbonate precipitation gradually reaches saturation. While precipitation continues to increase, the cementation between soil particles becomes uneven, and microbial activity declines, slowing the increase in soil strength. Additionally, excessively long curing times may lead to an overabundance of calcium carbonate precipitation, which could result in unstable crystal structures, reducing soil toughness and increasing brittleness.

4.4 The Relationship between Calcium Carbonate Content and Soil Strength

Calcium carbonate ($CaCO_3$) is the primary product formed during Microbially Induced Calcite Precipitation (MICP), and its precipitation quantity and distribution directly influence the physical properties of the soil, particularly its compressive strength and stability. Therefore, understanding the relationship between calcium carbonate content and soil strength is crucial for evaluating the effectiveness of MICP in soil improvement. The effect of calcium carbonate content on soil strength is positively correlated. As the MICP process progresses, the amount of calcium carbonate precipitation gradually increases, enhancing the cementation between soil particles and significantly improving the soil's compressive strength. Experimental results show that when the calcium carbonate precipitation is low, the soil's compressive strength remains low with limited strength improvement. However, as the amount of calcium carbonate increases, the compressive strength of the soil increases correspondingly. In MICP treatment, a 7-day curing period allows for a significant increase in calcium carbonate content, thereby substantially improving the soil's compressive strength.

At higher levels of calcium carbonate content, the mechanical properties of the soil show considerable improvement. This is because calcium carbonate precipitation not only fills the pores between soil particles but also strengthens the interaction between the particles, enhancing the overall structural stability of the soil. However, excessive calcium carbonate precipitation can increase the brittleness of the soil, a phenomenon that will be further discussed later.

Although calcium carbonate precipitation typically enhances soil strength, excessive generation can have a detrimental effect, as illustrated in Figure 12a. Excessive calcium carbonate can lead to uneven precipitation and the formation of large crystalline structures, which may result in uneven contact between soil particles and affect the soil's overall mechanical properties (Wu et al., 2021).

Additionally, excessive calcium carbonate precipitation may increase soil brittleness, reducing its ductility and crack resistance. As shown in Figure 12b, experiments indicate that when the calcium carbonate content is too high, the soil may exhibit reduced toughness, which could affect its response to external loads (Wei Yanchao, 2020). Therefore, while increasing calcium carbonate generation during MICP can effectively enhance soil strength, the amount of precipitation must be controlled to avoid excessive deposition that could lead to soil structure brittleness.

The mechanism by which calcium carbonate affects soil strength is closely related to its structure and distribution. Calcium carbonate precipitation fills the pores between soil particles and enhances the cementation between particles, thereby improving the overall strength of the soil. Research shows that an appropriate amount of calcium carbonate precipitation can effectively increase the soil's compressive strength. The uniform distribution of calcium carbonate crystals creates strong bonds between soil particles, reducing soil dispersivity and improving its resistance to wind erosion.

However, excessive calcium carbonate precipitation can lead to uneven crystal formation, which may cause unstable contact between soil particles, ultimately affecting the soil's strength and stability (Cui et al., 2022; Ren et al., 2024). Therefore, the generation of calcium carbonate should be controlled within an optimal range to ensure its effectiveness in soil improvement.

In conclusion, there is a significant positive correlation between calcium carbonate content and soil strength. During MICP, an appropriate amount of calcium carbonate precipitation can effectively improve soil compressive strength and stability. However, excessive calcium carbonate precipitation can lead to soil brittleness and negatively impact its mechanical properties. Thus, during MICP soil improvement, it is essential to precisely control the amount of calcium carbonate generated to enhance soil strength while avoiding the negative effects of excessive precipitation on soil performance.

4.5 Suggestions

Existing studies indicate that soils treated with lower concentrations of cementing solutions exhibit more effective improvement. First, for a given amount of sodium carbonate-induced pre-cipitation, a lower cementing solution concentration facilitates a more uniform distribution of calcite, particularly under low degrees of cementation (Wei Yanchao et al.,2020) Second, while Bacillus pasteurii urease demonstrates some tolerance to saline and alkaline conditions, it remains sensitive to environmental stresses, similar to other microbial enzymes. Optimal urease activity occurs under specific controlled conditions, whereas high concentrations of calcium salts can significantly inhibit enzymatic function, reducing calcium carbonate precipitation (Al Qabany A. et al.,2012)

MICP technology relies on microbially induced calcium carbonate precipitation to bond soil particles and fill voids, thereby enhancing soil properties. Urease activity reflects the ability of mi-croorganisms to hydrolyze urea, which serves as both a nitrogen source for microbes such as Bacillus pasteurii and a reactant in the mineralization process. Through urease catalysis, urea decomposes into ammonia (NH_3) and carbon dioxide (CO_2), which subsequently react to form carbonate ions (CO_3^{2-}). These carbonate ions then combine with calcium ions, resulting in calcium carbonate pre-cipitation.

At the initial stage of MICP treatment, when bacterial and cementing solutions are introduced into the soil, high urease activity and abundant urea promote rapid carbonate ion production, ac-celerating calcium carbonate precipitation. At this stage, nutrient availability is sufficient, leading to a high precipitation rate, rapid pore filling, and a significant increase in soil compressive strength. However, as curing progresses, the depletion of urea and calcium ions gradually reduces the availability of the cementing solution. Additionally, microbial metabolic activity declines due to substrate depletion and encapsulation by calcium carbonate, leading to reduced urease secretion and a subsequent deceleration—or even stagnation—of calcium carbonate precipitation. Over time, while calcium carbonate content may continue to increase slightly, its accumulation progressively fills soil pores, restricting the transport of nutrients and cementing agents, ultimately limiting fur-ther precipitation.

MICP induces the formation of water-insoluble $CaCO_3$, which preferentially nucleates at soil particle contact points, forming inter-particle bridges that enhance cohesion. Additionally, some $CaCO_3$ precipitates encapsulate soil particles, increasing surface roughness and filling inter-particle pores. As a result, $CaCO_3$ functions as a coating, filler, and binder, strengthening inter-particle bonds, increasing soil density, and enhancing structural integrity, ultimately improving resistance to erosion (DeJong J T. et al.,2010; Dadda A et al.,2019).

Challenges in Large-Scale MICP Implementation

The application of MICP technology presents a sustainable alternative to conventional chemical and mechanical soil stabilization methods. However, field-scale implementation faces significant challenges due to the inherent properties of dispersive soils and the complexity of microbi-al-mediated processes.

(1) Achieving Uniform Carbonate Precipitation in Soil

The low permeability of dispersive soils hinders the homogeneous distribution of calcium carbonate ($CaCO_3$) during large-scale MICP applications. Effective implementation requires precise control of reaction kinetics, including the concentration of chemical reagents (e.g., urea and calcium sources) and the delivery mechanisms for bacterial suspensions and reactants. Excessively rapid reactions must be mitigated to prevent premature pore clogging, which compromises cementation uniformity and overall stabilization efficacy.

(2) Addressing Soil Heterogeneity and Unsaturated Seepage in Field-Scale MICP
Natural soil heterogeneity and unsaturated seepage dynamics introduce substantial uncer-tainties in predicting MICP performance at the field scale. Existing theoretical models, constrained by extensive parameterization, computational complexity, and limited practical applicability, fail to provide reliable engineering guidance. Advancing microbial mineralization theory requires an in-novative framework that integrates multiphysics, multiphase interactions, and multiscale coupling.

(3) Mitigating Ecological Risks from Urea Hydrolysis Byproducts

The large-scale use of urea in MICP raises concerns over ammonium (NH_4^+) accumulation, particularly in ecologically sensitive environments. To mitigate eutrophication risks, a dual approach combining in situ monitoring and bioremediation is proposed. Additionally, integrating MICP with nitrogen-assimilating phytoremediation systems—such as hyperaccumulator plants or algae-biofilm hybrids—offers a sustainable pathway for nitrogen sequestration, reducing the environmental impact of microbial soil stabilization.

(4) Evaluating the Impact of Freeze-Thaw Cycles on MICP Performance

In certain regions, freeze-thaw cycles significantly affect soil stabilization during construction. However, research on the effects of freeze-thaw processes on microbial mineralization remains limited. Further studies are needed to assess the durability of MICP-treated soils under cyclic freezing and thawing conditions and to develop strategies for enhancing long-term stability in cold climates.

By addressing these challenges, future research can facilitate the practical application of MICP technology, improving its feasibility for large-scale soil stabilization projects.

5. Discuss

pH has a significant impact on the effectiveness of Microbially Induced Calcite Precipitation (MICP), with its mechanism closely related to microbial urease activity, the generation of carbonate ions, and calcium carbonate precipitation. In practical applications, the appropriate pH value should be selected based on the specific properties of the soil and the goals of the MICP technique to optimize improvement outcomes. A pH range of 7 to 8 is generally considered optimal for MICP treatment, as it effectively promotes calcium carbonate formation and maximizes the soil's compressive strength and stability.

Second, the concentration of the cementation solution significantly affects the MICP improvement results. At lower concentrations (e.g., 0.5 mol/L), the amount of calcium carbonate precipitation is insufficient, failing to effectively improve the soil's dispersive behavior and strength. At 1.0 mol/L, the precipitation of calcium carbonate is maximized, resulting in significant improvements in both the soil's dispersivity and strength. However, as the cementation solution concentration increases further, precipitation becomes uneven, potentially increasing soil brittleness and adversely affecting its mechanical properties. Overall, a cementation solution concentration of 1.0 mol/L is considered optimal for MICP-based soil improvement, as it enhances strength while effectively reducing dispersivity.

Third, curing time significantly influences the dispersivity and strength of MICP-treated soils. After a short curing period (7 days), significant improvements in soil dispersivity and compressive strength are observed, with rapid calcium carbonate precipitation and the most noticeable cementation effects. However, as curing time increases (e.g., 14 days or 28 days), the improvement effect stabilizes, the rate of calcium carbonate precipitation slows, and microbial activity declines, resulting in a decrease in soil improvement. Based on current research, the optimal curing time is generally between 7 and 14 days, during which the soil improvement effect is most pronounced.

Fourth, a significant positive correlation exists between calcium carbonate content and soil strength. In the MICP process, an appropriate amount of calcium carbonate precipitation can effectively enhance soil compressive strength and stability. However, excessive precipitation may lead to soil brittleness, negatively affecting its overall mechanical properties. Therefore, during MICP treatment, the amount of calcium carbonate generated must be precisely controlled to ensure that it strengthens the soil without causing detrimental effects due to over-precipitation.

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