Bio-precipitation of CaCO₃ for soil improvement: A Review

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Abstract. The bio-mineralization of calcium carbonates is an innovative and eco-friendly technique for improving soil, which has recently become increasingly popular in the field of geotechnical engineering. Different bio-cementation methods are employed for improving granular soils, including microbially-induced CaCO₃ precipitation (MICP) and enzymatic-induced carbonate precipitation (EICP). These methods offer innovativeness, effectiveness and sustainability when applied in geotechnical engineering, and have been suggested as possible solutions for various different geotechnical issues. More research has been conducted into MICP compared to EICP. Nevertheless, urease sourced from plants likely offers many benefits over the use of bacteria urease in bio-cementation processes. The present study reviews the mechanisms, possible areas for implementation, related benefits and drawbacks of the bio-cementation techniques. Additionally, it will concentrate on the techniques used in the precipitation of CaCO₃ involving the urease hydrolysis of urea. The study findings will enhance the comprehension of biotechnical mechanisms and ensure that geotechnical specialists are suitably informed with up-to-date knowledge on this subject.

1. Introduction

Bio-cementation methods comprise biochemical processes that occur inside a soil matrix, which produces calcium carbonate precipitation to improve the geotechnical characteristics of soil [1]. CaCO₃ causes a reduction in permeability while simultaneously enhancing the stiffness, strength, dilatancy through filling pores, roughening particles and inter-particle bonding. In the field of geotechnical engineering, the bio-mediated and bio-inspired ground improvement methods have been developed to offer different options to conventional methods of grouting, which has many negative impacts on the environment and global climate. In the two most known types of bio-cementation techniques, enzymatic induced CaCO₃ precipitation (EICP) and microbial induced CaCO₃ precipitation (MICP), the precipitation is induced via hydrolysis of urea (ureolysis).

With regard to the current research into bio-cementation techniques for improving soil, MICP has received the greatest attention. It involves a biological process where the bacteria are harnessed utilising urea hydrolysis to induce calcite precipitation between particle contacts within soil voids. EICP is another method for precipitating the CaCO₃, which is based on a urease enzyme sourced from plants. In comparison to MICP, EICP is not impacted by problems related to the growth and activity of microbes.
within soil, including insufficient oxygen for ureolytic bacteria to become active in deeper soil, and implementation in soil where the bacterial cells are larger than the soil pores [2].

The effective design and application of these methods would enable them to be implemented for various significant geotechnical issues, including fugitive dust management [3], liquefaction mitigation [4, 5], surface water erosion control [6, 7]. Such bio-minerals have the potential for use in engineering applications as they offer sufficient strength along with minimal environmental effects in comparison to traditional techniques. For instance, the manufacture of Portland cement requires extreme amounts of energy and produces a significant volume of carbon dioxide (CO₂) emission in addition to nitrogen oxides and sulphur. Therefore, biological precipitation of CaCO₃ has a prospect to be an environmentally-friendly geotechnical approach for ground improvement.

2. Microbially induced carbonate precipitation (MICP)

2.1. Mechanisms

Microbially-Induced Calcite Precipitation (MICP) processes occur frequently in natural environments. Calcite, the most stable form of calcium carbonate, is generated by various different microbial reactions, including microbial denitrification reactions and microbial ureolysis [8, 9]. The MICP method based on urea hydrolysis is largely dependent on the Bacillus pasteurii, which produces a high yield of urease [10]. The fundamental mechanism through which soil is improved in the MICP method is as follows: (i) The urease enzyme is microbially synthesised via metabolic activities, followed by hydrolysis of urea by the urease to generate carbonate and ammonia ions; (ii) the carbonate ions are bound to the calcium to assemble insoluble CaCO₃ in a medium rich in calcium [10]; (iii) particles of soil are coated in the resulting precipitated carbonate, which also acts as a filler in the empty spaces between particles and binds the particles together, thus enhancing the mechanical characteristics of the soil. Additionally, hydrolysis of urea generates a net rise in the pH level as a result of ionic equilibrium [11]. This process is formulated in Equations 1 and 2 below:

\[
CO\,(NH_2)_2 + 2H_2O \rightarrow 2NH_4^+ + CO_3^{2-}
\]

\[
Ca^{2+} + CO_3^{2-} \rightarrow CaCO_3
\]

Bacteria have a high propensity to adhere to soil particle surfaces. The formation of calcite surrounding the bacterial cells enables soil pores to be filled and bridged, which subsequently reduces the soil’s permeability and enhances its strength.

2.2. Limitations

It has been proposed that the MICP technique can be employed in various different geotechnical engineering fields. However, practical application of this approach presents numerous difficulties and constraints that require further investigation, such as problems associated with cost, environmental concerns, uniform treatment and types of soil in which the method is applicable.

2.2.1. Cost

Producing highly-active ureolytic bacteria as part of the MICP technique is associated with significant costs [12]. However, MICP could be more cost-effective in the long term as it is possible to reuse the bacterial enzyme in following treatment applications (two to three) utilising the same cementation solution [13, 8]. Ivanov and Chu [14] made a comparison of the costs of raw materials when using chemical and microbial techniques for grouting, and determined that the costs with chemical grouting ($2 – $7 per m³ of soil) were less than those for microbial grouting ($0.5 – $9 per m³ of soil). Various studies in the literature have proposed alternative approaches for reducing the costs associated with the practical application of MICP. For example, the utilisation of Ca²⁺ ions dissolved in salt water could be a possible replacement for commercially derived CaCl₂ [12]. How-Ji Chen et al. [15] investigated the application of pig urine as a substitute for industrial urea. Additionally, modification of the constituent
concentrations was found to increase the chemical efficiency, thus enhancing the yield of $[\text{CaCO}_3]_p/\text{[Ca}^{2+}\text{]}$ and $\text{[Ca}^{2+}\text{]}/[\text{urea}]$ in each treatment cycle [16].

2.2.2. Soil type

The MICP technique could be constrained to deeper soil environments as the growth and movement of bacteria is limited in subsoil. Furthermore, it potentially may only be applied to soils comprised of minimal amounts of fines as a result of the smaller pore spaces in fine-grained soils. Generally, the abundance of microbes is higher in soils with larger particles [17]. Hence, the application of MICP is restricted to soils of fine to medium-sized sand or larger. [18].

2.2.3. Environmental impact

Microbial-based urease leaves the organisms in the soil. Hence, injecting ureolytic bacteria into soil presents numerous challenges including the necessity to obtain permission and licenses from the relevant authorities and the continual inspection of the microbial ecology to ensure it is safe [19]. The elements and by-products of MICP could lead to significant environmental concerns. For instance, urea hydrolysis produces ammonia, which can be particularly harmful for people in addition to the aquatic eco-system and air, while also increasing the potential for corrosion due to elevated pH levels [20]. Furthermore, when the calcium is derived from calcium chloride, this increases the possibility that groundwater will become contaminated by chloride [21]. Consequently, further studies are required to solve these problems prior to considering this technique for practical applications.

2.3. Potential implementations of MICP

MICP has reportedly been opooused in various areas of geotechnical engineering for reducing permeability, mitigating liquefaction, increasing the strength of granular soil and controlling erosion of coastlines.

2.3.1. Permeability

The MICP technique can lead to a sustained decrease in the permeability of soil. Whiffin et al. [8] investigated the effects of microbial sedimentation of calcite as a technique for improving soils for different purposes. Subsequent to the injection process, it was found that the soil permeability had decreased approximately by 30%. van Paassen [9] stated that a reduction in the initial permeability of 60% was observed in soils treated with biological methods at around 100 kg/m$^3$ $\text{CaCO}_3$ precipitation, while Ivanov [22] reported a decrease in permeability of 50-99% when a 1 M cementation solution was used. Al Qabany and Soga [23] utilised a 0.5 M cementation solution and observed a 20% decrease in the initial level of permeability at 2% $\text{CaCO}_3$ precipitation.

2.3.2. Erosion

MICP technique can be employed in for controlling the erosion of granular soils. Yufeng Gao et al. [24] researched the seepage control of sandy soils stabilised with MICP. Their findings revealed that durable crusts with low permeability could be generated on the surface of the soil using MICP treatment, which led to a 379-fold reduction in the rate of seepage. Ning and Soga [7] studied the durability of MICP treated gravel-sand mixtures against erosion, and concluded that MICP can effectively mitigate the internal erosion of 25%-75% mix of sand and gravel.

2.3.3. Liquefaction mitigation

Various researchers have demonstrated that bio-cementation technologies have considerable promise for the efficient mitigation of liquefaction. Burbank et al. [25] made a comparison between the results of cyclic shear tests conducted on sand treated with bio-cementation and Portland cement revealing that the cyclic stress ratio (CSR) of the soil treated with MICP was greater than the soil treated with Portland cement. Zamani and Montoya [26] performed cyclic direct simple shear tests (DSS) on silty Nevada sand samples subjected to a cyclic stress ratio (CSR)... The findings revealed that the increased
resistance to liquefaction was due to a rise in density as well as enhanced load transfer and undrained shear strength from the cementation bonds. Xiao et al. [4] demonstrated that calcareous sands treated with MICP reduced surplus pore pressure and compressive strains, while considerably more cycles were required to initiate liquefaction in comparison to untreated calcareous sands.

3. Enzyme induced carbonate precipitation (EICP)

3.1. Mechanisms
Enzyme-induced carbonate precipitation is another method for precipitating the calcium carbonate (CaCO$_3$). EICP has certain similarities to ureolytic MICP, apart from the fact that the bacteria that produces urease is replaced by agricultural-free urease. Nevertheless, the EIPC is considered to be superior to MICP as it is more efficient and cost effective. Urease can be derived from various species of commonly-found plants, such as the pigeon pea as well as certain beans, squashes, melons and plants that belong to the Pinaceae family [27]. In geotechnical implementations, the most well-known and researched urease enzymes are sourced from the jack bean plant (Canavalia ensiformis) [28-30], soya bean [31, 24], and watermelon seeds [31]. The resulting chemical reaction is the same as presented in Equations (1) and (2) above. As with the MICP technique, the soil particles are coated in the precipitated CaCO$_3$, thus allowing them to bind together and improving the characteristics of the soil based on the amounts of precipitation.

3.2. Limitations

3.2.1. Cost
The enzyme may constitute the costliest ingredient of EICP treatment with 57%-98% of the EICP solution costs attributed to the enzyme [32]. One method of reducing the costs associated with the enzyme is to use crude extract rather than urease that has been purified commercially, or alternatively, the enzyme could be extracted from agricultural waste [21].

3.2.2. Soil type
The enzyme is approximately 12 nm in dimension [16]. Thus, the solubilized urease enzyme gives a distinct advantage over microbial urease due to its small size. The use of plant-derived urease can also reduce the possibility of bio-clogging as a result of CaCO$_3$ precipitation and biofilms formation, which could both limit the applicability of MICP [8]. In addition, it increases the chance of injecting the cementation solution into deeper and finer soils, with no concern about bacterial growth related to MICP.

3.2.3. Environmental impact
Similar to ureolytic MICP, the ammonia by-product is the primary environmental issue related to EICP. The lifespan of the urease enzyme is relatively short and its function and activity are progressively decreased [34]. This property has potential benefits in certain engineering fields as the enzyme will degrade in a natural manner, thus reducing long-term effects on the environment.

3.3. Potential implementations of EICP
Enzyme-induced carbonate precipitation (EICP) has similar application potential to MICP but over a broader selection of soils as a result of the smaller dimension of the urease enzyme and its solubility, to mitigate slope stability, erosion and scour, bearing capacity of shallow foundations, as well as seismic settlement and liquefaction.

3.3.1. Permeability
Nemati and Voordouw [35] utilised enzymatic calcium carbonate for reducing the permeability of unconsolidated porous media and Berea sandstone cores. Yasuhara et al. [5] investigated the hydraulic characteristics of sand specimens that had been treated by utilising carbonate precipitation induced enzymatically via permeability tests. The permeability of the treated specimens was found to be greater than one order of magnitude smaller than untreated samples.

3.4. Erosion and dust control

Knorr [6] investigated the impacts of water and wind erosion on soil treated with EICP employing various kinds of soil, such as Ottawa F60 sand, silty-sand and mine tailings. The findings revealed that EICP has significant promise for use in managing erosion caused by both wind and runoff of surface water. Hamdan and Kavazanjian [3] treated different types of sand, including uniform medium-grained silica sand, native Arizona silty sand, and fine sand-sized mine tailings, using a process in which the sand was sprayed in a series of pans. The effectiveness of the EICP treatment in stabilising the soil against fugitive dust emissions was tested in a wind tunnel environment. It is interesting to note that the results indicated the considerable promise of the EICP technique for mitigating fugitive dust emissions for all soil types. Cuccurullo et al. [36] examined the potential of utilising crude extracts of urease from soybeans to mitigate the effects of water erosion on silty clay. Preparation of the sample involved the compaction of the soil within an oedometric ring. The durability of treated soil was analysed on the basis of a series of immersion tests on treated and untreated specimens. The findings demonstrated that the treated samples showed a 3-fold improvement compared to the untreated specimens with regard to lost mass.

3.5. Liquefaction mitigation

Minson and Okamura [5] investigated the ability of sand cemented utilising EICP to resist liquefaction at distinct saturation levels (30% and 97%) during curing in undrained triaxial equipment at effective confining pressures of 50, 100 and 200 kPa. The results indicated that the capability of the treated soil to resist liquefaction was significantly improved, particularly when the calcite was precipitated at low levels of saturation. Simatupangb et al. [5] additionally performed undrained cyclic shear strength tests on Toyoura and Keisha No. 4 sands, taking into account various testing factors, such as the particle dimensions, percentage of calcite, confining pressure and the saturation level in the precipitation process. The study findings also supported the suitability of the EICP technique for mitigating liquefaction. Nafisi et al. [37] recently examined the effects of EICP and MICP treatments on the shear responses of two conventional sand soils: Ottawa 20–30 and Ottawa 50–70. It concluded that the shear wave velocity rate was increased in the EICP sample in comparison to the MICP sample, thus enhancing the liquefaction resistance capacity.

4. Conclusions

This study reviewed shortly the mechanisms, possible areas for implementation, advantages and disadvantages of the MICP and EICP methods. These techniques are still restricted to limited environmental conditions such as soil types, particle size, and treatment depth. MICP and EICP have been suggested as a promising solution for numerous geotechnical problems including permeability reduction, liquefaction mitigation, strengthening of granular soil, and controlling coastal erosion. Nevertheless, more studies are required to solve environmental problems associated with its by-products while reducing the treatment costs.
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