Review of Enzyme-Induced Calcite Precipitation as a Ground-Improvement

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Abstract

The examination of nonlinear dynamic soil-structure interaction (SSI) within the seismic responses domain uncovers noteworthy implications for the structural behavior. SSI impacts, encompassing lateral torsional coupling and alterations in base shear, hold a crucial role in transforming the seismic response of structures, particularly in the presence of extreme seismic occurrences. Studies underscore the significance of genuinely integrating SSI considerations into the structural design processes to precisely forecast parameters like natural period, modal mass contribution, lateral displacement, and base shear forces. The inclusion of SSI in the analyses holds the potential to induce modifications in the structure's performance, underscoring the essential need to account for the soil's flexibility and its interplay with the foundation. The incorporation of SSI considerations can markedly influence the foundation shear of structures, with the extent of these impacts contingent upon variables such as pile length, diameter, and soil characteristics. Dynamic models delineating soil-structure interaction are imperative for accurately assessing the behavior of structures upheld by pile foundations and comprehending the energy transmission mechanisms within the soil.

Keywords: Calcite-induced, enzyme-induced calcite precipitation, ground improvement, material, soil strength

Introduction

Numerous methods have recently been developed for ground improvement, such as soil densification, grouting, and stone columns. However, these methods require significant effort in terms of preparation, production, and application. Chemical grouting, for example, involves injecting a compound solution into the soil to enhance its properties. While this method is common, it can cause soil pollution and restrict the area of improvement. Therefore, alternative methods that are environmentally friendly and effective are being explored, such as the calcite-induced precipitation method. This method can enhance soil strength and reduce permeability.

Enzyme-induced calcite precipitation (EICP) is a ground-improvement technique that has shown promise in enhancing the mechanical properties of soil. However, there are limitations to its application. One limitation is the solidification inhomogeneity that occurs at high temperatures, which hampers the effectiveness of EICP [1]. Another limitation is the potential production of toxic ammonia by bacteria involved in the process, which can be harmful to the environment [2].Additionally, the use of cement or chemical products for soil improvement can disrupt the improved soil and create harmful byproducts [3]. Furthermore, the concentration of urease enzyme used in EICP can affect the effectiveness of the treatment, with higher concentrations leading to the formation of a crust on the soil surface[4]. These limitations highlight the need for further research and optimization of EICP as a ground-improvement technique.

2- CONCEPT OF CALCITE PRECIPITATION METHOD

In the calcite precipitation method, soil is treated with grouting material to produce CaCO3. A blended solution containing urea, calcium chloride, and a catalytic agent is prepared. Bacteria are often used in studies to hydrolyze the urea and provide carbonate ions, resulting in the formation of CaCO3. The formation of CaCO3 is described by Equations (1)-(3) in chemical processes.

$$CO(NH_2)_2 + 2H_2O \xrightarrow{catalyst} 2NH^+_4 + CO^{2-}_3 \qquad (1)$$

$$CaCI_2 \longrightarrow Ca^{2+} + 2CI^- \qquad (2)$$

$$Ca^{2+} + CO^{2-}_3 \longrightarrow CaCO_3 \downarrow \text{ (precipitated)} \qquad (3)$$

Enzyme Induced Calcite Precipitation (EICP) has recently been used to enhance soil strength and erosion resistance by decomposing urea into carbonate ions and ammonium using urease enzyme, followed by bonding calcium with carbonate ions to form calcium carbonate. Urease enzyme is typically sourced from plants such as soybeans, jack beans, melons, squash, and pine family plants [5], resulting in environmentally compatible calcium carbonate[6]. The precipitation of calcite improves the engineering properties of soil by binding soil particles and reducing porosity and permeability[7][8]. However, the use of microorganisms presents challenges, such as the need for careful bacterial cultivation management and the hindrance of bacterial effectiveness by excessive substances [9][10][21]. An alternative method called enzyme-induced calcite precipitation (EICP) employs enzymes to generate carbonate ions, making it more straightforward than relying on bacteria [7][8]. The EICP method involves mixing urease powder with dry sand and injecting a CaCl2-urea solution under pressure[8]. It is recommended to simultaneously apply a set of grouting solutions and researchers have assessed the feasibility of this technique using purified urease and reagents, yielding improved soil strength[9][10]. The schematic representation of soil strength improvement through calcite precipitation is shown in Figure 1. Enzyme-induced calcite precipitation (EICP) offers both advantages and disadvantages as a ground-improvement technique. It has the potential to enhance soil properties and improve strength, as well as decrease compressibility and increase soil permeability [1] [2][3][4] . EICP can also remediate soil pollutants and suppress dust [11]. However, considerations must be made regarding limitations, such as uneven solidification and the generation of harmful byproducts during the manufacturing process.

To overcome these limitations, urease inhibitors can be used to regulate urease activity at elevated temperatures, resulting in uniform solidification[1][2]. An alternative technique is bacterial-induced calcite precipitation (BCP), which can also enhance soil strength and reduce permeability [2][4].Additionally, the integration of plant-based urease enzymes, such as soybean extract, in EICP can mitigate desiccation cracking in clayey soils[11] . Further investigation is needed to optimize EICP and address its limitations.

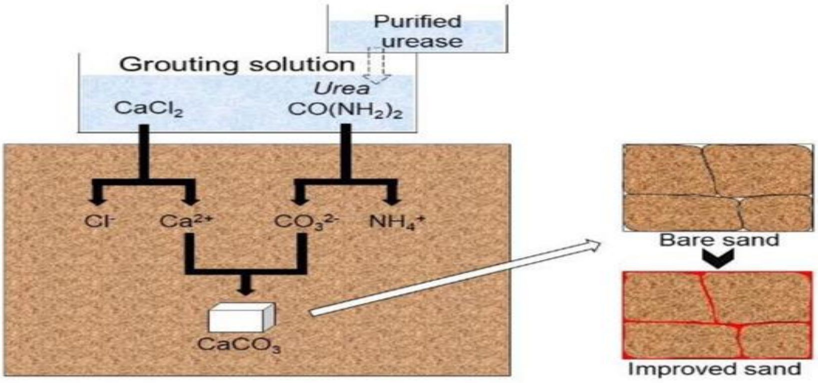

Figure 1. Schematic of precipitation process and grouting procedure in the enzyme-induced calcite precipitation (EICP) technique [9] [10].

3- THE AVAILABILITY AND COST OF UREASE ENZYME

The accessibility and cost limitations of the urease enzyme in enzyme-induced carbonate precipitation (EICP) have been extensively studied. Two separate studies propose using soybean powder as a financially viable alternative to commercial urease, as it exhibits similar urease activity [12][13]. Furthermore, a high-throughput assay developed by Cui et al[14] can be used to compare and assess urease-producing bacteria from different environments, aiding in identifying highly active UPB suitable for EICP. These investigations offer valuable insights into addressing the challenges associated with urease availability and cost in EICP. The efficacy of EICP can be enhanced by exploring alternative materials to address the availability and cost of urease enzyme. Soybean powder has been studied as a potential substitute for commercial urease and has shown comparable activity, making it a cost-effective option for soil improvement [12]. Waste concretes have also been investigated as a source of calcium ions for EICP[15]. demonstrating similar or better treatment effects compared to reagent calcium, thus increasing the cost-effectiveness and practicality of the technology.

Microbially induced calcite precipitation (MICP) has demonstrated long-term durability in treated soil, with the ability to withstand freezing-thawing cycles without significant strength loss[16]. The dissolution behavior of bio-cementation can be accurately modeled using existing chemically controlled kinetic models, indicating the permanence of bio-cemented geomaterials. MICP treatment has also been found to enhance the durability of slope soils, reducing soil loss and corrosion of CaCO3 in acid rain exposure, as well as improving the engineering properties of soft clay. Overall, MICP offers a sustainable and environmentally friendly approach to soil stabilization, with potential long-term durability in various soil types and environmental conditions.

The incorporation of urease enzyme commercial products from jack beans enhances soil properties through the EICP technique [10] [15]. The purification of urease from jack bean meal ensures high purity, [14][15] but large-scale implementation of EICP can be expensive, so alternative enzyme sources should be explored to reduce costs and simplify implementation. Recent investigations have explored potential alternative sources for urease enzymes, such as watermelon seeds, soybeans, and cabbage leaves. Conductivity tests revealed that the reaction rates of crude cabbage and soybean extracts were 93 and 104 U/g, respectively, while commercial urease production yielded 2950 U/g[17]. The utilization of crude watermelon seed, soybean, and cabbage extracts offers advantages in terms of simplicity and cost-effectiveness, as it eliminates the need for purification, thus reducing material costs[16][18] [19] Developing and exploring improved methods and alternative sources for the production and delivery of urease enzyme can enhance the applicability of EICP in different regions. For instance, Vinay Krishnan et al. proposed an improved approach to evaluate urease activity using electrical conductivity measurements[1] Similarly, G. B. S. Pratama et al. investigated the potential of soybean powder as an alternative to commercial urease for calcite precipitation [2], while Sai Sushma Dudala et al. isolated and optimized a potential uricase-producing bacterium [3]. These studies contribute to the development of better methods for urease production and the exploration of alternative sources, thereby increasing the applicability of EICP in various regions [4].

3-1 The potential long-term effects and durability of calcite precipitation in treated soil

Calcite precipitation in treated soil has exhibited potential for long-term durability, as evidenced by the maintained strength and stability of the treated soil even after 20 years of construction [19] [15]. The effectiveness of microbial-induced calcite precipitation (MICP) on sand-clay mixtures was found to be dependent on the proportion of clay content[17], with higher clay content resulting in reduced calcite precipitation [18]

3-2 The effect of calcite precipitation method on organic and clay soils

The impact of calcite precipitation techniques on organic and clay soils has been emphasized in various research studies. Enzyme-induced calcite precipitation (EICP) and microbial-induced calcite precipitation (MICP) are bio-mediated methods that have been explored as potential strategies for soil remediation [15], demonstrating positive effects in reducing drought-induced cracking in clay soils and enhancing the strength of sandy soil, respectively[8] Furthermore, the effectiveness of MICP in sand-clay mixtures is influenced by the proportion of clay content, with higher clay content resulting in decreased calcite precipitation[16]. These findings contribute valuable insights towards the development of suitable additives and treatment approaches for organic and clay soils[20].

4-CONCLUSION

This manuscript analyzes enzyme-induced calcite precipitation (EICP) in geotechnical engineering to enhance sandy soil properties. EICP increases soil strength and reduces permeability through enzyme-assisted breakdown of urea into calcium carbonate ($CaCO_3$), forming crystals that boost shear strength and cohesion. $CaCO_3$ precipitation in soil pores enhances impermeability. EICP is effective for soil stabilization due to increased strength and decreased permeability. Factors like urea and calcium chloride concentrations, and curing temperature influence EICP effectiveness. EICP is a sustainable method for improving soil properties, utilizing a solution with chemicals and urease enzyme to create an injectable calcite solution. The technique discusses practical application, benefits, drawbacks, and complexities, stressing the need for further research on suitable additives and treatment methods for organic and clayey soils.

4-1Future works suggested in this paper

Further study needed to analyze challenges of enzyme-induced calcite precipitation (EICP) in different soils and environments. Future research should focus on assessing long-term effects and durability of EICP in soil to guarantee its effectiveness as a sustainable ground improvement method.

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