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Soil bio-cementation treatment strategies: state-of-the-art review

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Bio-cementation is a new sustainable approach that has gained popularity due to its low energy and carbon dioxide footprint compared with those of existing technologies for geotechnical and geoenvironmental engineering applications. Bio-cementation is a soil improvement technique that involves binding the pore space of soil particles with calcium carbonate minerals by microbially induced carbonate precipitation (MICP) and filling the soil pore space. The purpose of this paper is to present the current state of the art and a comprehensive discussion on the development of bio-cementation for soil improvement/reinforcement. Premixing, injection, immersing and surface percolation are identified as four distinct bio-cementation treatment techniques. Furthermore, scholars have reported employing ureolytic bacteria such as *Sporosarcina pasteurii*, *Bacillus sphaericus* and *Lysinibacillus sphaericus* isolated from corals, limestone caves, soils, waste materials, seawater and other sources to accomplish effective bio-cementation. Some of the major issues (bacterial cultivation costs and ammonium production) that impede its industrial potential and promising remedial techniques are also discussed. This state-of-the-art review also discusses the benefits and drawbacks of bio-cementation compared with traditional approaches. The significance of enzyme-induced carbonate precipitation as a soil bio-cementation alternative to MICP is also highlighted. Finally, the sustainable procedure, bio-cementation principles and future implications are discussed.

Keywords: biomineralisation/circular economy/ground improvement/microstructure/soil stabilisation/sustainable development

Introduction

The bio-cementation process occurs at ambient temperature, is low energy and has a minimal carbon dioxide (CO_2) footprint ('carbon footprint') compared with conventional cement manufacturing (Ivanov *et al.*, 2015; Myhr *et al.*, 2019). Instead of using pyro-processing technology to produce cementitious building materials, bio-cementation is an alternative method for improving soil engineering properties by using microorganisms

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and their products (e.g. enzymes and biominerals) (Omoregie *et al*., 2016). Geological conditions often impact the design of infrastructure projects such as tunnelling (Choo and Ong, 2020; Peerun *et al*., 2020), road construction (Sun *et al*., 2021; Zhalehjoo *et al*., 2018), subgrade stabilisation (Liu *et al*., 2022; Luis *et al*., 2019) and ground improvement (Fatehi *et al*., 2021; Omoregie *et al*., 2017). Globally, the building and construction sector consumes a large amount of global energy and continues to contribute to climate change through its greenhouse gas (GHG) emissions. Therefore, it is important to focus on developing environmentally friendly materials and processes. Additionally, urbanisation and infrastructure development have generated a lot of environmental waste and pollution (Ojuri *et al*., 2022).

Sustainable options for manufacturing construction materials are a top priority due to the need to reduce GHG emissions and the air pollution associated with cement production (Farajnia *et al*., 2022). The construction industry needs a built environment with fewer cement-based materials and more environmentally friendly and innovative construction technologies (Mirkouei *et al*., 2017; Scrivener *et al*., 2018). If appropriate environmental actions are not taken, the construction industry will contribute significantly to GHG emissions, resource depletion and landfill overflow. In recent decades, the use of cement alternatives such as bio-cementation for soil improvement has increased due to the need for net-zero carbon dioxide emission construction practice (Kahani *et al*., 2020). As a result, researchers from various disciplines, such as biotechnology, chemical engineering, geoscience, environmental engineering and civil engineering, are increasingly using bio-cementation for soil improvement and other important applications. The bio-cementation treatment technique uses microbially induced carbonate precipitation (MICP) to produce calcium carbonate ($CaCO_3$) to increase the strength and rigidity of granular soil. It also can be applied at a large scale (Figure 1). The bio-cementation process significantly improves the interface shear strength of geo-structures, according to assessment trials, with an interface efficiency factor of at least 2 and up to 7. Friction piles, earth-retaining structures, strengthened slopes and embankments may benefit from this eco-friendly soil improvement technique (Mortazavi *et al*., 2021).

The efficiency of calcium carbonate precipitation is primarily determined by factors such as biological (enzymatic activity), chemical (cementation ingredients and concentration) and physical factors (soil nature) (Omoregie *et al*., 2021). While bio-cementation technology is becoming more popular, several factors still need to be standardised to optimise bacterial activity and allow real-time implementation of the method in a variety of planned operations (Hadi *et al*., 2022). In addition, while there have been many publications on the use of ureolytic bacteria in calcium carbonate precipitation, the appropriate nutrients required to promote microbial activity and high biomass production (Lapierre *et al*., 2020) and specific MICP conditions that help target desired calcium carbonate polymorphs during bio-cementation are yet to be established (Mokhtar *et al*., 2021). To

(a)

(b)

Figure 1. A sandbox (10 m^3) was subjected to bio-cementation treatment. (a) Front view of the treated soil mass after an outdoor trial treatment; (b) rear view of the treated soil mass

be feasible and practical at the field level, certain conditions are necessary. Another key issue to consider is bio-cementation life-cycle assessment (LCA), which is used to evaluate the environmental impact of any product. LCA quantifies and assesses the inputs and outputs that affect the environmental performance of a product, process or activity throughout its life cycle (Le *et al*., 2019). Therefore, LCA supports a more sustainable planning process and practice. Al-Gheethi *et al*. (2022) recently conducted a comparative study of the health of raw materials and their environmental impact on bio-cementation. Al-Gheethi *et al*. (2022) reported that calcium acetate ($Ca(CH_3COO)_2$) (the calcium source required for calcium carbonate precipitation) contributes nearly 60% to ozone layer depletion, while urea ($CO(NH_2)_2$) (which is a substrate for catalysing urease production and calcium carbonate precipitation) and molasses (a nutrient source for bacterial cultivation) contribute 38% and 13% to marine eutrophication, respectively. However, it would be helpful to know the health and environmental impact of calcium chloride ($CaCl_2$) and yeast extract, which are the commonly used reagents in bio-cementation.

During the bio-cementation process, the extracellular polymeric substances (EPSs) released by bacterial cells increase the calcium carbonate that fills the sand pores and improves sand solidification. The EPSs bind the soil particles together, creating a more stable and cohesive soil structure. The microstructure of bio-cemented soil is characterised by the presence of EPSs, which form a network of filaments and strands throughout the soil (Figure 2). This network helps bind the soil particles together and improves the mechanical strength and stability of the soil. The

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