Soil Improvement Using MICP and Biopolymers: A Review

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Abstract. Ground improvement techniques provide strong natural platforms for construction activities and save the need for designing more resistant structures which would have been necessary on weak ground. This paper discusses the biogeotechnical techniques for improving the resistance of unsaturated sand dunes against surficial erosion by natural processes of wave actions and storm surges. Mechanism of microbially induced calcite precipitation (MICP) and its optimization by utilizing sea water and minimal urea usage is discussed. Common factors affecting the MICP process are briefly discussed. Biomineralization using biopolymers is also described along with the soil strengthening mechanisms. Geotechnical applications of some commonly available biopolymers are described briefly. Advantages and limitations in both these mineralization methods are analyzed and some research opportunities are pointed out for future research.

1. Introduction
Tidal wave surges, strong winds and variations in the sedimentation transport disturb the morphology of the coastal sand dunes. These processes accelerate the erosion of these sand dunes and damage the infrastructure near the coastlines [1]. A study on the coastal erosion of Malaysian shoreline declared that about 29% of the Malaysian coastlines are damaged by erosion. Most of the heavily affected areas are highly urbanized and cater advanced agricultural developments [2].

The surficial strengthening of coastal sand dunes can improve their resilience against surface erosion and reduce the infrastructure damages alongside the coastlines. Compaction cannot be used for strengthening large volumes of sand dunes. Grouting and chemical stabilization methods are environmentally unfavourable, expensive and reduce the permeability thereby obstructing the long distance injections [3]. The carbon footprint produced by the use of cement in the geotechnical applications is already touching to 2% of the total CO₂ emissions by cement [4]. Since the last two decades, interdisciplinary solutions are being developed for ground improvement with minimal carbon footprint. Biomineralization is such a process in which minerals precipitate in the soil pores forming a strong micro-bone skeleton to improve their mechanical properties using biological organisms [5]. The variations in the pH, temperature, moisture content of the environment, cultivation and storage conditions of biological organisms affect biomineralization [6]. Microbially induced calcite precipitation (MICP) and direct use of biogenic excrements (biopolymers) are two forms of biomineralization [4].
2. Biomineralization

2.1. MICP

Microbially induced calcite precipitation (MICP) is the most established biomineralization technique to date [7]. It is a bio-triggered urea hydrolysis that results in the formation of inorganic minerals. Calcium carbonate (CaCO$_3$) precipitates when the calcium and carbonate ions supersede the solubility product of the solution. The micro-organisms, containing urease enzyme, facilitate the precipitation of carbonates (by hydrolysis), produce alkalinity (by increasing the localized pH value) and act as nucleation sites in super saturated solutions [3] (Figure 1). *Sporosarcina pasteurii* (strain designation: ATCC 11859), a bacterium, causes induced calcite precipitation because the mineral produced is dependent on the surrounding environmental conditions [8]. These bacteria are cultivated under sterile conditions and introduced into the soil medium along with the urea and calcium chloride solution [9].

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\text{Net Urea Hydrolysis Reaction: } \text{NH}_2\text{CO} - \text{NH} + \text{H}_2\text{O} \rightarrow 2\text{NH}_3 + \text{CO}_2
\]

**Figure 1.** Summary of biomediated MICP using hydrolysis of urea [5].

The urea hydrolysis is catalyzed by the urease enzyme to produce ammonium and carbonate ions which precipitate in the presence of calcium ions to form calcite crystals.

\[
\begin{align*}
\text{CO(NH}_2)_2 + 2\text{H}_2\text{O} & \rightarrow 2\text{NH}_3^+ + \text{CO}_3^{2-} \quad (1) \\
\text{Ca}^{2+} + \text{CO}_3^{2-} & \rightarrow \text{CaCO}_3(s) \quad (2)
\end{align*}
\]

These crystals develop a skeletal mesh of micro bones between soil grains and stabilize the soil mass (e.g. sand dunes) [10]. The SEM images of the post treated MICP samples are shown in Figure 2. The optimum pH value for maximum urease activity is 8.5 [11]. The higher concentration of calcium ions (1 to 2 M) decrease the urease activity and ceases the urea hydrolysis [12]. Urease activity increases linearly with temperature between 25$^\circ$ to 60$^\circ$ C, attains optimization at 70$^\circ$ C and decreases after 70$^\circ$ C due to enzyme deactivation [12]. Also, the size of bacteria (0.5μm to 5μm) does not allow their transportation through fine grained soils (silt, clay etc.) (Figure 3). Therefore, they cannot induce calcite precipitation in such strata [13].
Figure 2. SEM results showing the cemented soil samples after prescribing pulses of 0.25 M CaCO$_3$. (a) CaCO$_3$ crystals are covering the sand grain surface; (b) and (c) mesocrystals with a focus on their surface; (d) white arrows showing the center of calcification around which mesocrystals develop in size after subsequent pulse injections [10].
Figure 3. Comparison of typical sizes of soil particles and bacteria, geometric limitations, and approximate limits of various treatment methods [5].

The surficial resistance of sand dunes against erosion can be improved by MICP without employing any injection wells. Sand dunes are generally unsaturated in nature. The treatment solution is trapped within the menisci at the inter particle junctions and facilitates the calcite precipitation only at these particle contact surfaces thereby optimizing the biogrouting effect in the sand dunes [14].

MICP treatments for coastal sand dunes have been considerably optimized economically by using sea water instead of transporting fresh water for urea hydrolysis. This reduces the unconfined compressive strength (UCS) or in other words the resistive strength of sand dunes when compared with the fresh water treatment results due to breaking of chemical bonds in the weaker sodium based precipitations (Figure 4). This deviation is less significant at lower cementation levels and more favorable from an economic perspective. Moreover, the optimal urea influent calculations contribute towards a more sustainable and green environment by reducing the amount of effluent ammonia associated with the current MICP practices [15].
2.2 Biopolymers

Biopolymers are a type of organic polymers and are produced by biological organisms. They are easily available in the nature and are generally harmless. The exo-cultivated biopolymers can be directly used for ground improvement without the need of any nutrient injection and can strengthen even the fine-grained soils [8]. Beta-glucan, cellulose, chitosan, curdlan, polyacrylamide, starch and xanthan are commonly used biopolymers for ground improvement [16].

The highly charged specific surface of biopolymers enhances their interaction with fine soil particles and provides strong biopolymer-soil medium. The cohesive strength of this medium synergizes with the friction produced at the interface of coarse particles and the aggregates to strengthen soil mixtures of sand and clay (Figure 5) [4]. Moreover, the high quantity of water in the soils is absorbed by the dehydrated biopolymer gels (Figure 5 a, b) or biopolymer-clay network (Figure 5 c, d) [17].

The increase in water content significantly decreases the elastic properties (stiffness, tensile strength) of biopolymer hydrogels thereby reducing the soil strength by about 1/10th of the strength when in the dried condition in a completely saturated environment. However, the UCS values of biopolymer soil mixtures (i.e. sandy soil ≥ 50 kPa; clayey soil ≥ 200 kPa) which are re-wetted are higher than the untreated soils [18]. Although many biopolymers are highly sensitive to water, the biopolymers with thermo-gelation properties (gellan gum, agar gum etc.) have a high solubility product when temperature is about 85°C to 90°C and harden back as the temperature returns to room temperature. Such biopolymers retain their high strength even when they interact with water [19].
Figure 5. Schematic model for soil-biopolymer interaction: (a) chain type biopolymers with sandy soils; (b) gel type biopolymers with sandy soils; (c) chain type biopolymer with clayey soils; & (d) gel type biopolymers with clayey soils [4].

Figure 6. SEM images of (a) Gellan gum interlacing Kaolin clay; (b) Gellan gum film coating the sand grains (Jumunin, Korea) [18].

Biopolymers, being organic in nature, are susceptible to biodegradation with the passage of time. However, Xanthan gum biopolymer treated soils can show consistent strength parameters for about 2 years [20]. Protein based polymers (casein proteins) have lower hydrophilic properties than the polysaccharide biopolymers and may result in higher resistivity against water when used to stabilize saturated soils [20].

The scanning electron microscope (SEM) analysis indicates that gellan gum biopolymers form face to face clay layers when bonded with kaolinite clay layers and form film coatings when interacting with sand particles (Figure 6). These biopolymers provide maximum strength in the presence of fine grained soils (clay) because they form strong hydrogen and ionic bonds with the clay particles bearing electrical charges [18].

3. Conclusions
MICP shows promising results in both fully and partially saturated soils but the challenges of field upscaling, generation of effluent ammonia, limited application to coarse grained soils, highly specialized growth environment for the bacteria, their subsequent time consuming in situ growth and application pose difficulties in their usage in commercial geotechnical engineering practices. More research addressing these challenges can help in harnessing their true potential without disturbing the environment.

Biopolymers, being innocuous and abundantly available in nature, have the advantage of direct in field application compared to MICP because they can be produced outside their natural habitat and then applied in the field for eco-friendly ground improvement. Many biopolymers are very expensive till date because of their food grade production quality but, for geotechnical ground applications, such
purity is not required and hence the cost can be reduced if they are mass produced with lower than edible grade quality. Their water sensitive nature and biodegradation still pose challenges for their application on a large scale.

Further research in overcoming these limitations may carve out not only a promising green future but also offer sustainable ground improvement solutions with zero carbon footprint.

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