# A Review on Biological Process for Improvement of Soil Properties in Geotechnical Engineering

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***Abstract***

*The biological processing of soil, also termed as the bio-mediated soil improvement method, is known to improve the engineering properties of soil and other construcation materials in terms of their environmental sustainability and performance. This paper reviews the soil microorganism process and other environmental factors that affect their metabolic activities and their geometric compatibility with the soil particle sizes. Two approaches are practiced in geotechnical engineering; biologically-induced and biologically-controlled mineralization. Environmental and other factors that may be encountered in situ during microbially induced calcite precipitation (MICP) and their influences on the process were identified and presented. Improvements in the engineering properties of soil such as strength/stiffness and permeability as evaluated in some studies were explored. Potential applications of the process in geotechnical engineering and the challenges of field application of the process were identified.*

**Keywords:** *Biologging, Bio-mediated; Microorganisms, Biomineralization, Metabolic activities, Soil improvement, Calcite precipitation*

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## Introduction

Recent studies on applications of bio-mediated soil improvement method have proved the viability of the approach for effective performance and environmental sustainability. The promising outcomes of these studies have shown greater potential of exploring a wider application of the technique in geotechnical engineering. Bio-mediated method of soil improvement has been considered as an inventive and new approach in geotechnical engineering that can be utilized to prevent liquefaction and landslide in loose sand which usually results in foundation deformation and/ or failure. Nowadays the growth in global population is increasing the demand for housing and agriculture lands. Moreover, most of the ground soil cannot sustain the load and required to get its properties improve. Many studies showed the effect of Microbially Induced Calcite Precipitation (MCIP) in soil and their used calcite [1, 2]. Recently MICP is a method for soil improvement and new branch of geotechnical engineering. Soil improvement relates to factors such as increasing of stiffness, shear strength, decreasing of hydraulic conductivity, and compressibility to implement in the soil construction project. Presently there are different methods available for soil improvement but the most popular is MICP and this approach is desirable when it is used in the soil particle pores for bonding the particles chemically thus improving the soil properties. However, this method was declared as hazardous approach due to the presence of sodium silicate [3]. DeJong et al., (2006) defined the biggest challenge for soil engineering is improvement of soil in term of its physical and mechanical properties using various techniques [4]. Wath and Pusadkar (2019) suggested bacteria and microbes in a microbial process for enhancing the soil properties that can come to effect within the pores of the soil matrix [5].

Microbiological treatment is a more conveniently applicable method than other methods [5]. The shape of mineral admixture precipitation within the properties of soil is called bio-cementation. One common type of bio-mineralization process is the MICP that has bond grains and sand together and develops the properties of soil [4-6]. Another way of soil processing is microbial induced biochemical which is also called bio-logging process and is used to obtain the information about various geotechnical soil properties. Currently all soil engineers are focusing on the expansion of microbes and evaluation of the bacteria strength in the geotechnical engineering despite the evaluated performance of different microbes.

The main purpose of this paper is to review soil microorganism process and environmental factors which are affecting the metabolic activates and geometric compatibility with particle sizes of soil. Many researchers concentrated on bacterial ureolysis [7-16]. Wath and Pusadkar (2019) carried out experiments laboratory which showed high urease enzyme activity and working on geotechnical applications of soil properties [5]. Chou (2008); Mortensen et al. (2011); Soon et al. (2013); Dhami et al. (2013); Kim et al., (2014); Shahrokhi et al. (2015); Maleki et al., (2016); and Chang et al., (2016) illustrated the sustainability of geotechnical which is using microbial treatments for improvement of soil [17-24].

**1.1 Current Soil Improvement Techniques**

The demand for new, sustainable methods to improve soil continues to increase, with more than 40,000 soil improvement projects being performed per year at a total cost exceeding US$6 billion/year worldwide. [25-27].

The majority of these soil improvement techniques utilize mechanical energy and/or man-made materials, both of which required substantial energy for material production and/or installation. A common approach is to inject synthetic man-made materials, such as micro-fine cement, epoxy, acrylamide; phenoplasts, silicates, and polyurethane are the most popular technique [28]. Although it used into the pore space to bonding soil particles to each other and also using different types of chemical approach for soil improvement [26, 27]. In 1974, acrylamide grout was associated with five cases of water poisoning in Japan, resulting in the ban of nearly all chemical grouts [3]. This reverberated in the US, with pending federal regulations forcing the withdrawal of most products on the market. Recent initiatives in certain countries propose to ban all synthetic man-made grouting materials. Furthermore, all current grouting injection approaches suffer from low "certainty of execution", i.e., the ability to create the conditions specified in the original engineering design in-situ. In general, grouting treatment methods are only effective up to 1–2 m from the injection point, yet, quality control during construction is primarily limited to monitoring the injection volume and pressure; no real time measurements are made of the changes that actually occur in the subsurface. The uncertainty in the final constructed condition forces conservative over-design, resulting in unnecessary project costs and excess quantities of grout consumed.

Method of grouting injection is currently safer than before, for instance, execution certainty to have the ability to provide specific status for principal engineering design in-situ.

### 1.2 Soil Microorganism

Soil contains more microorganisms than other microbial habitats because it consists of many nutrients and mostly retains some liquid in pore spaces 25-27]. A number of microorganism types are existing in soils whereas some of them are not available in soil properties. Although survival and growth factors of microorganisms can't naturally be distributed among in-depth of the lithosphere [27]. Xanthakos et al., (1994) describes the genetically and physiologically adaptability and existence of the microorganism's status for more than 3.5 billion years [28]. Approximately microorganism per kilogram is present in the ground surface soils [29].

Eukarya and Archaea are the most popular bacteria in soil properties having significant feature e.g. archaea involvement of cell structure with more than one chromosome and separate chemical combination. Although without the membrane-enclosed nucleus. Also, the classification of microorganisms can be performed using the cell wall, shape, nutrients types and biochemical transformation type, as well DNA and RNA [30, 31]. According to Mitchell and Santamarina (2005) many microorganisms in soils are observed to be bacteria that can potentially withstand the environmental condition by making [32]. The bacteria have cell diameter limited round about 0.5mm to 3 mm having round, rod or spiral shape. They can survive at different temperatures. The urease enzyme produced by a number of bacteria and the method is using bio-mediated soil improvement. These bacteria consist of genera Desulfotomaculum, Bacillus, Clostridium Sporosarcina, and Spoloactobacilus [33]. The activity of microorganisms in the production of urea is divided into two groups according to response to the high presence of ammonium. The class one includes bacteria that urease activity cannot be repressed because of multiple ammonium concentration. The second one includes those bacteria that urease activity can be repressed to several ammoniums such as Pseudomonas, Bacillus, Eutrophus, Megaterium, Alcaligenes, Aeruginosa, Pseudomonas, and Klebsiella [33]. These urease activities cannot be repressed with high ammonium content as referred to as the technique of bio-mediated soil improvement [34]. Table 1 demonstrates the high urease activity without repressing the ammonium content.

**Table 1: Bacteria with High Urease Activity without Repress Ammonium [34]**

| Bacteria Name | Urea activity | No repressing with $NH_4^+$ | No genetically modified and/ or pathogenic |
|---|---|---|---|
| Ureplasmas | True | True | True |
| Proteus Vulgaris | Unknown | True | Medium |
| Sporosarcina Pasteurii | True | True | False |
| Helicobacter Pylori | True | True | False |
| Proteus Mirabilis | Unknown | True | False |

*Source: (Whiffin, 2004)*

Hence, all microorganisms are found to be good for bio mineralization applications because of their urease activity; they must also be safe for the environment during and after the treatment process. Therefore, urease-producing bacteria for bio-mediated applications should not be pathogenic, genetically being modified or enclosing any exchangeable elements that may enhance the pathogenicity of environmental microbes.

Based on Burne and Chen (2000) the evaluated urea hydrolysis typically following with dynasty chemical reaction which makes the development of carbon dioxide (CO2) and ammonia (NH3) [35]. The formula of chemical reaction as mentioned at the Figure 1 demonstrates the subtleties of urea hydrolysis responses for the precipitation of calcium carbonate by Sporosarcina pasteurii and are given in the following equations.

$$CO\,(NH_2)_2 + H_2O \rightarrow 2NH_3 + CO_2 \quad (1)$$

$$2NH_3 + 2H_2O \rightarrow 2NH_4^+ + 2OH^- \quad (2)$$

$$CO_2 + H_2O \rightarrow HCO_3^- + H^+ \quad (3)$$

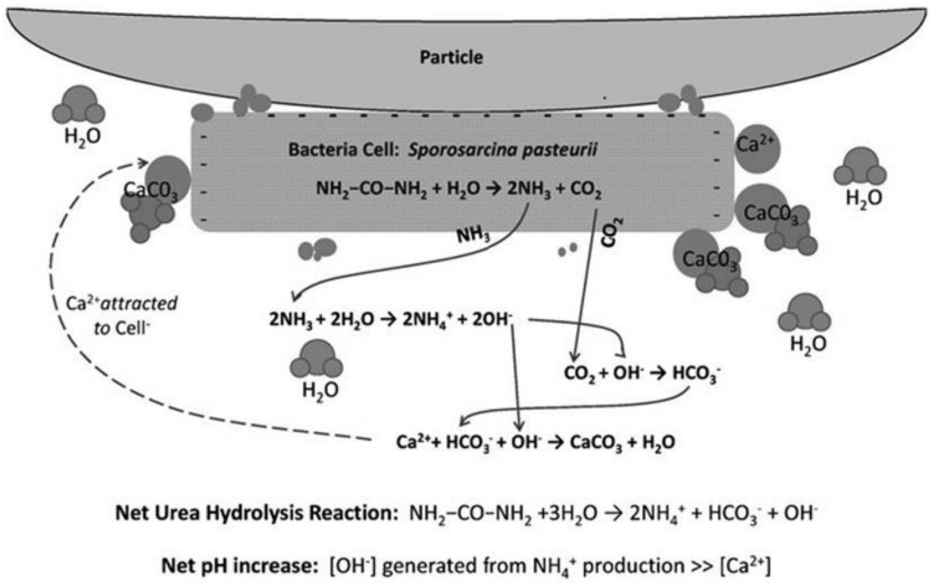
$$HCO_3^- + H^+ + 20H^- \leftrightarrow CO_3^{2-} + 2H_2O \quad (4)$$

$$Ca^{2+} + CO_3^{2-} \rightarrow CaCO_3 \quad (5)$$

$$CO(NH_2)_2 + 2OH_2O + Ca^{2+} \rightarrow 2NH_4^+ + CaCO_3 \downarrow \quad (6)$$

Environmental factors can be affected in metabolic response among the cells and other physical properties, for example, consistency and dispersion. The accessibility of microorganisms confines the current space for bacterial development action, and limits the number of inhabitants in bacteria. “The soil pH value which generally increases the salinity of an environment affects adsorption, surface charge and dissolution of some minerals in the soil” [36].

**Figure 1: Bio-mediated MICP using Hydrolysis of Urea [27]**



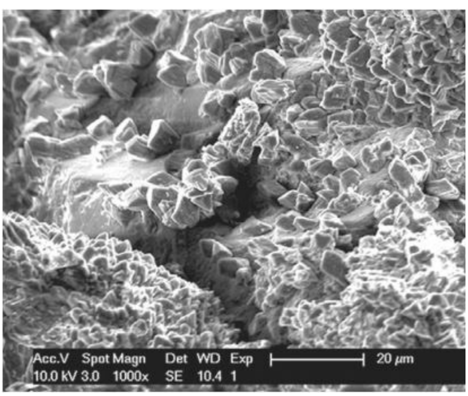

*Source: (DeJong et al., 2010)*

## 2 Biominralization

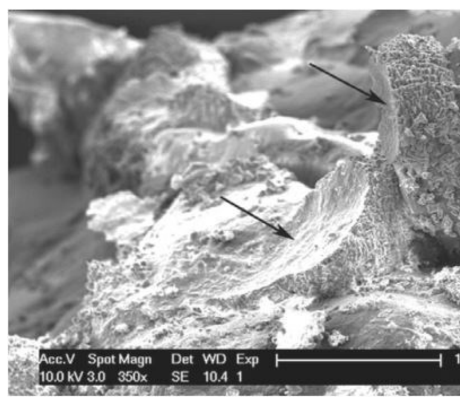
MICP is the most common technique in Bio mineralization today [37]. Inorganic minerals are produced by bio-triggered urea hydrolysis. Precipitations of Calcium carbonate (CaCO3) while carbonating ions and calcium replace product solution and the majority micro-organisms consist of urease enzyme. In spite of the fact that can be helped by precipitation of carbonates (with hydrolysis), "product alkalinity (by increasing the localized pH value) and act as nucleation sites in supersaturated solutions" [37]. Figure 1 demonstrates the "Sporosarcina pasteurii (strain assignment: ATCC, 11859), the explanations behind bacterium-initiated calcite precipitation in this manner mineral was created in ecological conditions" [38]. These microscopic organisms are refined under sterile conditions and enter the soil condition with urea and calcium chloride arrangement [39]. This "urea hydrolysis is catalysed by the urease enzyme to produce ammonium and carbonate ions which precipitate in the presence of calcium ions to form calcite crystals" [2]. In Figure 2 the SEM image of MICP samples. The maximum values of pH urea activities are 8.5 [40]. The calcium ions concentration is 1 to 2 M and reduces the activity of urease as well as urea hydrolysis [34]. The activity of urease can be increased in temperature from $250^0 \, to \, 600^0$ C, obtaining optimum values at $700^0$C addition reduces since $700^0$C because of enzyme deactivation [34]. 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 [35].

MICP can be improved on surficial resistance of sand dunes versus soil blowing without applying any infusion wells. Usually sand dunes are available in unsaturated form in nature. “The treated solution is trapped within the menisci at the antiparticle junctions and facilitates the calcite precipitation only at these particle contact surfaces thereby optimizing the bio-grouting effect in the sand dunes” [4].

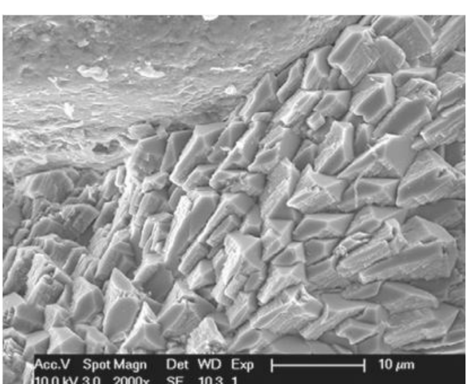
MICP treats the coastal sand dunes by using sea water instated of fresh water for urea hydrolysis, and this method is very economical. It can reduce the unconfined compressive strength (UCS) by increasing strength of sand dunes [40]. Figure 4 the analyses of fresh water treatment showing the broken chemical bonds because of a direct impact of weaker sodium-based precipitations.



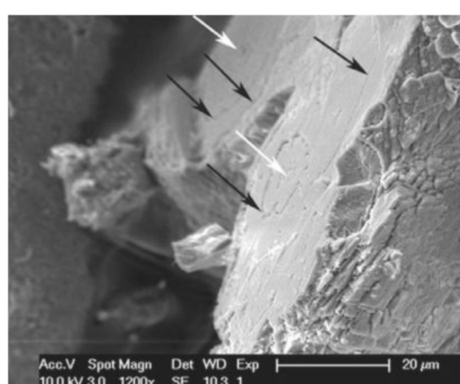

(a)




(b)



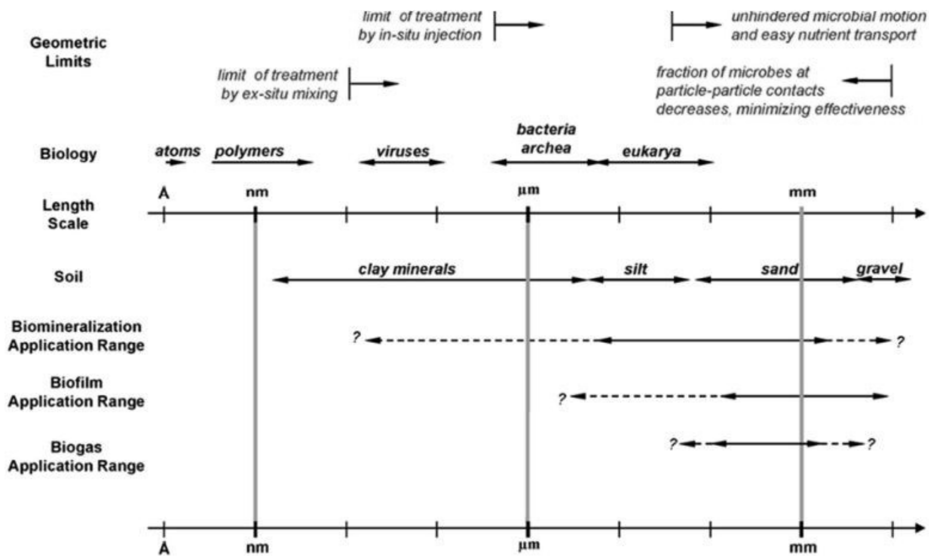

(c)




(d)

*Source: (Stocks et al., 1999)*

Figure 2 SEM picture illustrated “for the sample cemented after prescribing pulses of 0·25 M calcium chloride: (a) calcium carbonate crystals covering the sand grain surface; (b) and (c) microcrystals with a focus on their surface; (d) a calcification centre is observed (white arrows) around which the microcrystals grow in size upon subsequent pulse injections" Stocks [40].




*Source: (Mitchell & Santamarina, 2005; DeJong et al., 2010)*

**Figure 3: Comparison of Soil Particles Sizes, Geometric Limitations and Microorganisms [32] and [27]**

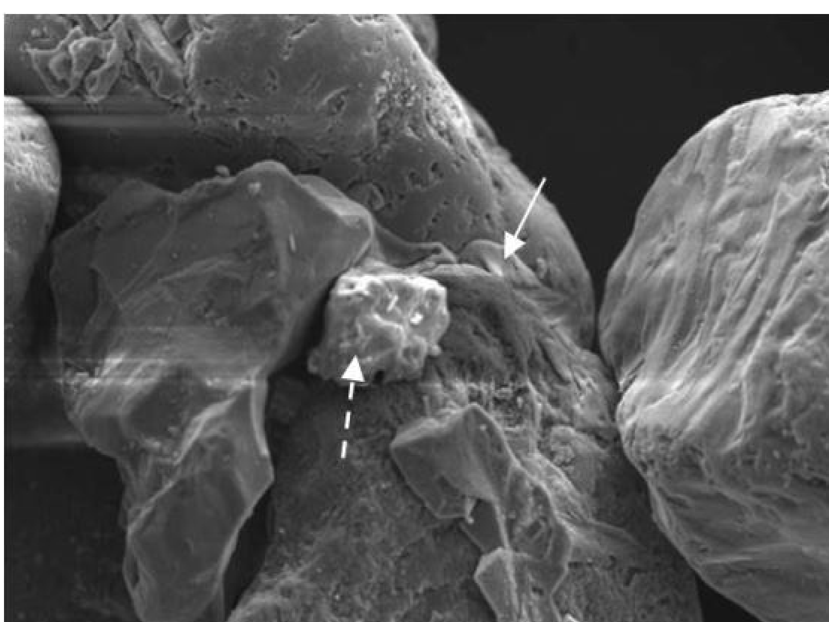


Figure 4 "SEM image of salt water treated North Carolinian dune sand (100x), the solid arrow points towards the sodium-based cementation, the broken arrow shows the salt grain" [41].

## 3 Microbiology Mechanism

The mechanisms for microbiological applications to geotechnical engineering can be divided into two main categories: bioclogging and biocementation. Bioclogging is a process where the soil void is filled by the product from microbial-induced biochemical process. Biocementation is to enhance the strength and stiffness properties of soil and rocks by introducing bacteria and cementation reagents into the soil.

Ivanov and Chu (2008) describes different possible microbial processes that can lead potentially to bioclogging and biocementation. Bioclogging includes formation of impermeable layer of algal and cyano bacterial biomass. [42]. Bioclogging includes the development of an impermeable layer of bacterial biomass of Algae and Cyano. Biocementation includes the development of the soil particles by sulfides of metals created by sulfate lessening microscopic organisms and incumbent of the particles with carbonates of metals delivered as result of hydrolysis of urea [35-41]. Incumbent of the particles with ferrous and ferric salts and hydroxides are created because of action of iron diminishing microorganisms [42].

## 4 Factor affecting MICP Process

Microbial induced calcium carbonate precipitation as a characteristic procedure that includes metabolic activates of the microorganisms and some chemical responses is the most part as represented by some natural conditions.

Mortensen and DeJong (2011) evaluated the effects of some factors that may be encountered in field during MICP treatment and are likely to affect bacterial growth, metabolism and the precipitation induced by the bacteria using the bacterium Sporosarcina pasteurii [13]. Soil column and the batching test was utilized to assess the subsurface of a surrounding factor in the treatment process. Development of Microbial and carbonate precipitations were surveyed in sea and freshwater the conceivable watery environment in situ. Oxygen accessibility, mineralogy, Ammonium assemblage inclusion molecule sizes of soil parts of the conditions that can be affected in the action of microscopic organism's evaluation. Numerous scientists proved MICP treatment can be achievable by using a wide range of soil types, ammonium chloride assemblages, soils molecular size and range of salinities. Many researchers describe the impact of various ecological components assessed, such as bacterial cell assemblage, urea, and calcium particles collection [40-43].

The study inferred that the estimation of urea hydrolysis enhances likewise enhance bacterial cell assemblages [43]. The previous study revealed that the rate of urea hydrolysis increases with the increase in bacterial cell concentrations and a tremendous increase in calcium carbonate precipitates of 100% was recorded when the calcium ions were increased by ten times [20-30]. The authors also reported that urease-catalyzed ureolysis is temperature-dependant like any other enzymatic reaction, as such a temperature range of 20 to 37°C provided efficient MCP depending on environmental conditions and concentrations of other reactants in the system.

## 5 Application of Microbial in Soil Properties

The microbial can be widely used in soil improvement in various ways. Most of process injection mode can be used for bacteria intrusion while in some cases mixing with soil can be taken place before placing in position [4]. Some of the areas where improvement needs are:

- Reinforcing or stabilizing soil to facilitate the stability of tunnels or underground constructions.
- Increasing the bearing capacity of piled or non-piled foundations.
- Reducing the liquefaction potential of soil;
- Treating pavement surface.
- Strengthening tailings dams to prevent erosion and slope failure.
- Binding of the dust particles on exposed surfaces to reduce dust levels.
- Increasing the resistance of offshore structures to erosion of sediment within or beneath gravity foundations and pipelines
- Stabilizing pollutants from soil by the binding.
- Controlling erosion in coastal area and rivers

Table 2 summarizes various studies performed to enhance the geotechnical properties of soil. The bacterial can enhance sandy soil and dark cotton soil resulting in improved solidity, decreasing porousness and swelling attributes. Table 3 demonstrates some reaction conditions revealed in the literature for the generation of calcium carbonate through microbial urea hydrolysis for bio-cementation, biological, and different applications. Despite the fact that diverse techniques for injecting the cementation reagents into the soils are utilized in the treatment forms, fundamental enhancement in quality and decrease the hydraulic conductivity of soils. The significant concern in regards to the typically embraced techniques for 'injecting the cementation' reagent from surface descending is the differential dissemination of the calcite, with many being reserved at the surface contrasted with that at the base of the van example [44].

**Table 2: Improvement of Soil Properties in Geotechnical Engineering**

| No | Soil type | Bacteria | Process of Microbial | Improvement | Reference |
|---|---|---|---|---|---|
| 1 | Ottawa 50-70 Sand | Bacillus Pasteurii | Cementation Process | Increase axial and elastic capacity | [5] |
| 2 | Itterbec k Sand | Sporosarcina pasteurii | Activity of urease | Decrease porosity 90% Increase strength | [6] |
| 3 | Sand | Mineralization of urease enzyme | Enzyme for urea hydrolyze | Limited compressive strength increases also permeability decrease | [51] |
| 5 | Sand | Sporosarcina Pasteurii | Precipitation of calcite | Limited compressive strength increases also permeability decrease | [23] |
| 6 | Black cotton soil | Tryptic Soy Broth used for Fastidious or non-Fastidious | Tryptic Soy Broth | Shrinkage limit will increase, plastic limit decreased also swelling stress decrease | [22] |
| 7 | Sand | Bacillus Sporosarcina Spoloactobacil us Clastridium also Desulfotomacu lum | Hydrolysis | Shear strength was increased, limited stuffiness, compressive strength and liquefaction can resist | [24] |

*Source: Author's Compilation*

**Table 3: Reaction Status for The Generation of Calcium Carbonate Utilizing Microbial Urea Hydrolysis**

| No | Application | Urea. (mM ) | $Ca^{2+}$ (mM ) | Activity of urease (mM urea/min ) | Microorgani sm | Type of soil | Refe renc e |
|---|---|---|---|---|---|---|---|
| 1 | Bio-cementation | 1500 | 1500 | 4-18 | Sporosarcina pasteurii | Sand | [34] |
| 2 | Bio-cementation | 500 | 500 | n/s | Bacillus megaterium | Sand/silt | [43] |
| 3 | Bio-cementation | 500 | 500 | 5-20 | Bacillus sphaericus. | Silica sand | [44] |
| 4 | Bio- | 1000 | 1000 | 10 | Sporosarcina | Silica | [45] |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | cementation | | | | pasteurii | sand | |
| 5 | Bio-cementation | 500 | 500 | 0.65 | Sporosarcina pasteurii | Sand | [46] |
| 6 | Bio-deposition | 330 | 25 | 0.67-1.33 | Sporosarcina pasteurii | Sand | [47] |
| 7 | $CO_2$ Sequestration | 650 | 250 | n/s | Sporosarcina pasteurii | - | [1] |
| 8 | Bio-deposition | 25 | 25 | n/s | Sporosarcina pasteurii | Sand | [48] |
| 9 | Biological | 1500 | 740 | 6.2 | Bacillus sphaericus | Sand | [49] |
| 10 | Removal of $Co^{2+}$ From wastewater | 16 | 14 | 0.293 | Isolates closed to Bacillus sphaericus | - | [50] |

*Source: Author's Compilation*

## 6 Conclusion

Microbial-induced calcite precipitation is another handy methodology in geotechnical engineering. It may enhance current and new soil structures. It is utilized in various geotechnical engineering applications like slope stabilization and subgrade reinforcement. This procedure has incredible potential in engineering application; however, significant work ought to be done to get an appropriate outcome. One kind of research configuration was connected for this paper which similar investigations, the relative examination can be directed to assess the possibility MICP attainability with that of traditional grouting, particularly with regard to environmental variables and economic factors.

Although MCP has been investigated extensively both in natural environments and under controlled laboratory conditions, the exact mechanism of precipitation and the function of this process within the microbial ecology of the precipitating organism remain unresolved. Thus, the existence of different possible mechanisms with regard to the role of microorganisms in the carbonate precipitation describes the complexity of the biomineralization process and the need to explore more into the process.

Many factors influence bacterial ureolysis and the subsequent calcium carbonate precipitation. These factors include temperature, bacterial cell concentrations, type of bacteria, salinity, humidity, pH value of the medium, concentration of calcium ions, availability of nucleation sites, mineralogy and particles sizes of the soil and many more. Only some of these factors were evaluated in relation to bacterial carbonate precipitations mostly in coarse-grained soil, i.e. sand. Therefore, more studies need to be carried out to assess the effects of these factors particularly in residual soil for field implementation of the process.

Although studies have been conducted to evaluate the strength/ stiffness and permeability of different soils using calcite precipitation induced by microbes, a lot of work has to be done to evaluate the compressibility and settlement properties of soils in their natural state. The main challenge in the success of this approach is to overcome the mass transfer limitations and effectively transport the cementation reagents to deeper parts of the area to be treated. Since most of the studies conducted used injection methods to pump the reagents into the soil vertically either in continuous or stepped applications, studies conducted revealed that more calcite is precipitated at the upper part of the specimen than that at the lower part, thereby causing disparity in the calcite formation within a soil mass.

Though measures were suggested by some authors with regard to the pumping pressure/rate based on the soil types in order to minimize clogging at the inlet and allow for more penetration of the reagents downward, less work has been done for lateral flow of the reagents which may likely be the case in field application for treating large volume of soil. Although the potential advantages and application of the process have been identified in the study, optimization and up scaling of the process, education/training of researchers/ practitioners were identified as the challenges ahead. Hence, it is needed to evaluate the long-term durability of strength induced by the process.

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