Journal of Civil Engineering and Environmental Technology
p-ISSN: 2349-8404; e-ISSN: 2349-879X; Volume 5, Issue 8; October-December, 2018, pp. 551-555

http://www.krishisanskriti.org/Publication.html

Stabilization of Weak Soils by Microbially Induced Calcite Precipitation (MICP) - A Review

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Abstract—*Ground improvement techniques provide a natural platform for construction activities and save the need for designing more resistant structures which would have been otherwise necessary on weak/soft soils. Mechanical compaction and chemical grouting are the two most widely used methods in geotechnical engineering for ground improvement. However, the disadvantages of the methods including high cost, high energy consumption, and potential environmental pollution are obvious. A new ground treatment technique, i.e., microbial induced carbonate precipitation, was developed recently. Bio-cementation is a green treatment technique which makes use of MICP process to enhance the geotechnical features of sub-standard soils. A review of ground improvement using microbial induced carbonate precipitation technique was performed in this study. The mechanism of microbial induced carbonate precipitation-treated soils was first introduced followed by the review of other aspects of the microbial induced carbonate precipitation technique. Thereafter, the related engineering applications of MICP treated soils were presented and summarized. Common factors like the type of microbe, the curing period, temperature, concentration of the microbes, treatment time etc. affecting the MICP process are briefly discussed. Some recommendations were proposed for a wider application of this technique. Advantages and limitations are analyzed and some research opportunities are pointed out for future research in this area of specialization.*

Keywords*: Ground improvement; Microbes; Bio-cementation; MICP.*

1. INTRODUCTION

Microbial process that alters the chemical environment favoring mineral formation is known as Biomineralization [1], [2]. It is a natural phenomenon that leads to precipitation of more than 60 different biological minerals that are formed through extracellular or intracellular pathways [3]. This occurs by a sequence of chemical reactions and physiological pathways which results in the precipitation of a range of different forms of solid mineral structure. These minerals often form structural features such as sea shells and the bone in mammals and birds. Organisms have been producing mineralized skeletons for the past 550 million years.

1.1 Mechanism of Microbially Induced Calcite Precipitation (MICP)

- First, urea ($CO(NH_2)_2$) and water (H_2O) are decomposed into ammonium (NH_4^+) and carbonate (CO_3^{2-}) ions with the presence of urease enzyme. This process is scientifically known as urea hydrolysis. It is important to supply urease positive type bacteria, i.e. genera Bacillus, Sporosarcina, Spoloactobacilus, Clostridium and Desulfotomaculum into soil to promote the production of urease enzyme, and hence the urea hydrolysis process .

$$CO(NH_2)_2 + 2H_2O \xrightarrow{\text{urease enzyme}} 2NH_4^+ + CO_3^{2-}$$

- The release of ammonium (NH^{4+}) is essential for increasing the pH of soil as the subsequent calcite precipitation process favours a slightly alkaline environment. The carbonate (CO_3^{2-}) ions will react with the calcium ion (Ca^{2+}) from the supplied calcium chloride to form calcium carbonate or calcite ($CaCO_3$)

$$Ca^{2+} + CO_3^{2-} \longrightarrow CaCO_3$$

The calcite ($CaCO_3$) precipitated is responsible for improving inherent engineering properties of soil through bio cementation and bio clogging.

In the last two decades, multiple mechanisms have been recognized for the precipitation of calcium carbonate. The methods include photosynthesis [4, 5], urea hydrolysis [1], [6-9], sulfate reduction [10, 11] and extracellular polymeric substances [12, 13]. Each mechanism promotes a different chemical pathway (Figure 1), all of which may be effective for mineralization. However, the microbially induced calcite precipitation via urea hydrolysis is the most commonly exploited mechanism.

Urease activity is found in a wide range of micro-organisms, one of the most commonly studied bacteria is Sporosarcina pasteurii. It is a soil, non-pathogenic, endospore producing bacteria with an optimum pH for growth of 6.5 to 9.0 and can tolerate extreme conditions. Multiple studies have been conducted with Sporosarcina pasteurii for MICP [6], [8], [14-16]. Additionally, Achal and Mukherjee [17] developed a mutant strain (BP-M-3) of Sporosarcina pasteurii MTCC 1761 which resulted in an enhanced level of urease activity and carbonate precipitation compared to the natural type. The most important criteria to consider for the selection of a bacterial strain for MICP process is its ability to synthesize urease enzyme. However, a further consideration is that there are many pathogens among urease producing bacteria. For example, active urease producers includes Helicobacter pylori which infects the human stomach, and the opportunistic human pathogens such as Proteus vulgaris, Staphylococcus aureus, and Pseudomonas aeruginosa [18].

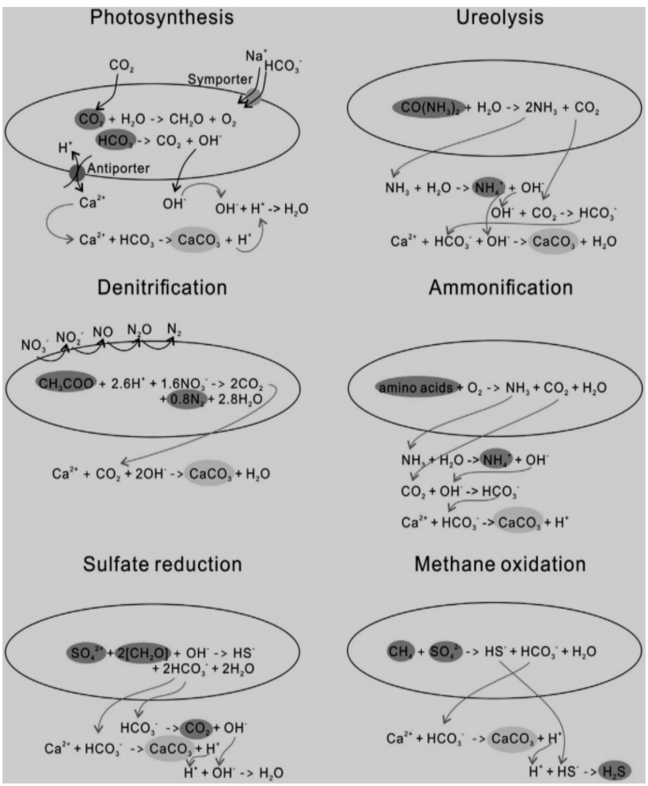

Figure 1: Processes that generate supersaturated environments essential for carbonate precipitation modified from [23].

Hammes and Verstraete [19] and Silva-Castro, Uad [20] reported that urease influences the MICP through four different factors; pH, dissolved inorganic carbon (DIC) concentrations, calcium concentrations and the availability of nucleation sites. The first three factors influence the carbonate ion concentration (CO^{2-}) while the last parameter promotes stable and continuous calcium carbonate formation [1], [21]. During the MICP process, bacteria commonly serves as the nucleation site. These four factors have a major influence on both ureolytic activity and calcium carbonate formation. Ca^{2+} ions bind to the negatively charged bacteria surfaces, creating a favorable environment for Ca^{2+} adsorption. Thus, Ca^{2+} ions bind more frequently onto the negatively charged cell surface of bacteria [22]. Bacterial cells are very important for the precipitation of $CaCO_3$, because the bacteria both provide nucleation sites and affect the types of minerals being formed. Okwadha and Li [8] found that a high concentration of bacterial cells increases the amount of carbonate precipitation via MICP. This occurs because of the increase in the concentration of urease increasing the rate of urea hydrolysis.

2. APPLICATIONS

2.1.1 Removal of Heavy Metals and Radionuclides

Given the current rate of urbanization and industrialization, heavy metals and radioactive waste released both into the atmosphere and into soils due to industrial processes have been observed accumulating in both in landfills and residential environments [25-27]. These accumulated heavy metals and radionuclides pose serious health problems for humans and other living organisms within the environment. Some heavy metals in small dosages are beneficial to humans, but the rate of industrial release can be very toxic to humans [28]. The mobility of the released heavy metal ions may increase the threat to the lives of humans and effective methods need to be implemented to impede their transportation especially through groundwater [29].

Heavy metals including arsenic, cadmium and lead are commonly identified in most landfills at medium to high concentrations [26], [30]. Fu and Wang [28] proposed that heavy metals can be immobilized from the environment using MICP. However, heavy metal toxicity will also affect microbial growth and thus efficiency of MICP may be reduced; several researchers have identified and isolated heavy metal tolerant microbes with ureolytic capability from diverse environments which could improve the efficiency of the MICP process in contaminated ground [31], [32]. During the MICP process, calcium ions are added to a solution to precipitate calcium carbonate, in the heavy metal containment MICP process, calcium carbonates can also incorporate heavy metals (e.g., Cd and Pb^{2+}) into their surfaces via substitution of suitable divalent cations (Ca^{2+}) in the carbonate lattice, which alters the chemical form of these carbonates and alters the heavy metals from soluble to insoluble forms reducing their potential for toxicity.

The disposal of radionuclide wastewater from commercial nuclear plants is a major issues associated with nuclear waste management because it is highly toxic to the environment, particularly to human health. Fujita, Taylor [9] assessed a pump and treat method, but it was unsuccessful at radionuclides removal from the contaminated environment. In such scenarios, MICP can be applied to immobilize the radionuclides safely from the environment. The basic process behind MICP method involves ureolytic microorganisms to precipitate $CaCO_3$, this in turn leads to promote coprecipitation of radionuclides by substitution of Ca^{2+} ion and formation of radionuclide carbonate minerals [9], [33].

2.1.2 Improvement of Engineering Properties of Soils

2.1.2.1 Strength properties The research about engineering characteristics of MICP treated soils mainly focuses on the modification of soil strength, rigidity, permeability, and liquefaction resistance. Fischer, Galiant, and Ban (1999) found that C. pasteurianum can produce more calcium carbonate crystals in sandy soils which strengthen the bonding among soil particles [34]. Whiffin (2004) pioneered the use of microbial technology for bonding loose sand particles [35]. Bacteria solution and cement solution were injected into a 50-mL syringe, then loose sand particles were successfully cemented together into the sand column. The results show that the strength of the treated sand was increased significantly. It is demonstrated that the microbial precipitation of calcium carbonate can be successfully used to bond loose sand into a whole sand matrix with a certain compressive strength.

Furthermore, the increase in strength of MICP-treated soils is greatly affected by the amount of precipitation of calcium carbonate crystals among soil particles. Harkes et al. (2008) used microbial technology to reinforce 20 sand column specimens and tested their unconfined compressive strength and amount of calcium carbonate precipitation [36]. It is indicated that the amount of calcium carbonate precipitation was closely related to the strength of treated sand specimen. Chu et al. (2014) found that the unconfined compressive strength of MICP-treated sand specimen was linearly related to the amount of calcium carbonate precipitation [37].

2.1.2.2 Permeability Due to the MICP among soil particles, the water flow in soils is impeded, and the porosity and permeability of soil is decreased. Ferris et al. (1997) found that the permeability of soil was reduced by 15–20% as compared to the initial value of untreated soils [38]. Whiffin, Van Paassen, and Harkes (2007) found that permeability of treated soil was reduced by 22–75% [39]. Zhang et al. (2015) adopted potato nutrient solution to conduct plugging test on sand specimen and found that the permeability of treated sand was reduced to 1/50 of the initial level [40]. The permeability of treated soils by MICP technique is not uniform, and the reduction of permeability of soils is more as soil is located more close to the bacterial and nutrient solution injection port [41]

3. LIMITATIONS

MICP has a great potential for sustainable environmental remediation. However as MICP is still a new methodology in terms of engineering application, there are a few limitations which must be addressed prior to field implementation:

- MICP is not 100% environmentally friendly, as ureolysis plays a major role in precipitation generating by-products including ammonium and nitrate. These compounds are toxic and thus hazardous both to human health and to indigenous microbial consortia especially at high concentrations [42]. This limits its application for biocementation as ammonium present inside building materials have the potential to be converted into nitric acid by bacteria, which might decrease the bio-deterioration of materials. Ganendra, Muynck [43] found that replacing calcium chloride with calcium formate did not result in the release the ammonia to the air or produce nitric acid. More investigation and optimization is required to advance the process such that the volume/concentration of unwanted byproducts is reduced. Reduction of these byproducts would greatly improve the validity of the assessment that MICP is an eco-friendly treatment.
- MICP greatly depends on temperature, pH, calcium concentration, DIC and the presence of nucleation sites [44]. This makes it a complex and time consuming process in comparison to the chemical process under standard environmental conditions. MICP has to be optimized for time effectiveness before it's used for large scale field applications.
- The economic limitations makes MICP less industrially friendly, as laboratory grade sources needs to be used. Since there is a potential of inefficient MICP when using non-laboratory grade chemical reagents. Although alternative inexpensive nutrient sources for MICP such as lactose mother liquor have been implemented, consideration of a wider range of alternative sources would provide a better assessment of its cost effectiveness [17]. In addition to this limitation, application of insitu MICP would require the generation of substantial volumes of chemical reagents and microbial solutions. Although recently indigenous bacteria capable of MICP are reported, more studies that target specific criteria need to be implemented to resolve this issue [9], [45], [46].

Given the discussion above, although studies of MICP have generated promising results, its application at the large scale is still challenging. This technology is however worth of further study, and the resolution of the issues outlined would promote its implementation as a replacement for less sustainable alternative methods.

4. RECOMMENDATIONS FOR FUTURE DEVELOPMENTS

- Microbial technology has been widely used to reinforce soils, but the problem of heterogeneity of soil reinforcement generally exists in engineering practice. The uniformity of soil reinforcement is affected by the reaction solution concentration, dosage ratio and perfusion process, and other factors included. The current solution is to increase perfusion times, but it is costly. Thus, it needs a lot of experimental work to optimize the reactant mixture ratio as well as the continuous improvement of perfusion process.

- It is necessary to establish a microbial growth model under different soil environments to simulate the formation of contact among soil particles. But the changes in growth, enzyme activity of bacteria are difficult to be accurately quantified and controlled. Hence, further consideration needs to focus on the establishment of micro-organism and soil particle model. The model parameters are numerous, complex environment, thereby how to consider the importance of each influence factor must be the first priority.
- MICP technique is still limited to laboratory tests in relatively small scale. When it is applied in engineering applications of complex environmental factors, it will be a big challenge to find a simple and efficient microbial nutrient solution used as soil micro-organisms.
- Under the marine environment of complex alkaline salinity, mineral composition, microbial concentration and activity, species and concentration of salt, and pH value, the research on the mechanism of MICP technique has just started. The influence of such factors on the engineering characteristic of treated soils is not clear. Therefore, it is necessary to study the strength, stiffness, stress–strain behavior, dynamic characteristics of the MICP-treated marine soils with different salt contents, acidity, alkalinity in different depositional stages, and the concentration and activity of bacteria.

5. ACKNOWLEDGEMENT

We wish to express our sincere gratitude and thanks to the Dept. of Geotechnical Engineering, National Institute Of Technology, Srinagar. We are extremely grateful to all the professors and the technical staff of geo-tech lab, without their guidance this work could not have been accomplished.

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