IJESKA
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www.ijeska.com
ISSN: 2687-5993

International Journal of Earth Sciences Knowledge and Applications

REVIEW ARTICLE

A Review on the Microbial Induced Carbonate Precipitation (MICP) for Soil Stabilization

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INFORMATION

Article history
Received 20 April 2020
Revised 27 April 2020
Accepted 28 April 2020
Available 30 April 2020

Keywords
Soil
Soil stabilization
Bio-geochemical process
Bio-cementation
Microbial Induced Carbonate Precipitation

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ABSTRACT

Soil stabilization known as the process of improving the engineering properties of soils is a method applied when the engineering properties of soil are not suitable for purpose. There are several methods of soil stabilization that could be implemented to improve the physical characteristics of the soils. MICP is one of the most popular bio-mediated processes for improving the engineering properties of porous geomaterials as alternative to other methods. The MICP, nowadays as a subject of intense research interest in the field of biogeotechnology providing solutions to a wider range of engineering applications, utilises bacteria to hydrolyse urea to give carbonate ions which react with a calcium-rich solution to produce calcium carbonate that binds the soil particles together leading to increased soil strength and stiffness. In this bio-geochemical process, MICP increases the strength and stiffness of the soil due to binded the sand grains together at the particle-particle contacts, which increases the strength and stiffness of the soil. It is concluded that MICP can be used for geotechnical engineering purpose of improving soil properties. This cheap and eco-friendly technique improves strength parameters of the soil such as shear strength and decreases the permeability of gravelly and sandy soil.

1. Introduction

Soil is a natural body consisting of layers of mineral constituents of variable thickness, which differ from the parent materials in their morphological, physical, chemical, and mineralogical characteristics (Birkeland, 1999; Hamzah et al., 2015). In practice, it is difficult to find natural soil that provided high strength and high durability. A large number of executive plans such as construction of irrigation and drainage networks, roads, and earth dams might face the shortage of appropriate earth materials. Therefore, the currently existing materials needs to be improved and reinforced. The use of weak soil at the site becomes possible and feasible and decrease in the extravagant costs in the transportation of materials (Mitchell, 1981; Shahiri and Ghasemi, 2017). If strength of soil is poor, the soil stabilization is generally required to enhance the mechanical properties of soils (Andavan and Kumar, 2020). Soil stabilization is widely identified to improve durability, enhance the engineering properties and mitigate the volume change behavior of the soils (Ta'negonbadi and Noorzad, 2017; Behnood, 2018).

There are various methods of stabilization including either mechanical stabilization or chemical stabilization. Mechanical techniques densify the soil expelling air from the voids. Chemical techniques incorporate additives that improve the properties of problematic soils and the chemical stabilizers are characterized as traditional and non-traditional additives. Traditional stabilizers include calcium-based stabilizers such as lime and cement (Tingle et al., 2007; Pooni et al., 2019).

Some of the drawbacks of calcium-based stabilizers have fostered the use of more sustainable and effective non-traditional stabilizers such as enzymes. The enzyme based stabilizers can provide an economical and sustainable alternative in soil improvement compared to traditional stabilizers. Various researchers reported that the enzyme based stabilizers produces maintenance free roads with an increase in bearing capacity (Velasquez et al., 2006; Shankar et al., 2009; Venkatasubramanian and Dhinakaran, 2011; Agarwal and Kaur, 2014; Chandler, et al., 2017; Eujine et al., 2017a; Eujine et al., 2017b; Patel et al., 2018; Pooni et al., 2019). On the contrary, Parsons and Milburn (2003) mentioned that the enzyme based stabilization produced no significant increase in soil strength. It was claimed that the inconsistency of results among researchers can be attributed to differences in sample preparation, type of enzyme and curing methods (Chandler et al., 2017).

Traditional grouting methods for ground improvement employ particulate (cement/bentonite) or chemical grouts that can be rather expensive and environmentally unfriendly (Ivanov and Chu, 2008). Recently, novel grouting techniques (DeJong et al., 2006; Whiffin et al., 2007; DeJong et al., 2010; Khatami and O'Kelly, 2013; Stabnikov et al., 2011) have been developed to treat unsaturated coarse-soils by stimulating natural processes. One of these methods, termed biogrouting, has shown some promise in soil cementation via MICP. This approach mimics natural processes by depositing calcite on the soil grains, thereby increasing the material's stiffness/strength and reducing its erodibility. The microbiological process relies on ureolytic (non-pathogenic) bacteria such as Sporosarcina pasteurii or Bacillus pasteurii to hydrolyse urea in the presence of calcium ions, resulting in the precipitation of calcite crystals (Shahrokhi-Shahraki et al., 2013).

The MICP is a bio-geochemical process that induces calcium carbonate to precipitate within the soil matrix. The induced mineral precipitation binds the sand grains together at the particle-particle contacts, which increases the strength and stiffness of the soil. Subsurface bacteria can catalyze the reaction network to induce calcium carbonate precipitation and act as nucleation sites for the mineral (Fujita et al. 2000; Mortensen et al., 2011).

In the geotechnical application, synthetic materials are frequently injected into the subsurface bind sand grains together to improve the strength and stiffness of the soil. However, these materials are often costly, difficult to distribute uniformly and may introduce hazardous substances. Therefore, the MICP being a bio-geochemical process is effective providing an alternative method to potentially uniformly improve the strength and stiffness of the soil (DeJong et al. 2010; Mortensen et al., 2011).

The MICP is one of the most popular bio-mediated processes for improving the engineering properties of porous geomaterials. Previous studies have shown that MICP occurs at both pore throats and the bulk surface of particles. This increases the stiffness and shear strength of granular soils (Al Qabany et al., 2012; Al Qabany and Soga, 2013; Cheng et al., 2013; Bibi et al., 2018; Wang et al., 2019; Zamani et al., 2018; Jiang et al. 2016; Gao et al. 2018a; Gao et al. 2018b; Jiang and Soga, K., 2019). The studies demonstrated that MICP can be employed to improve the mechanical properties of weak porous materials (DeJong et al., 2010; Nayanthara et al., 2019) and cater to a number of technological applications including soil reinforcement, slope stabilization, liquefaction prevention, erosion prevention of dams and levees, toxic metals removal from contaminated waters, immobilization of hazardous contaminants in soil, and CO_2 sequestration and others (Khan et al., 2016; van Paassen et al., 2010a; van Paassen et al., 2010b; Canakci et al., 2015; Gomez et al., 2016; Okyay et al., 2016; Zhao et al., 2017; Wu et al., 2017; Gowthaman et al., 2019; Mwandira et al., 2019; Nayanthara et al., 2019).

The application of the MICP technique has shown promise in various fields, including improvement in the stiffness/strength of sandy soil (Rong et al., 2012; van Paassen, 2009; Whiffin et al., 2007; Shahrokhi-Shahraki et al., 2013), reductions in foundation settlement and soil permeability (Dennis and Turner, 1998; Seki et al., 1998; DeJong et al., 2010), liquefaction mitigation (DeJong et al., 2006; Montoya et al., 2012), strengthening of concrete and remediation of cracks (Achal et al., 2010; Bang et al., 2001; Ramachandran et al., 2001), microbially enhanced oil recovery (Nemati et al., 2005), dust control (Meyer et al., 2011) and wastewater treatment (Hammes et al., 2003). There are a few studies reported on the investigations of MICP for soil erosion control, such as surface erosion that occurs in coastal environments (Shanahan and Montoya, 2014; Salifu et al., 2016), fugitive dust control by Enzyme-Induced Carbonate Precipitation (EICP) (Hamdan and Kavazanjian, 2016), wind erosion control of sandy soil (Maleki et al., 2016), surficial soil stabilization (Wang et al., 2018) and effectiveness of internal erosion control by MICP (Jiang et al., 2017; Jiang and Soga, 2017).

This paper presents a review on on the MICP for soil stabilization. It specifically discusses the effectiveness of MICP in soil stabilization and compares the results obtained from the applications of different soil types with the other conventional techniques in terms of the low-cost and environmentally impact properties.

2. Soil Stabilization

Soil is defined as a mixture of minerals, organic matter, gases, liquids, and countless organisms together supporting life on Earth. It continually undergoes development by way of numerous physical, chemical and biological processes, which include evaporation which in turn results into increased plastic limit of soil. The soil does not always meet the desired features. For this reason, it is necessary to intervene the soil to gain needed properties (Afrin, 2017).

Geotechnical properties of soils are improved by using various methods. Soil stabilization is one of the most important issue in geotechnical engineering practices. For this purpose, cement-based materials have been widely used for various soil improvement strategies because of their benefits such as safety, workability and affordability (Achal et al., 2010; Choi et al., 2016). The process of improving the engineering properties of soils is called soil stabilization. By soil stabilization, the soil becomes more stable by the reduction in the permeability and compressibility and by the increase in shear strength (Andavan and Kumar, 2020).

It is absolutely known that the stabilization not necessary a magic wand by which every soil property can be improved for better. The decision to technological usage depends on which soil properties have to be modified. The stabilization incorporates various methods employed for the modifying properties of a soil to improve its engineering performance.

The stabilization is performed by mechanically mixing the natural soil and stabilizing material together so as to achieve a homogeneous mixture or by adding stabilizing material to an undisturbed soil deposit and obtaining interaction by letting it permeate through soil voids. By using these stabilizing agents can improve and maintain soil moisture content, increase soil particle cohesion and serve as cementing and water proofing agents (Perloff, 1976; Chen, 1981; Afrin, 2017).

In the soil stabilization application, there are some methods such as removal and replacement, precompression, vertical drains, in-situ densification, grouting, stabilization using admixtures and reinforcement. Each of these methods is appropriate for certain soil types and applied to the suitable soil types. In the geotechnical applications, it is very important to select the right and suitable stabilization method for the soil type to achieve success in the soil stabilization.

The methods are needed that could offer enhanced soil stability, without the problems current approaches face. The MICP offers an alternative soil stabilization approach and, if applied properly, can be a cost efficient, long term, and a relatively environmental friendly approach (Ivanov and Chu, 2008; Anbu et al., 2016). The MICP typically involves the use of common soil borne microbes to promote calcite precipitation; calcite in return acts as the cementing agent for loose soils (Dhami et al., 2013; Cheng and Shahin, 2019).

The MICP's final result is similar to geochemical calcite precipitation, where both utilize calcite as the cementation agent. However, the MICP is less expensive and more energy efficient because it requires less mechanical energy and man-made materials to apply (DeJong et al., 2010; Mujah et al., 2016; Saneiyan et al., 2018).

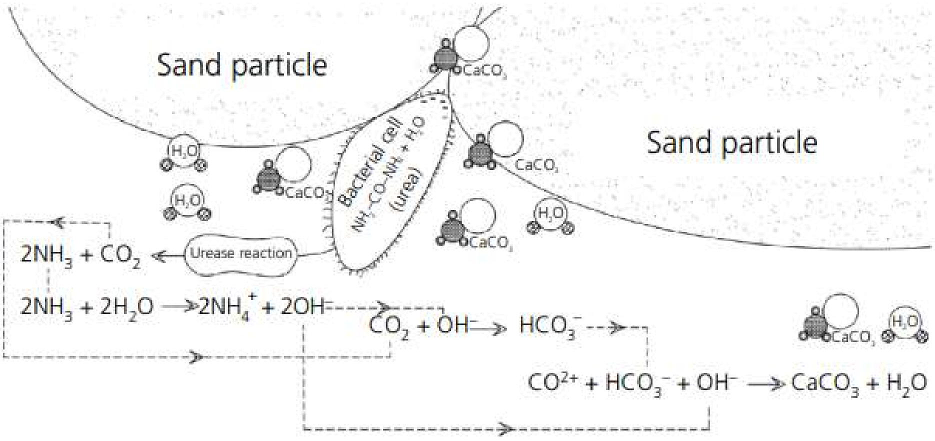

Fig. 1. The MICP process by urease-producing bacteria in the presence of urea and calcium chloride (Behzadipour et al., 2019)

2. MICP Mechanism

The MICP method is a bio-geochemical process that induces calcium carbonate to precipitate within the soil matrix. In the soil stabilization performed by using MICP mechanism, the induced mineral precipitation binds the sand grains together at the particle-particle contacts, which increases the strength and stiffness of the soil (Mortensen et al., 2011). This method deploys the bacterial activity that decomposes urea into carbonate and ammonium ions. The carbonate ions (CO_3^{2-}) combine with calcium ions (Ca^{2+}) to form calcium carbonate and precipitated calcium carbonate can cement sand grains. The mineralogy of precipitated calcium carbonate mostly proves to be calcite (Choi et al., 2017; Harkes et al., 2010; Inagaki et al., 2011; Montoya et al., 2013; Choi et al., 2020).

It is an accepted fact that the MICP naturally occurs from bio-mineralization process, where bacteria in soils induce the precipitation of calcium carbonate. The bacteria capable of producing urease enzyme can be used for MICP because the MICP mechanism arises from bacterial production of urease enzyme and the hydrolysis of urea (Boquet et al., 1973; Stocks-Fischer et al., 1999; DeJong et al., 2010; Siddique and Chahal, 2011; Al-Salloum et al., 2017; Wang et al., 2017; Choi et al., 2020).

As seen in the Eq. 1, the bacteria produce urease enzyme, following which urea hydrolysis is produced by the urease enzyme, whereby urea is decomposed into ammonia (NH_3) and carbon dioxide (CO_2) (Güllüce, 2019). The dissolution of ammonia (NH_3) into water produces ammonium ions (NH_4^+) and the hydroxide ions (OH^-), consequently increasing local pH (Eq. 2). The dissolution of carbon dioxide (CO_2) into water generates bicarbonate ions (HCO_3) and hydrogen ions (H^+) (Eq. 3). This bicarbonate (HCO_3) reacts with the hydroxyl ions (OH) to form the carbonate ions (CO_3^{2-}) in the high pH condition (Eq. 4). As a result, calcium carbonate ($CaCO_3$) is formed in the presence of calcium ions (Ca^{2+}) and soon precipitated out due to its low solubility in water (Eq. 5) (Choi et al., 2020).

$$CO(NH_2)_2 + H_2O \rightarrow 2NH_3 + CO_2 \quad (1)$$
$$2NH_3 + 2H_2O \rightarrow 2NH_4^+ \ 2OH^- \quad (2)$$
$$CO_2 + H_2O \rightarrow HCO_3^- + H^+ \quad (3)$$
$$HCO_3^- + H^+ + 2OH^- \leftrightarrow CO_3^{2-} + 2H_2O \quad (4)$$
$$Ca^{2+} + H^+ \ \ CaCO_3\ (S) \downarrow \quad (5)$$

The calcium carbonate minerals exist in nature as three types of anhydrous polymorphs and amongst the three, calcite is the most stable mineral. The calcium carbonate minerals produced by the MICP mechanism is mostly calcite (de Leeuw and Parker, 1998; DeJong et al., 2010; Rodriguez-Navarro et al., 2012; Shahrokhi-Shahraki et al., 2013; Choi et al., 2020). The preceding equations show the process through which bacteria consumes urea and the MICP takes

place. A schematic of how a urease positive microorganism in the presence of calcium chloride, urea and water drives calcite production and precipitation was clarified in Fig. 1.
The MICP method for the bio-mineralization is a bio-geochemical process and suggested for geotechnical engineering applications (Whiffin, 2004; Mitchell and Santamarina, 2005; Choi et al., 2020). There are numerous of previous studies on the MICP, mainly focusing on geotechnical engineering applications (DeJong et al., 2006; van Paassen et al., 2009; Meyer et al., 2011; Al Qabany and Soga, 2013; Burbank et al., 2013; Cheng et al., 2013; Chu et al., 2013; Montoya et al., 2013; Soon et al., 2013; Zhao et al., 2014; Choi et al., 2016; Han et al., 2016; Maleki et al., 2016; Salifu et al., 2016; Choi et al., 2017; Feng and Montoya, 2017; Jiang and Soga, 2017; Jiang et al., 2017; Smith et al., 2017; Li et al., 2018; Choi et al., 2020; Liu et al., 2020; Osinubi et al., 2020; Wang et al., 2020). The bio-calcification process relies on the creation of bonds at particle to particle contacts. This mechanism helps to strengthen and improve the mechanical performances as calcite precipitation results in a decrease in the pore space and an increase in solid content (DeJong et al., 2010; Haouzi and Courcelles, 2018).

The engineering properties of stabilized soils by using MICP are affected by several environmental factors and conditions, including the injection flow rate of nutrients (Al Qabany et al., 2012; Soon et al., 2014), chemical concentration (Al Qabany and Soga, 2013; Sharma and Ramkrishnan, 2016), source of calcium ion (Zhang et al., 2014; Choi et al., 2016), temperature (Rebata-Landa, 2007; Cheng et al., 2014), urease enzyme activity (Hammad et al., 2013; Cheng et al., 2017), pH (Ferris et al., 2004) and host soil type (Jiang et al., 2017; Zamani and Montoya, 2017). Although such numerous influencing factors militate against the optimization of the MICP treatments, the majority of the engineering properties of the stabilized soils with the MICP can be related to the calcium carbonate content.

4. Literature Survey

4.1. Bibi et al. (2018)

It is expressed by Bibi et al. (2018) that the biomineralization plays a key role in the stabilization the geological properties of soil. Therefore, the soil stabilization by using biomineralization methods against to wind erosion is very effective especially in areas such as Arabic Gulf region characterized by harsh weather and harsh soil. They carried out a study aiming to characterize the soil bacterial populations exhibiting ureolytic activity and investigate their diversity and distribution in a region with harsh weather conditions. The innovation in this study was the establishment of a screening program of isolated bacteria based on rapid estimation of urease activity and biomodification of soil. Furthermore, their study addressed the current knowledge gaps related to the microscale response of bio-mediated soils. Accordingly, it can be concluded that the indigenous ureolytic bacteria present in Qatari soil has the potential to carry out soil stabilization in the presence of urea by enhancing biomineralization. Therefore, introduction of urea into the soil can also be one of the management measure to control the soil erosion caused by winds and to enhance soil stabilization in Qatar (Arabic Gulf region).

4.2. Akoğuz et al. (2019)

Akoğuz et al. (2019) emphasized that several soil improvement techniques are successfully implemented today. The performed studies showed that the interest are increasingly becoming popular on the MICP as an environment-friendly and sustainable method that is an alternative to other soil improvement techniques. In this study, Akoğuz et al. (2019) examined the effects of different sources of calcium on an improvement that was carried out on a sand soil by using the MICP method. There are some researches to reduce costs and to observe how these affected the process of soil improvement and the structures that formed as a result by using a different source of calcium (Zhang et al., 2015; Choi et al., 2017). In this study, in difference to the previous studies, using a different species of bacteria and a different implementation method, the effects of different sources of calcium on improvement were determined on a sand soil. Based on the obtained results, it was observed that different sources of calcium provided different results in terms of both strength and permeability. While better results were obtained in the specimens treated with calcium chloride and calcium nitrate in terms of strength, better results were obtained in terms of permeability in the specimens treated with calcium acetate. It is considered that the cost of calcium nitrate is higher and calcium acetate and calcium chloride had similar percentage permeability decrease results. The using calcium chloride may provide better results in the process of reducing permeability and obtaining better strength values.

4.3. Behzadipour et al. (2019)

The MICP is a bioinspired improvement method of granular soils, as it can significantly affect their engineering characteristics. In fact, calcite nanoparticles produced through MICP increase the angle of internal friction and cohesion intercept of granular soils. As a consequence, the shear strength values of granular soils are improved following the increase in these two parameters (Behzadipour et al., 2019). According to the preceding conclusions, soil indigenous ureasepositive microorganisms can be used for designing selfstrengthening layers as an ideal method in geotechnical engineering. Also, the authors suggested that the effects of the dissolved oxygen of liquids, history of natural biocementation, shape and mineralogy of soil particles, changes in nutrients in the soil medium and biocemented soil response to non-isotropic loadings, need to be studied in detail in future researches. In this study, it was emphasized that to address all these questions, more investigations into the effect of MICP on sand mixtures are required. As a result, the findings obtained in this study showed that there was a significant improvement in the shear strength of the samples and fine particles reduced the MICP potential for strengthening of sandy soils. Although MICP increased the cohesion intercept and the angle of internal friction of the samples, a great amount of the gained strength was due to cohesion growth.

4.4. Jiang and Soga (2019)

Jiang and Soga (2019) tested the effests of the MICP on the internal erosion resistance of gravel-sand mixtures under laboratory conditions. For this purpose, the samples of gravel-sand mixtures stabilized by using the MICP were prepared by either the pre-mixing method or the injection method. All samples were subjected to the internal erosion tests and their erosion rates were obtained based on the weight measurement of the sand particles in the outflow. Meanwhile, the axial deformation and the pore water pressure were measured every second until the end of the test. They saw that when applied to stabilize gap-graded granular soil, the MICP can potentially bind smaller particles together as aggregates and bring about cementation between small and large particles. They mentioned that the MICP is able to provide successful erosion resistance under the tested flow conditions for soils having a gravel-supported structure. The unstabilized samples including 25% sand/75% gravel exhibited much faster backward erosion and suffusion. In contrast, the unstabilized samples including 50% sand/50% gravel showed slow backward erosion only. On the other hand, the MICP was very effective in mitigating internal erosion of the stabilized soil including 25% sand/75% gravel within the tested conditions. However, for the stabilized soils including 50% sand/50% gravel, the MICP stabilization was only successful when the injection method was applied and the erosion test was performed at a low axial stress.

4.5. Choi et al. (2020)

The study carried out by Choi et al. (2020) reviews the fundamental mechanisms of biological soil improvement methods such as the MICP and biopolimer treatment. It is expected that the compilations and correlations presented in this study provide insights into the extent of modification in engineering properties by such methods and eventually contribute to the development of new and alternative soil improvement strategies using these bio-based materials and techniques. Accordingly, the MICP method can be applied to specific engineering practices. It is presumed that the MICP stabilization induces the strength improvement, while maintaining permeability up to a certain calcium carbonate content value. Consequently, the MICP can be utilized as a method for permeating to soil in coarse sands. Also, it can also be used for mitigation of liquefaction effects because MICP stabilized-sands can maintain hydraulic conductivity, thereby allowing the dissipation of excess pore water during seismic loading (van Paassen et al., 2010a; DeJong et al., 2013). However, it is emphasized in this study that to be practically and economically applicable at in situ fields, various factors such as workability, cost, proper equipment, and environmental issue need to be further assessed.

4.6. Islam et al. (2020)

Islam et al. (2020) pointed out that the several ground-improvement techniques can be employed to overcome the geotechnical insufficiencies. Some of these methods are impractical in certain situations and unsustainable in others due to their economic and environmental impacts. The MICP could provide a more sustainable alternative. This research investigated the viability of indigenous bacteria in stabilizing clayey soils of varying plasticity. The research team envisaged the applicability of the biostimulation technique using natural microbes present in clayey soils to precipitate calcite and alter clay behavior. The natural and artificial soils were investigated to test this hypothesis. Both of them helped to study the application of the MICP in soils with varying plasticity and microbial communities and the impact of clay content on the MICP effectiveness by keeping the origin of the microbial communities constant. Based on obtained findings, it can be concluded that it is viable for the MICP technique via biostimulation to alter the engineering properties of the clayey soils with varying plasticity characteristics. However, the authors confissed that further studies are needed for better understanding of this phenomenon and establish proper treatment methodologies to ensure consistent performance.

4.7. Liu et al. (2020)

In their studies, Liu et al. (2020) expressed that the desiccation cracking is a common natural phenomenon in clayey soils. These desiccation cracks considerably reduce the mechanical and hydraulic properties of clayey soils. Traditional satbilization methods are associated with high labor costs, high maintenance costs and the usage of environment-unfriendly chemicals. In this study, the wet-dry cycle tests were carried out to characterize the effect of MICP onthe desiccation cracking behaviors of clayey soils. To investigate the influences of porefluids on soil cracking behaviors, four groups of soil samples sprayed with deionized water, bacteria solution, cementation solution, and both bacteria and cementation solutions were prepared. The wet-dry cycle tests were carried out with soil desiccation cracking behaviors captured by imaging tools and quantified through image analysis. From the obtained results, it was seen that the soil samples treated with MICP present the highest resistance to cracking as reflected by the less distributed cracks on soil surface. The quantitative analysis results based on image processing validate that MICP works most effectively in improving soil cracking resistance. The geometrical parameters including surface crack ratio, average crack width, total crack length decrease with the increasing treatment cycles, especially within the first two treatments. Under the MICP process, it was obseved taht the densely distributed $CaCO_3$ crystal clusters on soil particle surface and inside inter-particle pores contributed to the improved mechanical integrity of soil sample as well as desiccation cracking resistance. The increasing number of the MICP treatment cycles significantly remediates soil desiccation cracking and changes soil microstructure. This study validates the applicability of the MICP treatment in reinforcing clayey soils for wet-dry cycle conditions. The surface spraying method is easy to operate and provides a new possibility for field-scale implemen-tations. Also, it was mentioned that the MICP has the potential benefit to remediate the desiccation cracking of bentonite under the laboratory condition. Also, it was emphasized that the MICP has the potential benefit to remediate the desiccation cracking of bentonite under the laboratory condition as the result of a study performed by Guo et al. (2018).

4.8. Osinubi et al. (2020)

In the their study, Osinubi et al. (2020) specified that the engineers dealing with geotechnical applications either ignored or neglected the role of microorganisms in geotechnical engineering until recently. Whereas these microorganisms can serve for soil improvement. The MICP research technique is an innovative and relatively green technology which consists in a biological process through which microorganisms react with minerals to produce calcite

($CaCO_3$) as a by-product that modifes and improves the engineering properties of soil. It is considered that the soil is a living environment enabling the prospect for original and workable solutions to geotechnical problems. Although biogeochemically based soil improvement technologies will not replace in totality standard ground enhancement methods, they are favorable because of their potential environmental friendliness (DeJong et al., 2013). As a result, the MICP is a sustainable green technique for improving the engineering properties of soils. It was observed that there is a direct relationship between the strength of treated soils and the bacterial suspension density in the MICP processes. Similarly, there is an indirect relationship between the permeability and bacterial suspension density. Based on this review, larger-scale use of the MICP processes, targeting the improvement of the engineering properties for sandy and residual soils for various engineering applications, represents a research opportunity that could be explored in the near future.

4.9. Tang et al. (2020)

In this study, Tang et al. (2020) investigated the factors affecting the performance of the MICP in the application of soil stabilization. The various physical, chemical, biological, and environmental factors that afect the performance of ureolysis-based MICP-treated geomaterials were reviewed. Based on these factors, it emphasized existing studies regarding the optimization of the MICP technology and gave an insight into how to achieve the MICP optimization in various applications. Mineral composition in soil could change the chemical and thermodynamic properties of the pore fuid, thus providing more nucleation sites for calcium carbonate precipitation. Therefore, the soils with diverse mineral compositions are better hosts for the MICP. The soil particle size is another important soil property that controls the MICP efciency and the soil particle size is directly related to the pore throat size in soil matrix, which controls whether bacteria can fow freely and distribute uniformly in soil matrix. Therefore, soils containing particles smaller than bacterial size could prevent the free fow of bacteria in soil matrix, leading to limited and heterogeneous calcium carbonate precipitation (Mitchell and Santamarina, 2005). Moreover, larger particles have less intergranular contacts and larger inter-granular distance. Therefore, the majority of calcium carbonate coats on the surface of coarse particles rather than the contact points, which could also weaken the overall cementation efciency (Rebata-Landa, 2007).

4.10. Wang et al. (2020)

The performance of the energy geo-structures is strongly affected by the saturation conditions of soils and the heat exchange efficiency of saturated soils is more as compared with that of dry soils. Because moisture content is the primary influence factor of soil thermal conductivity as compared with other factors. As a result, greater soil moisture content leads to higher heat exchange efficiency (Hepbasli et al., 2003; Choi et al., 2011; Venuleo et al., 2016). Starting from this point, Wang et al. (2020) performed an investigation on the thermal conductivity of the MICP treated sands. Whith the experimental studies, the sand samples treated by the MICP technique with different treatment cycles were prepared and then thermal conductivity was measured in drying process by using a newly developed dual probe heat pulse sensor. The results obtained from tests indicated that the improvement in thermal conductivity of the treated sands is significant as compared with the untreated sand. Furthermore, the thermal conductivity increased as the number of treatment cycles increased. The improvement in thermal conductivity is mainly because of the formation of precipitated $CaCO_3$ crystals acting as ‘‘thermal bridges’’ among sand grains, offering more highly effective heat transfer path for heat exchange by increasing the surface contact area (Venuleo et al., 2016). Additionally, the relationships between thermal conductivity of unstabilized and stabilized sands and dry density, treatment cycles and $CaCO_3$ content were established from obtained data.

5. Conclusion

The MICP is a bio-geochemical process that induces calcium carbonate to precipitate within the soil matrix. The induced mineral precipitation binds the sand grains together at the particle-particle contacts. It is a sustainable green technique for improving the engineering properties of soils. This paper presents a review on on the MICP for soil stabilization. It specifically discusses the effectiveness of MICP in soil stabilization and compares the results obtained from the applications of different soil types with the other conventional techniques in terms of the low-cost and environmentally impact properties. The MICP is one of the most popular bio-mediated processes for improving the engineering properties of porous geomaterials. The studies demonstrated that MICP can be employed to improve the mechanical properties of weak porous materials and cater to a number of technological applications. These applications include soil reinforcement, slope stabilization, liquefaction prevention, erosion prevention of dams and levees, toxic metals removal from contaminated waters, immobilization of hazardous contaminants in soil, and CO_2 sequestration and others. The application of the MICP technique has shown promise in various fields, including improvement in the stiffness/strength of sandy soil, reductions in foundation settlement and soil permeability, liquefaction mitigation, strengthening of concrete and remediation of cracks, microbially enhanced oil recovery, dust control and the wastewater treatment. The engineering properties of stabilized soils by using the MICP are affected by several environmental factors and conditions, including the injection flow rate of nutrients, chemical concentration, source of calcium ion, temperature, urease enzyme activity, pH and host soil type. Although such numerous influencing factors militate against the optimization of the MICP treatments, the majority of the engineering properties of the stabilized soils with the MICP soils can be related to the calcium carbonate content. Based on this review, larger-scale use of the MICP processes, targeting the improvement of the engineering properties for sandy and residual soils for various engineering applications, represents a research opportunity that could be explored in the near future.

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