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Microbial Ground Improvement for Sustainable Construction: Processes and Challenges

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Abstract

Civilization is disturbing the balance of the earth. Sustainable construction material with economy is a need of the hour. The environmental and sustainability issues related with concrete and other construction chemicals necessitate better alternative approach in the construction industry. Exciting opportunities for bio-geological processes to modify the engineering properties of the soil have been recently emerged in the field of geotechnical engineering. This bio improvement method has additionally been viewed as valuable in many designing applications like improvement of engineering properties of materials, cementation of permeable media, improvement in strength and firmness of soil and concrete. liquefaction, and disintegration moderations. This paper presents an overview of bio-geological ground improvement systems, research advancements and challenges for field application in the construction industry. A milestone achieved in the worldwide research has been highlighted and the effect of biological intervention on the properties of soil overviewed. Processes and challenges of this novel technique are highlighted. Finally, the major challenges like optimization of the processes and scale up applications are briefly discussed.

Keywords: Bio geo technology, Engineered Soil, Geotechnical engineering, Ground Improvement, MICP

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Introduction

Since civilization we know number of conventional approaches for treatment of the soil for engineering use. Various methods of ground improvement techniques by using chemical solutions or grout has been established and widely used in geotechnical applications. Most of the methods are expensive in nature and hazardous to the environment. [1]. In recent years, urease enzyme become extremely useful in geotechnical ground applications termed as 'Microbially induced carbonate precipitation (MICP)' which produces a cementing mineral used for soil stabilization process. This multidisciplinary technology involving geotechnical engineers, chemists and microbiologists have merged a new discipline naming 'Construction Biotechnology' is growing exponentially[1]. Use of non-pathogenic, aerobic bacteria for bio-geotechnical engineering applications was first reported in late 90's,using urease enzyme from bacteria *Sporosarcina pasteurii*, which hydrolyzes urea to produce calcium carbonate ($CaCO_3$) which precipitates as a cementing agent[2].

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This inspired researchers for numerous studies on the utilization of MICP for soil improvement that are environment friendly [3].MICP combines the usage of microorganisms, cementation reagents, and various biological methods, to improve engineering properties of the soil as a construction material [3]. No release of carbon dioxide, silent procedure, minimal uses of chemicals, soil friendly bacteria are some of the features making this method eco friendly. MICP has been demonstrated at various scale up levels by researchers worldwide [4]. This method can be used to increase bearing capacity of the soil, reduce permeability, stabilization of the slopes, filling the cracks and many more applications of geotechnical engineering related to bio cementation and bio clogging. MICP involves addition of aerobically cultivated bacteria with highly active urease enzyme into soil, harnessing the urease enzyme to produce ammonium and carbonate ions by hydrolysis of urea process.

Microbialaly Induced Carbonate Precipitation (MICP)

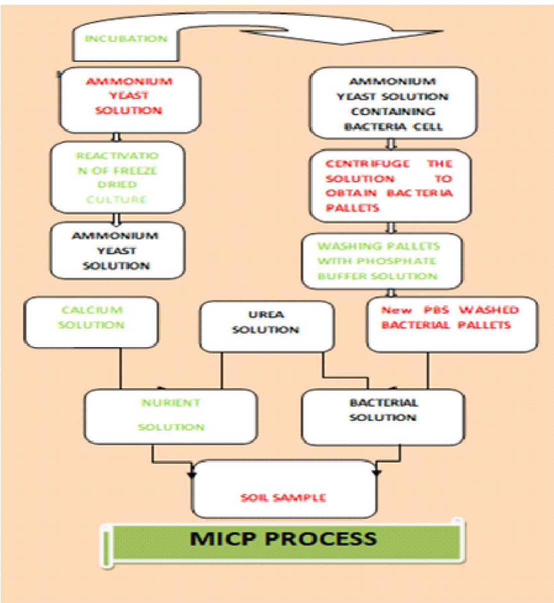

Figure 1: MICP Process

The chemical reaction in MICP is as follows:

$CO(NH2)2 + 2H2O \rightarrow 2NH4+ + CO3^{2-}$

In the presence of an introduced calcium source, calcium chloride (CaCl2), the calcium carbonate (CaCO3, calcite) forms throughout the soil matrix which is based on the following chemical reaction:

$Ca^{2+} + CO3\ ^{2}- \rightarrow CaCO3 \downarrow$

This produced microbial induced carbonate precipitation bridges soil particles by cementing the soil grains together to form cemented sand illustrative of calcareous rock [4].

In most of the studies commonly used bacteria are *S. pasteurii*, *Clostridium, Desulfotomaculum. And Sploactobacilus*, Of these, *S. pasteurii*, an aerobic,alkalophilic non-pathogenic bacterium containing highly active urease enzymes, has been found to be one of the most efficient and widely used bacteria in the studies.

Microbial-induced calcite precipitation method uses naturally occurring microbes penetrated in the soil pores to bind soil particles together through calcium carbonate precipitation, thereby increasing the strength of the soil. This is the result of natural metabolic process of the microbes. As per the various worked out models, the expected life span of treated MICP soil is about 50 years, which is at par with the expected life of most of the geotechnical structures [4]. MICP also offers potential of being a comparatively inexpensive technique besides a eco friendly process.

Table-1: Comparison of MICP with other methods [05-12]

Properties	Chemicals	Cement	Geosynthetic	Biomeditation
Basic Material	Polimer	Cement slurry	Geosynthetic material	Micro organisms and nutrient media
Methodology	Grouting and spray	Injection and deep mixing	Direct installation at site	Microbe Injection With nutrient media
Soil competitiveness	Coarse grained	Fine and coarsed grained	Coarsed grained	Coarse grained
Reaction	Solidification and chemical bonding	Hydration of cement	Acts as tensile reinforcement	Calcite precipitation by hydrolysis of urea process
Advantage	Strong and durable	Strong and durable	Ready to use	Ecofriendly, Economical
Challenge	Environmental impacts, uneconomical	Harmful for local ecosystem	Suitable for shallow foundations only	Flow rate, nutrients and other engineering parameters required to monitor carefully
Strength	0.8MPA	2 MPA	Tensile strength	2 MPA
Costing (average)	200USD/ton	46USD/ton	2.5 USD/sq.m	91USD

Till date the worldwide research on MICP is primarily focused on biogeochemical technology. The metabolic activity of microbes creates calcite carbonate in soil pores [14]. Calcite precipitation can also be achieved by many chemical and bio geo logical processes. Urea hydrolysis is also one of the processes to achieve calcite precipitation. [15] Other researchers also worked on denitrification [16] sulphate reduction, inducing dolomite precipitation[17] iron reduction, inducing ankerite and other mixed mineral precipitation [18]. Urease activity is found by metabolism of many soil suited, aerobic, non pathogenic bacteria. Hydrolysis of urea by microbes is the most efficient of these processes [4].

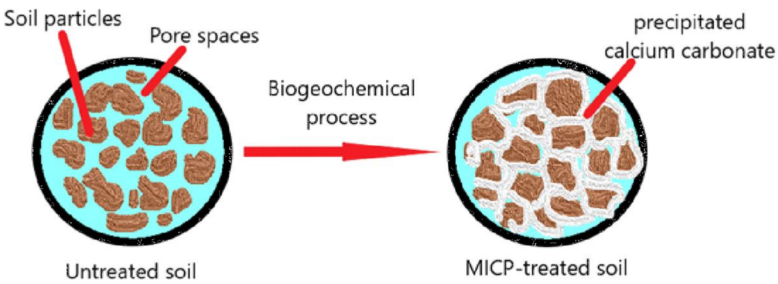

Figure:2 Biogeochemical Process

Table-2: MICP processes leading to potentiality for bio cementation [13]

Microorganism physiological group	Biocementation mechanism	Essential conditions for bio cementation	Potential Geotechnical application
Ammonifying Bacteria	Increase in pH and release of CO_2 creates formation of undissolved carbonates of metal in soil.	Presence of dissolved metal salt and urea	Increase in Bearing capacity of foundation, Mitigate liquefaction, Stability of retaining wall
Sulphate reducing bacteria	Undissolved sulphides of metal	Aerobic conditions; Presence of carbon source and sulphate in soil	Stability of slopes,
Iron reducing bacteria	Precipitation of undissolved ferrous and hydroxide in soil	Presence of ferric mineral, Shifting from Anaerobic condition to aerobic condition	To reduce liquefaction, Densify the soil

CaCO3 precipitation is a common chemical reaction occurring in grond water system, in oceans so it has been studied by geologists, microbiologists from long time [26]. In MICP the current understanding of the whole process and CaCO3 precipitation has been modulated and predicted that this bonding will give a life span of about 50 years. These studies are at micro level and the result may vary in field applications as the kinetics of precipitation may vary as per bacterial cell distribution.

Current research on MICP as ground improvement technique is application-driven. The basic aim of all current MICP studies is field application of the process in different environmental conditions. Researchers are focused on 1) making MICP-treated soils strong and durable 2) control the properties of CaCO3 crystals formed in the soil to spread homogeneously and 3) making the procedure simplified and economical.

Table-3: Literature Review of Different Geotechnical Applications of Microbes

Bacteria Used	Soil	Process Adopted	Result	Reference
Bacillus megaterium	Coarse soil	Bio-cementation	Improvement in shear strength	[19]
Sporosarcina pasteurii	Coarsed sand	Bio-deposition	Strength improved	[20]
Bacillus sphaericus	silica	Bio-cementation	Lower permeability Better strength	[21]
Sporosarcina pasteurii	Sand	Bio-clogging	Permeability reduced	[22]
Bacillus subtilis	Silt	Bio-cementation	Improved compressive strength	[23]
Bacillus subtilis	Silty sand	Bio-clogging	Lowered permeability	[24]
Sporosarcina pasteurii	Silty sand	Bio-cementation	Strength improved	[25]

Challenges in Microbilal Ground Improvement

One of the most challenging considerations in MICP is the monitoring technique during the entire process. As the research is mostly in laboratory stage the durability and performance over long time is yet to be tested significantly [4].

Another challenge is to develop the skilled workers for field implementation as this process requires multidisciplinary peoples to monitor. Fundamentals of microbiology and chemical reactions besides basic knowledge of geotechnical engineering are required for effective monitoring of the process. The factors like pH value of the nutrient solution, temperature, injecting methods also required to consider before practical implementation of the method. Other factors like sensitivity to ground water, biological degradation are also area of concern for practical implementation of MICP. One more challenge in $CaCO_3$ precipitation is production of two types of $CaCO_3$, first one calcite and second one is vaterite. The soil samples containing calcite are found to be strong and durable in nature while vaterite content samples were weak. [27].

Conclusions

Since human civilization Ground improvement techniques are intensively used and developed. Use of lime and in later stage use of cement can be consider as the modern era for geotechnical ground improvement, thereafter various chemicals and denitrification became popular techniques for ground improvement purpose. Later with the demand of green energy in construction field, worldwide research on calcium carbide penetrating microbes is in boom.

Ground enhancement methods have been intensively studied and developed over centuries.

The use of cement in geotechnical engineering could be considered the beginning of modern ground enhancement methods, and numerous studies have since been performed to enhance the properties of cement. However, in the late 20th century, environmental concerns gave rise to increasing demand for environment-friendly construction methods. The development of green cement and several possible cement substitutes, including the direct use of biopolymers in the soil layer, have been proposed.

This paper reviewed developments in this novel technique over the last 20 years. MICP has significant potential to become environmentally sustainable solution for geotechnical engineering problems like increasing the strength of the soil and concrete, reducing the permeability of the soil. Though there are some limitations for practical application on the field but as study will progress on large scale, this method will get popular for field implemention all over the world.

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