Performance evaluation of microbial carbonate precipitation method compared with resin and fiber stabilization on the strength of compacted sandy soils

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Abstract

One of the methods that have recently linked the fields of civil engineering, geochemistry and microbiology, have a good compatibility with the environment, and have a lower administrative cost than other methods of soil improvement is Microbial Induced Carbonate Precipitation (MICP). This new idea is inspired by nature, involves using certain species of soil bacteria to bind soil particles together and stabilize the soil structure. In this study, the performance of MICP method on the strength of sandy soil compared with another two methods of mixing treatment for soil improvement (resin stabilization and fiber/resin reinforcement). Unconfined compression strength test (UCS) were performed in 3 graded for one type of sandy soil to investigate the optimum results for each methods and comparison between them. the results indicate that the highest increased of strength in resin/fiber reinforcement occurs in T90 soil with 1831 Kpa and resin stabilization raised the strength to1611 Kpa in T60 soil . In addition, the MICP method has improved the strength from 51 Kpa to 1109 Kpa and the results in this process indicate the importance of soil granular and percent of bacteria. Therefore, comparison of these three methods shows the MICP method as a new and environmental method of soil improvement can be considered in future.

Key words: MICP, Resin stabilization, Fiber reinforcement, Unconfined strength test, Sandy soil

1. Introduction

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 (Dejong et al., 2010).

In previous techniques such as: cement (Savastano et al., 2003), lime, fly ash(Brooks, 2009) and bitumen were used widely for loose and expansive soil improvement. Since 1980, soil improvement with new chemicals has begun and in 1990 has revolutionized (Tolleson et al., 2003). For instance, the compressive strength of artificially cemented sandy soil has been studied in the past by several investigators (e.g., Consoli et al., 2006). In addition, studies of the reinforcement of sand by the inclusion of fiber have also been reported (e.g., Consoli et al., 2006; Yetimoglu et al., 2003).

In recent years, new, exciting opportunities for utilizing biological processes to modify the engineering properties of the subsurface (e.g. strength, stiffness, permeability) have recently emerged. Enabled by interdisciplinary research at the confluence of microbiology, geochemistry, and civil engineering. This new field named "Biogeotechnology" and is a branch of Geotechnical Engineering that deals with the applications of biological methods to geotechnical engineering problems. Biogeotechnology have advantages of low investment and maintenance costs. It also offers benefits to environment and aesthetics (Karol, 2003).
Microbial-induced carbonate precipitation, known as MICP, is a recently developed method by which some undesirable properties of soils could be remediated (Whiffin et al., 2007). This is one of the bio-geochemical processes investigated by researchers in recent years in order to reinforce the soils (Harkes et al., 2010). In this method, special microorganisms from Bacteria domain are induced to produce $CaCO3$ as precipitates within the soil matrix which could binds the sand grains together and increase the strength and stiffness of the soil (Al Qabany et al., 2011). Several types of microorganisms are known to precipitate mineral carbonates in various natural environments including soils, geological formations, freshwater biofilms, oceans, and saline lakes (Hammes et al., 2003).

MICP has experienced an increased level of interest in recent years, for applications such as restoration of calcareous stone materials (Castanier et al., 1999; Stocks-Fisher, 1999), bioremediation (Ferris et al., 2003; Fujita et al., 2000), wastewater treatment (Hammes et al. 2003), strengthening of concrete (Ramachandran et al., 2001) and selective plugging for enhanced oil recovery (Nemati and Voordouw, 2005). From a geotechnical perspective, the potential of MICP has been identified as a means of adapting soil properties to suit desired land-uses. Controlled precipitation of minerals in the pore space in such a way as to change macro-soil properties or so called “pore-space engineering,” is a new innovative approach in soil geotechnics with significant scope for development. MICP can occur via a variety of processes whereby microbial activities result in the generation of carbonate in a calcium rich environment (Castanier et al. 1999). The resulting $CaCO3$ precipitation is governed by four key parameters: (i) calcium concentration, (ii) carbonate concentration, (iii) pH and (iv) the availability of nucleation sites (Hammes and Verstraete, 2002). Many biological reactions can result in the production of carbonate or carbonate species.

Most studies on biological soil improvement use microorganisms containing the enzyme urease and, in particular, the bacterium *Sporosarcina pasteurii* DSM33, renamed from *Bacillus pasteurii* (Whiffin, 2004; De Jong et al., 2006; Whiffin et al., 2007). These microorganisms are cultivated aerobically before being introduced in the soil and supplied with a solution of urea and calcium chloride. The microbial urease catalyzes the hydrolysis of urea into ammonium and carbonate. Calcium carbonate precipitation can be induced when microorganisms produce inorganic carbon and alkalinity in the presence of dissolved calcium ions. After conversion of the carbon source to carbonate in situ, precipitation takes place between the sand grains, which results in increased strength. To ease transport through the porous soil, the calcium and carbon source need to be in soluble form when introduced into the ground. High concentrations are preferred to limit the required amount of flushed solutions (Fig.1).

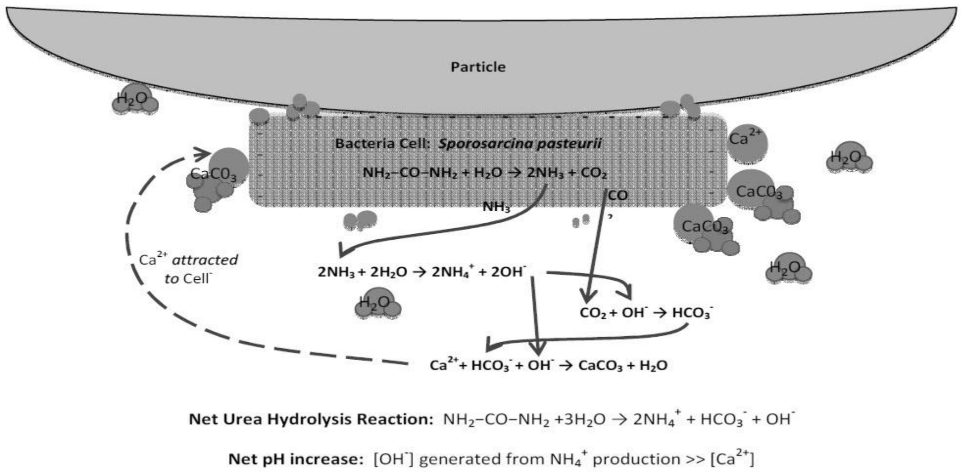


Fig.1: Microbial Induced Carbonate Precipitation process in soil (Dejong et al., 2006)

2. Data and Material

2.1. Microbial treatment

2.1.1. Microorganism and Biomass Preparation

Sporosarcina pasteurii PTCC 1645 (DSM 33), an alkalophilic urease positive bacterium, was purchased from Persian Type Culture Collection as lyophilized cells. The bacterium was restored at Nutrient Broth and cultured at a previously described liquid medium containing 20 g/L yeast extract and 10 g/L NH4Cl (Harkes et al., 2010). Gram staining, urease test, and colony characteristics of the microorganism were checked to prevent any probable contamination during the experiments. Cell densities were obtained by culturing the bacterium at yeast extract-ammonium chloride medium for approximately 48 to 72 hours, namely to late exponential phase. The bacterial cells were harvested by centrifuging (Sigma, Germany) at 4000 rpm for 10 min. Optical density (OD600) measured using a spectrophotometer served as an indication for biomass concentration (Harkes et al., 2010). The prepared biomass concentrations were stored at 4 ^{o}C, for a maximum delay of 48 hours, before use for soil treatments. Urease activity of the suspension was measured immediately before using the biomass in order to confirm the uniformity of bacterial activity in all the tests. (Mobley et al., 1986)

2.1.2. Nutrient solution

The amount of urea ($CO(NH_2)_2$) and $CaCl_2$ applied to the soil samples was considered as another parameter affecting the MICP process. In order to determine the effect of this factor, four levels of the final concentration of the nutrient solution were examined and optimized amount (urea 3M and $CaCl_2$ 1.5M) were used.

2.2. Resin treatment

Polyethylene terephthalate (sometimes written poly(ethylene terephthalate)), commonly abbreviated PET, PETE, or the obsolete PETP or PET-P, is a thermoplastic polymer resin of the polyester family and is used in synthetic fibers. The term 'polyethylene terephthalate' is a source of confusion because this substance, PET, does not contain polyethylene. Thus, the alternate form, 'poly (ethylene terephthalate)' is often used for the sake of accuracy and clarity. Depending on its processing and thermal history, polyethylene terephthalate may exist both as an amorphous (transparent) and as a semi-crystalline polymer. The semi crystalline material might appear transparent (particle size < 500 nm) or opaque and white (particle size up to a few microns) depending on its crystal structure and particle size. PET consists of polymerized units of the monomer ethylene terephthalate, with repeating C10H8O4 units (Fig.2).

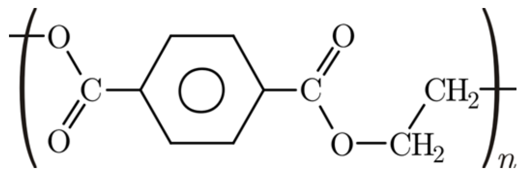


Fig 2: Polyethylene terephthalate resin formulation

2.3. Fiber

The fibers that used with resin for reinforcement of soil was a polypropylene fiber (PP) and had a length of 12 mm and thickness of about 0.021 mm. PP fibers are hydrophobic, non-corrosive and resistant to alkalis, chemicals and chlorides. The characteristics of polypropylene fibers used are shown in Table 1.

Property	Value
Length (mm)	12
Aspect Ratio	300
Density (g/cc)	0.91
Tensile Strength (MPa)	450
Elongation at break (%)	15-25
Melting Point (^{o}C)	165
Heat Resistance (^{o}C)	<130

Table 1: Characteristics of polypropylene fibers

2.3. Soil type

A poor sandy soil (SP) in three graded was obtained from Chirook Foundry Sand Co located in Tabas desert, an arid area in the center of Iran (fig. 3). This kind of soil is used in casting industries, known as “foundry sand”. Table 2 and Table 3 show the chemical and physical properties of the soil samples.

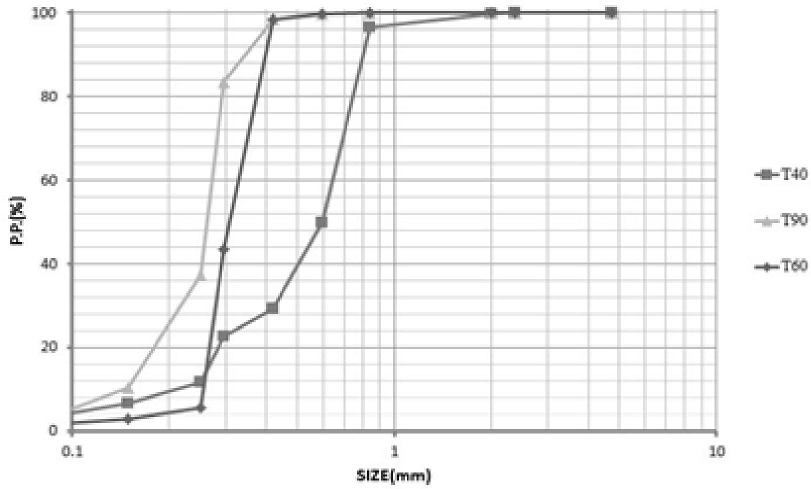


Fig. 3: Gradation curve of the prepared soil samples (T40, T60, and T90)

Chemical	SiO_2	Fe_2O_3	Al_2O_3	CaO	Na_2O	K_2O	MgO	L.O.I
Percent	98	0.6	1.5	0.2	0.01	0.06	-	0.35

Table 2: XRF measurement of Tabas sandy soil

Properties	Soil type		
	T40	*T60*	*T90*
Unified Soil Classification (ASTM-D2487)	SP	SP	SP
Particle Type	Silty sand	Silty sand	Silty sand
Specific Gravity (ASTM-D854)	2.87	2.79	2.73
Uniformity Coefficient	1.3	1.4	1.29
Roughness Coefficient	1.11	1.17	1.22
Pyro metric Cone Equivalent (P.C.E) (^oC)	1730	1730	1680

Table 3: Physical properties of soils

3. Research Methodology

For preparing the specimens, the mixture of soil and treatment was compacted in three layers at the state of Optimum Moisture Content (OMC) in a PVC column with a dimension of 180 mm of length and 4.1 mm of diameter. The compaction was performed according to the ASTM D698 standard instruction. All the experiments were conducted in duplicates (n=2) and the arithmetic mean of the results and S/N ratio of each experimental trial were applied for analysis. the incubation time were considered 28 days and after this time the specimens were submitted to Unconfined Compressive Strength test (USC) (Van Paassen, 2010). Figure 4 shows the specimens assessed in the experiments.

For preparation of samples containing resin and fiber, at first, four different percentages of fiber at 0.5%, 1.0%, 1.5% and 2.0% by weight of dry soil were used randomly to carry out UCS tests. Results of the tests were used to calculate the optimum fiber proportion in soil based on the maximum UCS values. The optimum fiber content (1.0%) was used as a judgment factor for carrying out other tests and comparing with other methods (Masumi et al., 2011). (Fig. 4)

Fig. 4: left: soil specimens- right: 12mm polypropylene fibers

MICP samples prepare in three types with different percent of bacteria (0.5%, 1.5% and 2%). the concentration of nutrients consist, urea and $cacl_2$ was constant in optimum amount of 3M and 1.5M. In addition, optical density (O.D. 600) of bacteria was 2.5 in all MICP specimens.

4. Results and Analysis

According to figure 5 and 6, results of UCS test show the highest strength occurs in resin and fiber sample of T90 soil. It is due to the interaction between fiber to fiber and fiber to grain soils in dune grains is much better. In resin stabilization samples, soil granular is less effective and strength is reduced than previous method. Moreover strength results in MICP is completely depends on soil type and percent of bacteria. With increasing bacteria suspension in T40 with larger grain size, strength improved. Because porosity in this soil gradation need to much more solution treatment to fill this spaces with cementation materials. However, in two other types of soil (T60, T90) increasing strength stopped in 1.5 percent of bacteria.it is due to amount of produced cementation in this percent of bacteria is enough and more cementation have a less efficiency.

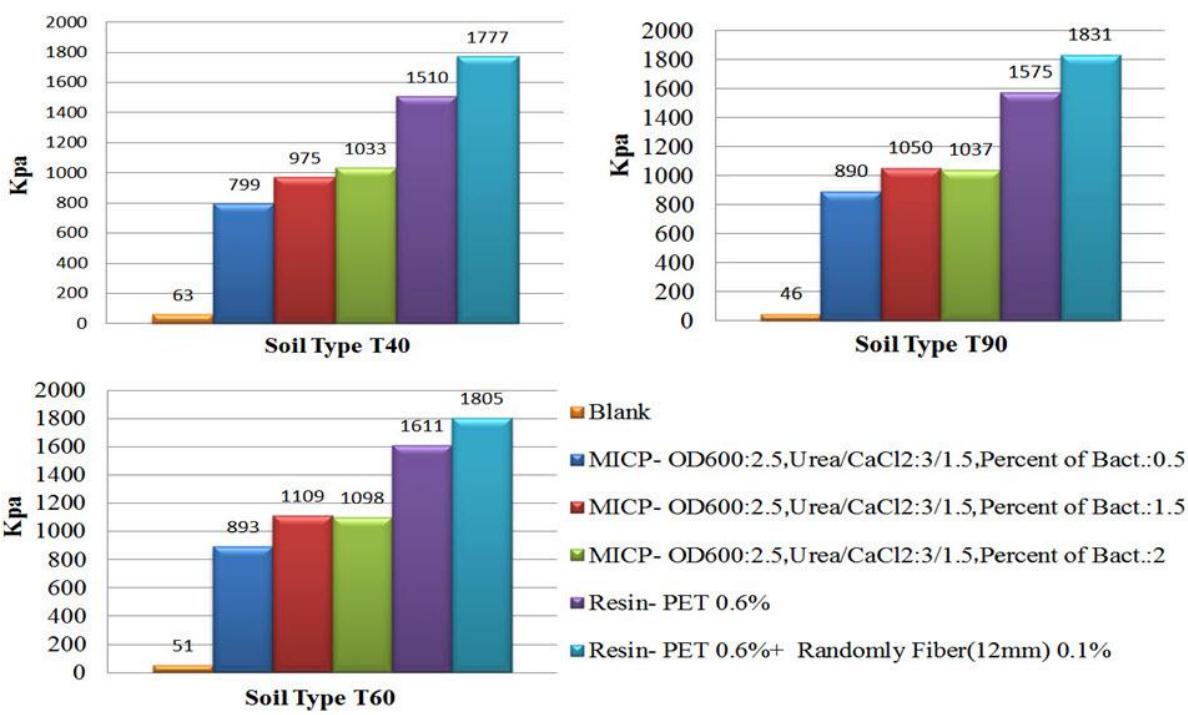


Fig. 5: Results of unconfined compression strength test in various methods

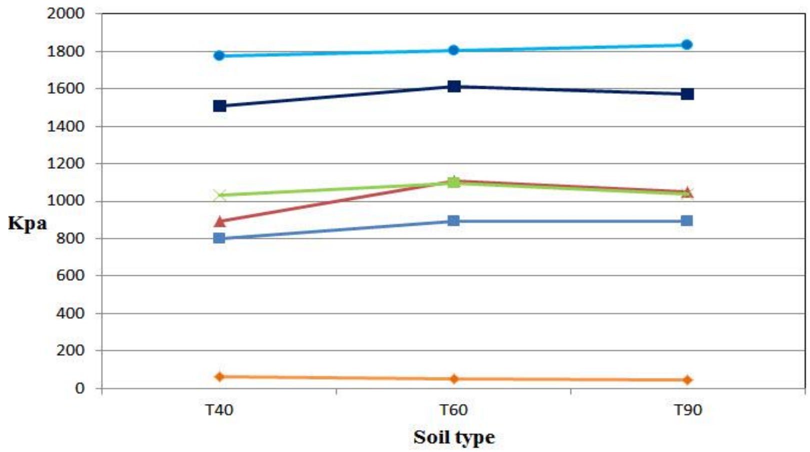
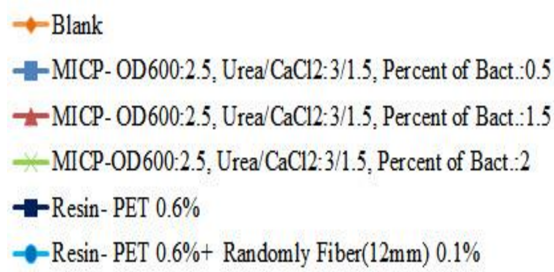


Fig. 6: effect of soil granular in different methods

5. Conclusions

The following conclusions can be drawn from this work:

- In MICP method, two factor of soil type and percent of bacteria is the effective strength value.
- Resin and fiber treatment compared with other tested treatment has higher strength.
- Soil granular does not have much impact in resin stabilization technique.



- In resin/fiber method, strength grows with decreasing grain size.
- The amount of bacteria used in samples has a direct related to porosity and grain size of soil.
- This work demonstrated that microbial carbonate precipitation can be applied for large-scale soil improvement work and further development of the technique for this application area is warranted.

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