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Study on effect of Microbial Induced Calcite Precipitates on strength of fine grained soils☆

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Summary For construction purposes, it is very essential to provide a strong foundation for the structure. If required, the suitability of soil has to be improved; this process of improving properties of soil is called Soil Stabilisation. This study intends to experimentally analyse the effectiveness of use of an unorthodox liquid soil stabiliser, Microbial Induced Calcite Precipitates (MICP) for improving the shear strength parameters of two different types of fine grained soils. For this process, a species of *Bacillus* group, *B. pastuerii* was used to activate and catalyse the calcite precipitation caused by reaction between urea and calcium chloride. Two types of soils, i.e. intermediate compressible clay and highly compressible clay were used for the study. Parameters included concentration of *B. pasteurii*, concentration of the cementation reagent and duration of treatment. These parameters were applied on both the soils in a specified range in order to optimise their usage. The results proved that with the use of MICP, there was a noticeable improvement (1.5—2.9 times) in the unconfined compressive strength of both type of soils. It was also found that the strength increased with an increase in duration of treatment. Based on this study, optimum quantity and concentration of liquid additive to be added for different soil types for better strength increments were established.
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Introduction

Ground improvement or stabilisation is a process of improving ground (soil or rock) characteristics or parameters such as strength, permeability, compressibility etc. using mechanical or chemical aids. Present study undertakes a possible implication of a new, green, economic and sustainable technique i.e. MICP, which uses chemicals and micro-organisms to improve soil properties. According to the previous studies (Lee Min Lee et al., 2012; Chu et al., 2012; DeJong et al., 2006) MICP has had successful implication on sandy soil. Present study deals with the effect of MICP on fine grained soils. Successful laboratory application can lead to further scope for field implication of the technique. To study the effect of MICP on fine grained soil under various conditions, chemical and field parameters were considered and were varied accordingly. Their results and variations were observed and conclusions were drawn accordingly.

Microbial Induced Calcite Precipitation

Recently, a comparatively clean and sustainable technique, called Microbial Induced Calcite Precipitation (MICP) has been introduced in the field of ground improvement. The applications of this method shows potential in various fields like improvement of strength and durability of concrete, bricks, sand impermeability, soil strength etc., and various works are being conducted on these fields in the current scenario.

Lee Min Lee et al. (2012) studied the effect of MICP (Lee Min Lee et al., 2012) on shear strength and reducing hydraulic conductivity of sandy soils and residual soils (Sandy Silt). The results showed that MICP could effectively increase the shear strength (1.41—2.64 times) and reduce hydraulic conductivity (1.14—1.25 times) for both soil types. Wei-Soon Ng et al. (2012) conducted a study to find optimum conditions for improving engineering properties of residual soil using MICP (Wei-Soon Ng et al., 2012; Ng Wei Soon et al., 2013). Under optimum conditions, the improvements achieved for the undrained shear strength and hydraulic conductivity were 69.1% and 90.4% respectively.

In general, MICP can be achieved by urea hydrolysis, aerobic oxidation, denitrification, sulphate reduction, etc. Van Paassen et al. (2010) suggested that urea hydrolysis possesses the highest calcite conversion rate compared to other studied processes (Harkes et al., 2010; Whiffin et al., 2007). Urea hydrolysis refers to a chemical reaction where urea ($CO(NH_2)_2$) is decomposed by Urease enzyme that can be either supplied externally (Greene et al., 2003), or produced in situ by Urease-producing microorganisms (DeJong et al., 2006). The latter process requires Urease positive type bacteria, i.e. genera Bacillus, *Sporosarcina*.

1 mole of urea decomposes into 2 moles of ammonium according to following reaction:

$$CO(NH_2)_2 + 2H_2O \rightarrow 2NH^{4+} + CO_3{}^{2-}$$

The release of ammonium (NH^{4+}) causes a hike in pH, which in due course, creates a perfect circumstance for calcite precipitation with the availability of calcium ion (Ca^{2+}) from the supplied calcium chloride:

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

The $CaCO_3$ precipitates formed are gelatinous in nature and thus helps in bonding the soil particles together.

Table 1 Soil samples — basic properties.

Description	Symbol	Soil sample 1	Soil sample2
Gravel	G	0.3%	0.24%
Sand	S	47.1%	17.48%
(Silt + clay)	M + C	53.6%	82.28%
Liquid limit	W_L	45.4%	61.38%
Plastic limit	W_p	16.8%	28.2%
Plasticity index	I_p	28.5%	33.2%
Shrinkage limit	W_S	8.2%	7.6%
Specific gravity	G_s	2.5	2.7
Soil classification		CI	CH
Optimum moisture content	OMC	16.8%	19.7%
Maximum dry density	$\gamma_{d\ max}$	1.86 g/cc	1.64 g/cc
Unconfined compressive strength	q_u	0.99 kg/cm^2	1.28 kg/cm^2

Methodology

For this study, the materials used were soil samples and Microbial Induced Calcite Precipitates (MICP).

Soil samples

Two types of soils were considered for this study. Both soil samples were collected from Chennai (Tamil Nadu, India). The basic properties of the collected samples and soil classification are tabulated in Table 1. These samples were then treated with additives and then tested for strength increment.

Microbial Induced Calcite Precipitates

In this method, Calcite Precipitates were induced with help of aerobic Urease producing bacteria, i.e. *Bacillus pasteurii* or now known as *Sporosarcina pasteurii*. The soil materials were directly mixed with the prepared solutions of cementation reagent and *B. pasteurii*.

B. pasteurii

B. pasteurii culture was ordered from MTCC(1771), *S. pasteurii*. A medium for growth of the culture was prepared and a nutrient broth was used for the growth of culture. Concentration of *B. pasteurii* was a varying parameter and was varied by 1×10^5, 1×10^6 and 1×10^7 cfu/ml (Lee Min Lee et al., 2012).

Table 2 MICP Results — soil sample 1 — UC Test results.

Bacillus pastuerii	Cementation reagent	UCS (kg/cm^2)		
		0 days curing	3 days curing	7 days curing
1×10^5 cfu/ml	0.25 M	2.15	2.26	2.38
	0.5 M	2.20	2.58	3.00
	0.75 M	2.13	2.63	2.90
	1.0 M	1.92	2.41	2.71
1×10^6 cfu/ml	0.25 M	2.38	2.44	2.58
	0.5 M	2.40	2.73	3.72
	0.75 M	2.41	2.63	2.96
	1.0 M	2.16	2.32	2.90
1×10^7 cfu/ml	0.25 M	1.95	2.32	2.84
	0.5 M	2.40	2.97	3.45
	0.75 M	2.20	2.63	2.87
	1.0 M	2.15	2.23	2.73

Cementation reagent

The following chemicals were added to make the cementation reagent: Urea, Calcium Chloride, and Nutrient Broth. Concentration of cementation reagent was one of the varying parameters for this study. A fixed amount of nutrient broth i.e. 3 gm/lt was added into solution because it is the most viable amount for survival of bacteria as per previous studies (Al Qabanny et al., 2012; Lee Min Lee et al., 2012). Cementation reagent was prepared by adding equal molars of Urea and Calcium Chloride ($Ca^{2+} + CO_3^{2-} \rightarrow CaCO_3$). Concentration of cementation reagent was a governing parameter and hence was varied as 0.25 M, 0.5 M, 0.75 M and 1.0 M.

Mixing & curing

Initially, bacteria was added to the soil and mixed properly, which was followed by addition of the cementation reagent. The amount of bacteria and cementation reagent to be added was decided based on the study by Lee Min Lee et al. (2012). Unconfined Compression (UC) Tests were performed on soil samples by inducing MICP on dry side of OMC so as to obtain 95% Maximum dry density. Proper mixing was ensured for proper fixation and distribution of bacteria in soil (Al Qabanny et al., 2012). Soil was compacted and was tested according to IS: 2720 (Part X). Since treatment duration was a parameter, soil samples of given bacterial and molar concentrations were allowed for curing or treatment duration of 0, 3 and 7 days. The treatment duration was provided in order to provide sufficient time period for the chemicals to react and further allow $CaCO_3$ precipitates to develop. The samples were kept under maintained temperature of 20–30 °C (Greene et al., 2003), through a combination of moist sand and moist gunny bags.

Results and discussions

Test results—Microbial Induced Calcite Precipitation — UC Tests

The UCS value for virgin soil sample 1 was 0.99 kg/cm^2, which on treatment with MICP was found to increase further. The test results of soil sample 1 are tabulated in Table 2. It was observed from the test results that by increasing the treatment duration, UCS values further increased. For soil sample 1, highest increment was observed for bacterial concentration of 1×10^7 cfu/ml and molar concentration of 0.5 M of cementation reagent. UCS value further increased on increasing the treatment duration.

The UCS value of virgin soil for soil sample 2 (CH) was initially 1.28 kg/cm^2. On treatment with MICP, the values further increased. It was also found that the UC test values further increased on increasing the treatment duration. The combination of bacterial concentration and cementation reagent molar concentration for the highest increment was 1×10^6 cfu/ml and 0.5 M respectively for soil sample 2 (Table 3). Usually the microbes range from 0.5 to 3.0 μm (Al Qabanny et al., 2012), hence that provides us with the optimum pore size for the movement of microbes through the soil composite. Both the soil types offered high percentages of the optimum range for microbial movement, yet relatively higher increment ratio in UCS value was observed in case of soil sample 2. This can be attributed to finer particle size of CH soil which provided a dense arrangement of soil particles and offered more particle-to-particle contact for the bond formation. It further offered more specific surface area for the precipitate formation; hence the precipitates formed were bound intimately with soil composite, which ultimately lead to higher bonding between the soil particles. This higher bond formation in soil then lead to increase in cohesion of soil which is one of the parameters for the soil's shear strength and hence increase in soil strength.

Graphical representation

MICP results — soil sample 1 — UC Test results

The comparison of the results obtained from the UC tests on soil sample 1, with varying concentrations of MICP are graphically represented in Fig. 1(a)—(c) respectively. The comparison of the results obtained from the UC tests on soil sample 2, with varying concentrations of MICP are graphically represented in Fig. 2(a)—(c) respectively.

Table 3 MICP results — soil sample 2 — UC Tests.

Bacillus pastuerii	Cementation reagent	UCS (kg/cm^2)		
		0 days curing	3 days curing	7 days curing
1×10^5 cfu/ml	0.25 M	1.47	1.53	1.85
	0.5 M	1.60	1.82	2.03
	0.75 M	1.70	1.71	1.88
	1.0 M	1.57	1.78	1.83
1×10^6 cfu/ml	0.25 M	1.43	1.58	1.86
	0.5 M	1.71	1.89	2.18
	0.75 M	1.72	1.79	1.90
	1.0 M	1.57	1.70	1.82
1×10^7 cfu/ml	0.25 M	1.62	1.65	1.87
	0.5 M	1.78	1.96	2.24
	0.75 M	1.67	1.92	2.09
	1.0 M	1.50	1.61	1.97

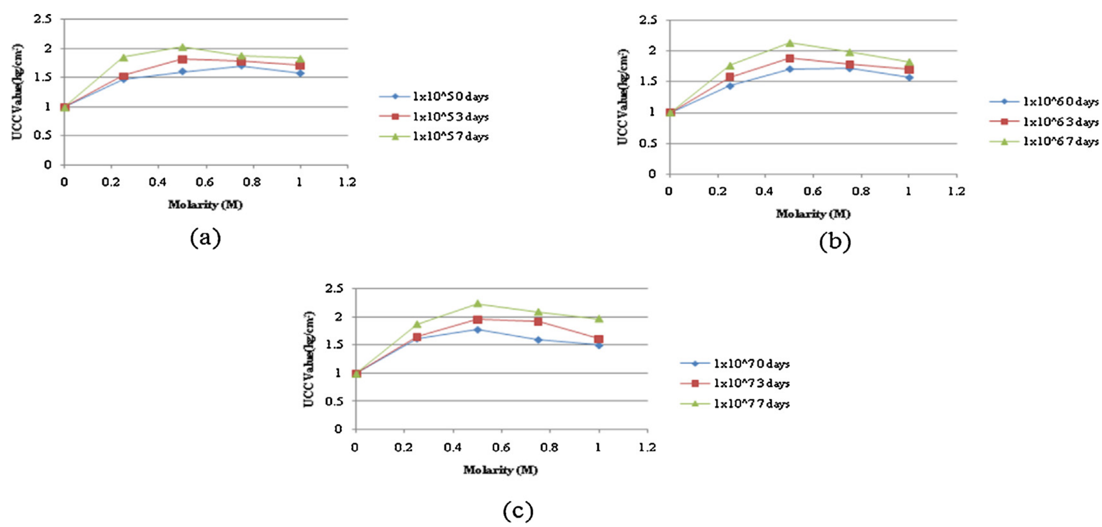

Figure 1 Comparison of variation of UC values treated with MICP — soil sample 1 (a) with 1×10^5 cfu/ml; (b) with 1×10^6 cfu/ml; (c) with 1×10^7 cfu/ml.

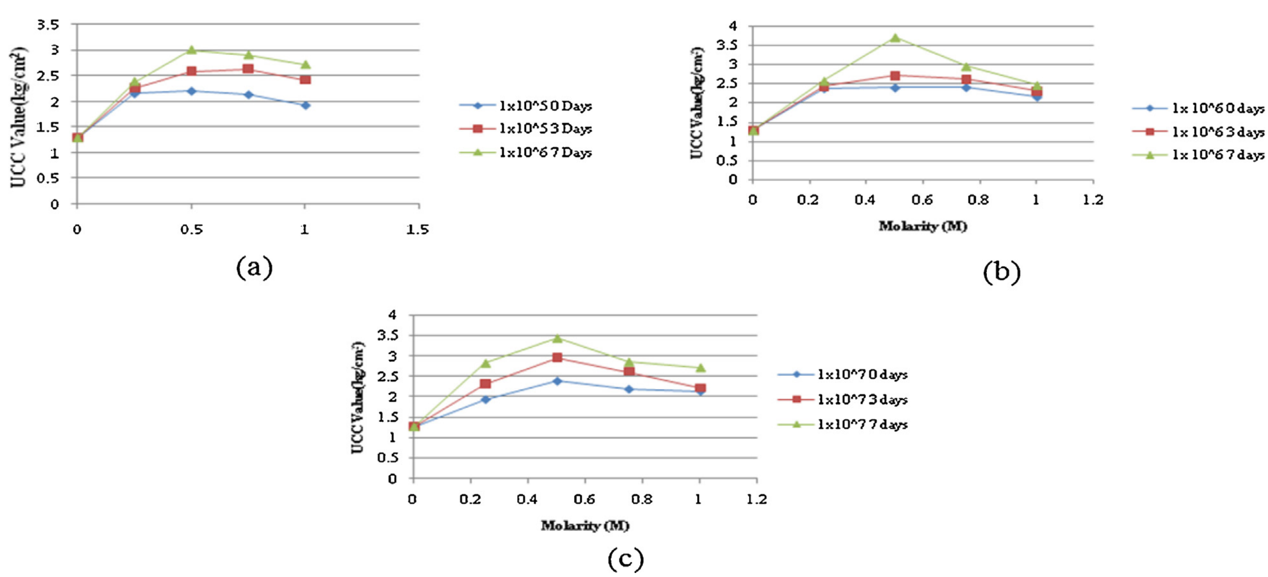

Figure 2 Comparison of variation of UC values treated with MICP — soil sample 2 (a) with 1×10^5 cfu/ml; (b) with 1×10^6 cfu/ml; (c) with 1×10^7 cfu/ml.

It can be inferred from the graphical representations from Figs. 1 and 2 that MICP improved the unconfined compressive strength of soil sample 1 noticeably, with an increment ratio varying from 1.45—2.26. *B. pasteurii* concentration of 1×10^7 cfu/ml and 0.5 M cementation reagent gave the optimum results; with its UCS value increasing from 0.99 kg/cm^2 to 2.24 kg/cm^2, which was observed when the soil was cured for 7 days.

In soil sample 2 also, addition of MICP was found to increase the unconfined compressive strength. Maximum strength of 3.72 kg/cm^2 was observed when the soil was cured for 7 days with a *B. pasteurii* concentration of 1×10^7 cfu/ml, and 0.5 M cementation reagent.

In both the soil samples, increase in soil strength can be attributed to the Calcite precipitates produced in presence of Urease positive bacteria, which strengthened the bonding between the soil particles, and filled up the remaining voids in the soil mass, which in turn increased soil strength. It can be observed that the strength increased with curing duration too.

Conclusions

MICP was found to increase the unconfined compressive strength of both the soils. Effect of MICP on the UCS of CH soil (1.50—2.91) was slightly more when compared to that in CI soil (1.45—2.26). For CI soil, bacterial concentration of 1×10^7 cfu/ml gave the best results, while for CH soil 1×10^6 cfu/ml gave the best results. It was also found that strength increased with curing duration. Both types of soils offered a viable range for microbial movement through the soil composite, yet higher increment was found in CH soil. The reason for higher increment in CH soil type can be attributed to the closer arrangement of the soil matrix in it. More particle-to-particle interaction caused the soil matrix to bond with the calcite precipitates firmly. This led to denser packing of the soil composite. On the other hand, CI soil, even though offering optimum pore size for microbial movement, had coarser arrangement of soil particles which led to lesser particle-to-particle interaction. Hence the calcite bond formation was relatively weaker. In other words, CH soil type offered more specific surface area for bond formation of calcite precipitates than CI soil. This led to a stronger bond formation in CH soil type.

MICP was found to increase the undrained cohesion of soil. Enhanced strength parameter can be co-related with other properties and possible implications will further lead to increased bearing capacity, minimised settlements, reduced permeability of soil, reduced shrink-swell behaviour and even reduction and a check in the development of pore pressure within the soil matrix.

Use of MICP can be very cost effective as it can be produced in excess quantity at a very low price. Bacterial solution can be prepared in huge amounts at very low costs and cementing reagents also are very economical compared to other soil improvement techniques in practice. As an added advantage, stabilisation using MICP is a very green, sustainable and eco-friendly technique which promises a great future.

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