Unconfined compressive strength of microbial induced calcite precipitation (MICP) treated soils

Résistance à la compression non confinée des sols traités par la précipitation de la calcite induite par des microbes (MICP)

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ABSTRACT: Microbial induced calcite precipitation (MICP) is an enhanced and accelerated natural process where bacteria precipitate calcite and bind soil particles together and therefore increase its strength. Since 2005, there have been significant number of journal articles published on MICP in the field of engineering geology and civil engineering. A critical scrutiny revealed that only part of these articles put effort in correlating engineering property of soil e.g. unconfined compressive strength, UCS with total calcite precipitation in a MICP treated soil. This article compiled UCS data with the total amount of calcite precipitation. It is hypothesised that soil grading significantly affects the throat-size of soil particle which influences the bonding created by calcite precipitation. Therefore, soil-grading properties such as D_{10} and C_c were considered with calcite to find foreseeable relation for UCS. A regression model can be developed for UCS with total calcite precipitation and D_{10}. This is preliminary study which shows a pathway of such modelling approach.

RÉSUMÉ : La précipitation par calcite microbienne induite (MICP) est un processus naturel accéléré et accéléré où les bactéries précipitent la calcite et lient les particules de sol ensemble et augmentent par conséquent sa force. Depuis 2005, il existe un nombre important d'articles de revues publiés sur MICP dans le domaine de la géologie et du génie civil. Un examen critique a révélé que seule une partie de ces articles met l'effort à corréler la propriété d'ingénierie du sol, par ex. Résistance à la compression non confinée, SCU avec précipitation totale de calcite dans un sol traité au MICP. Cet article a compilé des données UCS avec la quantité totale de précipitation de calcite. On émet l'hypothèse que la classification du sol affecte significativement la taille de la gorge de la particule du sol qui influence la liaison créée par la précipitation de la calcite. Par conséquent, les propriétés de classification du sol telles que D10 et Cc ont été considérées avec calcite pour trouver la relation prévisible pour UCS. Un modèle de régression peut être développé pour l'UCS avec la précipitation totale de la calcite et D10. Il s'agit d'une étude préliminaire qui montre une voie d'une telle approche de modélisation.

KEYWORDS: MICP, calcite precipitation, urea hydrolysis.

1 INTRODUCTION

Population and civil infrastructure demands continue to expand worldwide, with the availability of suitable soils for construction decreasing. Strengthening soil is now an integral part of development. The most common methods to strengthen soils use either one or a combination of several mechanisms such as compaction, vibration and grouting. These techniques have proved to have a different degree of effectiveness in improving strength over time. But these techniques consume a substantial amount of energy either in their application or production or both.

Technological advancement and new knowledge in the field of biology and microbiology during the past years has made accessible new pathways to investigate in the field of geotechnical research and innovation. In recent years one such opportunity by exploiting natural biological process to bind the soil particles together thereby increasing the strength and stiffness of soil has been explored by many researchers. This process is claimed as sustainable and environment friendly approach over the conventional soil improvement methods and is referred as microbial induced calcite precipitation (MICP). MICP utilizes naturally occurring bacteria to plug the voids in soil or bind the particles together (cementation) through calcium precipitation thereby altering the strength and stiffness of the soil mass.

Research in the field of MICP accelerated after Mitchell and Santamarina (2005) introduced microbiological concept to increase the states of knowledge and practice in the geotechnical field. Then, the US National Research Council (NRC, 2006) also recognized the biological processes existing in nature for future possibilities in geomechanical applications. DeJong et al. (2006) was the first publication to examine the effect of biological treatment on strength properties of cohesionless soil. Since then a number of studies have been conducted on different soil types to investigate the process of MICP in altering soil properties with primary focus to optimize the process and make it more economical. These studies demonstrated the effectiveness of MICP to alter the engineering properties of soil namely strength and permeability, improve resistance against liquefaction, to create impermeable crust for catchment facilities, reduce wind and water erosion, treating waste, immobilizing heavy metals, restoring /stabilizing cracks in concrete and masonry, increase cone tip resistance and execute shallow carbon sequestration.

Although these studies focused on the effect of MICP on engineering properties, there are limited efforts to correlate improved engineering properties with calcite precipitation which is the primary factor that alter soil structure i.e. engineering properties. The purpose of this paper is to review the past work on MICP treated soils and investigate the correlation between engineering properties of soil mainly unconfined compressive strength (UCS) with total calcite precipitation in a MICP treated soil.

2 LITERATURE REVIEW

2 .1 *MICP process*

MICP can be carried through different mechanisms such as urea hydrolysis (Benini et al. 1999, Hussain et al. 2016), denitrification (van Paassen et al., 2010), sulphate reduction (Warthmann et al. 2000) and iron reduction (Roden et al. 2002 and Ivanov et al. 2014). However urea hydrolysis is the most energy-efficient and a vast range of microorganisms inhabit urease activity (DeJong et al, 2010).

Alkalophillic soil bacteria such as *Sporosarcina pasteurii* with high active urease enzyme is generally used for urea hydrolysis. The metabolic action of this bacteria consumes the urea (NH_2CONH_2) and disintegrates into ammonia (NH_3) and carbamate (NH_2COOH) through chemical reaction (see Eq. 1). These chemical compounds spread out from the cell wall of microbe into the neighbouring media. In proximity with water ammonia converts into ammonium, ${NH_4}^+$ (see Eq. 4) and carbamate transforms into carbonate, carbonic acid and bicarbonate ions (${HCO_3}^-$). The reaction of ammonia with water also produces hydroxyl ions (OH^-) which increases the pH of the media and helps in precipitation of available Ca^{2+} into calcium carbonate ($CaCO_3$) (see Eq. 5).

$$NH_2CONH_2 + H_2O \rightarrow NH_3 + NH_2COOH \quad (1)$$
$$NH_2COOH + H_2O \leftrightarrow H_2CO_3 + NH_3 \quad (2)$$
$$H_2CO_3 \leftrightarrow H^+ + HCO_3^- \quad (3)$$
$$NH_3 + H_2O \leftrightarrow NH_4^+ + OH^- \quad (4)$$
$$Ca^{2+} + {HCO_3}^- + OH^- \leftrightarrow CaCO_3\ (\downarrow) + H_2O \quad (5)$$

Over the last few years, most studies have used the above urea hydrolysis for MICP process in treating soil or altering its engineering properties (DeJong et al 2006, Whiffin et al 2007, L. A. van Paassen et al 2009, Burbank et al 2011, Mortensen and DeJong 2011, Al-Qabany A., Kenichi Soga and Carlos Santamarina 2012, Burbank et al 2013, Martinez et al 2013, Cheng, Cord-Ruwisch and Shahin 2013, Gomez et al 2014, Montoya and DeJong 2015). The studies used two different approaches - bioaugmentation and biostimulation. In bioaugmentation, external microbes are either injected or percolated into the soil along with nutrient medium to help in their growth and calcite precipitation. Whereas, in biostimulation indigenous microbes of the soil are stimulated with external nutrient medium thereby inducing growth and calcite precipitation. Both approaches comprise of some advantages and disadvantages however generally in practice bioaugmentation is globally employed (Dejong et al., 2013). However, this study considers total $CaCO_3$ as a parameter irrespective of these two approaches.

2.2 *Unconfined compressive strength (UCS) tests on MICP treated soils*

The calcite precipitation through MICP in turn modifies or enhances the strength of the sample and different studies have investigated this influence through various laboratory tests namely unconfined compressive strength (UCS) (Al-Thawadi et al 2008, Cheng and Cord-Ruwisch 2012, Cheng et al 2013, Cheng et al 2014, Gomez et al 2014), triaxial test (DeJong et al, 2006) and cone penetrometer (Burbank et al. 2011). A summary of the studies can be found in Table 1. Initial study conducted by Al-Thawadi et al. (2008) to achieve cementation on column size samples and investigate the influence on strength of sandy soil observed a range of UCS values between 8.73 – 19.55 MPa. Later Cheng and Cord-Ruwisch (2012) analysis shows an increase of 20 MPa in the value of UCS whereas Cheng et al. (2014) data did not show any significant increase in the UCS value although both the studies investigated the surface percolation method on column size samples.. The variation could be due to many factors such as specimen type, size, sample preparation method and testing method. Rather the data from Cheng et al (2013) shows a constant increase in UCS with increase in calcium carbonate precipitation. All of the above studies incorporated bioaugmentation approach for MICP. Alternatively Gomez et al. (2014) implemented biostimulation in a variety of soils to assess the ability of native bacteria to facilitate calcite precipitation. A compilation of the data points of UCS and $CaCO_3$ precipitation from these studies presents a scatter of the data points as shown in Figure 1. This dispersed distribution of data points does not allow an interpretation of contribution of $CaCO_3$ on UCS as the particle geometry and pore space between them significantly influences the bond established due to calcite precipitation. The pore throat size is dependent on smallest fraction of particles and can be approximated as 20% of soil particle size that corresponds to 10% passing in a sieve analysis (Holtz and Kovacs, 1981). This can be a lower limit estimate for effective MICP treatment. However the upper limit for effective treatment primarily counts on the fraction of microbes participating in the chemical reaction at particle contact points. Therefore, an assumption that characteristics parameter from particle size distribution (PSD) curve along with values of UCS and $CaCO_3$ content may give a better correlation.

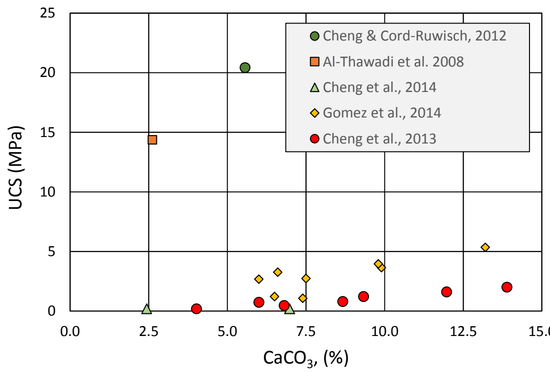

Figure 1. Variation of unconfined compressive strength with total $CaCO_3$ precipitation.

2.3 *Data screening to reduce variability*

Research work to date has examined the potential of bioaugmentation and biostimulation to modify the physical and mechanical properties of soils which are two different approaches of MICP. In both approaches urea hydrolysis contributes towards the byproducts which makes it difficult to differentiate between the two. These studies applied MICP on soil samples of variable size and soil characteristics, different chemistry and concentration for treatment solution, different environments and tested under diverse conditions. These discrete factors are challenge to compare the results of the past studies.

The primary limitation before the initiation of chemical reactions and generation of by-products is the size of pore throat (space) available for the microbes to pass through the soil matrix. The pore throat or the void space where $CaCO_3$ precipitates consecutively depends on the soil particle size. Although the crystal structure and formation of $CaCO_3$ around the soil particle depends on specimen size, pore throat available, degree of saturation, percolation method and environment however to minimize the influence of these factors the amount of calcium carbonate precipitate was used, directly, as one parameter in this study. To reduce the impact of testing method the study examined the data sets of UCS testing although inconsistency due to human error during testing cannot be fully ignored.

The present study considered small laboratory specimens of approximately 100 mm in height and 50 mm in diameter treated with MICP in saturated soil. All these specimens were prepared at approximately 50% relative density, therefore reduce the effect of density between soils. Despite the scrutiny of the literature it may be unlikely to eliminate altogether the influence of all the above factors.

2.4 *Inverse distance of power gridding method*

The data of UCS and $CaCO_3$ from the past studies on MICP treated soils does not represent a satisfactory plot in a 2D space as shown in Figure 1. Therefore, in a separate study characteristics parameter such as D_{10}, C_u and C_c from particle size distribution were added with UCS and $CaCO_3$ in a 3D plot to reveal an observational trend (Hora et al., 2016). These parameters were selected due to their influence on particle arrangement and pore space between them which generally affects the calcite precipitation. An inverse distance of power gridding method (IDP) for interpolation was adopted due to the irregular scatter of data points. The interpolated value of grid node "*j*" by this method can be calculated by the following equation:

$$\hat{C}_j = \frac{\sum_{i=0}^{n} \frac{C_i}{(h_{ij})^{\beta}}}{\sum_{i=1}^{n} \frac{1}{(h_{ij})^{\beta}}} \quad (6)$$

where h_{ij} is the effective separation difference between grid node "*j*" and the neighboring point "*i*", C_i is the value at grid node "*i*" and β is the weighting power or the power parameter. Contour plots were then plotted through these grid points. The D_{10} and $CaCO_3$ data points are plotted in x and y axis respectively (see Figure 2) whereas C_c and $CaCO_3$, and C_u and $CaCO_3$ relations were also investigated in a previous study (Hora et al, 2016). C_u and $CaCO_3$ data points does not correlate with UCS. The plot between C_c and $CaCO_3$ presents a general trend of increase in UCS with increase in calcite precipitation and C_c value. Similar trend is visible in the 3D plot between D_{10}, UCS and $CaCO_3$. However, a strong influence of D_{10} on overall behaviour is noticeable as shown in Figure 2.

2.5 *Regression analysis*

A contour map is a good presentation of 3D correlation, however it does not provide a close form of mathematical relation. Therefore, a regression analysis was done with the data sets normalized by UCS of corresponding soil at 10% $CaCO_3$. A best-fit equation can be found as-

$$UCS / UCS_{10\%CaCO3} = 0.689 - 3.85D_{10} + 0.073CaCO_3 + 2.75D_{10}^2 + 0.196D_{10}CaCO_3 - 0.0017(CaCO_3)^2 \quad (7)$$

The root mean square deviation (RMSD) of equation (7) is only 0.0082 which is only 11% of the average value of $UCS/UCS_{10\%CaCO3}$. A 3D presentation of D_{10}, UCS and $CaCO_3$ data points and Equation (7) as a mesh is shown in Figure 3. The regression coefficient between measured and predicted data was R^2 of 0.95.

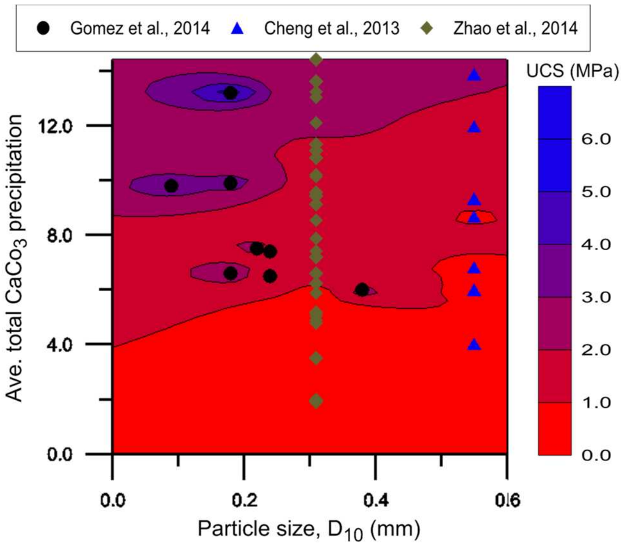

Figure 2. Contour plot of UCS (MPa) with D_{10} and $CaCO_3$ (%).

Table 1. A summary of literature on MICP and UCS

	MICP Process								Testing Method		
Sand type	Mechanism	Throat size (mm)	DOS (%)	PM	D_{10} (mm)	D_{60} (mm)	C_u	C_c	Size H x D (mm)	Method	Ave. UCS (MPa)
[1]Plaster sand *	BS	0.036	100	Gravity Fed	0.18	1.26	7	0.7	102 x 51	UCS	3.25
[1]Concrete sand *	BS	0.036	100	Gravity Fed	0.18	1.81	10.1	0.6	102 x 51	UCS	3.64
[1]Cushion sand *	BS	0.018	100	Gravity Fed	0.09	0.32	3.6	1.3	102 x 51	UCS	3.95
[1]Russian River *	BS	0.048	100	Gravity Fed	0.24	2.09	8.7	0.7	102 x 51	UCS	1.22
[1]Folsom Lake *	BS	0.048	100	Gravity Fed	0.24	1.66	6.9	0.7	102 x 51	UCS	1.07
[1]Napa Bay*	BS	0.036	100	Gravity Fed	0.18	0.29	1.6	0.8	102 x 51	UCS	5.34
[1]Cemex Fill *	BS	0.076	100	Gravity Fed	0.38	3.18	8.4	1.2	102 x 51	UCS	2.67
[1]Granite sand *	BS	0.044	100	Gravity Fed	0.22	1.7	7.7	0.6	102 x 51	UCS	2.73
[2]Silica sand *	BAUG	0.11	100	Injection	0.55	0.7	1.27	0.1	110 x 55 mm	UCS	4.02 – 13.89
[3]Silica sand	BAUG	0.05	100	Injection	0.25	-	-	-	1000 x 45	MPP	8.73 – 19.55
[4]Pure silica sand	BAUG	0.046	Unsat	SP	0.23	-	-	-	1000 x 45	PP	19.61
[5]Silica sand	BAUG	0.07	Unsat	SP	0.35	-	-	-	2000 x 55	UCS	0.065
[6]Ottawa Silica*	BAUG	0.04	100	Submerged	0.20	0.35	1.75	1.1	102 x 51	UCS	1.94 – 14.42

* Used in further analysis; BAUG – Bioaugmentation; BS – Biostimulation; DOS – Degree of Saturation; PM – Percolation Method; UC S – Unconfined Compressive Strength; MPP – Modified pocket penetrometer; PP - Pocket penetrometer; SP – Surface Percolation;[1] – Gom ez et al. 2014, [2] – Cheng et al., 2013; [3] – Al-Thawadi et al., 2008; [4] – Cheng & Cord-Ruwisch , 2012; [5] - Cheng et al., 2014; [6] – Zha o et al., 2014

2.6 *Limitation of the study*

While equation (7) has some predictive capability, reader must be warned that the result of this study are preliminary outcome of limited data sets, which were evaluated through some screening criteria. The data sets as shown by '*' in Table 1 are used in the analysis and may not be ready for any further generalization. However, this preliminary study shows a pathway for development of such model.

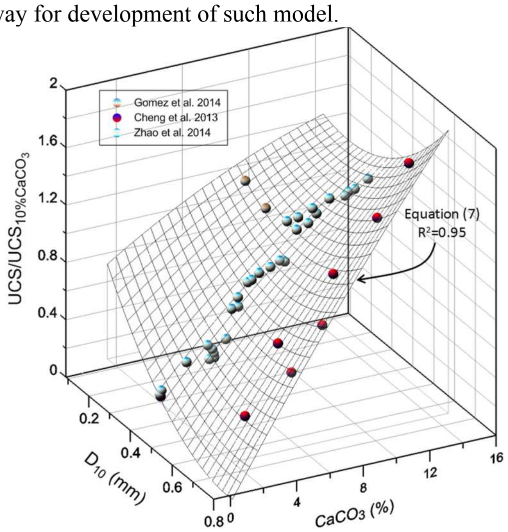

Figure 3. 3D plot of D_{10}, UCS and $CaCO_3$ data points and equation (7) as a mesh.

3 CONCLUSION

This study critically reviews existing literature on UCS tests for MICP treated soil and put effort to develop a preliminay regressional model. The major findings are-

- MICP is rapidly growing field in geotechnical engineering. There are many variables that may affect UCS of MICP treated soils. A multi-variable analysis of D_{10}, UCS and $CaCO_3$ shows a general trend in contour plot.
- A regressional corelation can be developed among D_{10}, UCS and $CaCO_3$ with screened datasets. However further study is needed to develop a general understanding of the all parameters affecting UCS of MICP treated soils.

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