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A review of the unconfined compressive strength of microbial induced calcite precipitation treated soils

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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 thereby increase its strength. This is an environmentally friendly approach for ground improvement which has attracted significant research interest. Since 2005, there have been approximately 70 journal articles published on MICP in the field of engineering geology and civil engineering. A critical scrutiny reveals that only some of these articles focus on the engineering properties of soil e.g. unconfined compressive strength (UCS) with total calcite precipitation in a MICP treated soil. This article examines UCS data with relating to calcite precipitation and finds there is a wide range of results. It is hypothesised that soil grading significantly affects the throat-size of soil particles which influences the bonding created by calcite precipitation. Therefore, soil grading properties such as Cu, D_{10} and Cc were considered to find a suitable relationship for UCS. The lack of data was overcome with the use of the Inverse Distance to a Power (IDP) gridding method. The contour plot of UCS in the space of total calcite precipitation and grading properties such as D_{10} and Cc provided a general trend for estimating the UCS of MICP treated soils.

1 INTRODUCTION

Substantial increases in infrastructure development have led to the need to develop new and feasible soil improvement methods. In the past, many soil enhancement techniques have been developed which have a different degree of effectiveness in improving strength of soil over time. One of these techniques is mixing artificial cement with soil to bind soil particles together to enhance its strength. Artificial cement requires a large amount of energy for manufacturing and application, produces carbon, utilizes large volume of natural resources combined with land deterioration. Therefore, mixing cement with soil is not considered as an environment friendly approach. However, soil cementation occurs naturally at a slow rate which can be enhanced and accelerated as an alternative via an engineering process. This process is claimed as sustainable and environment friendly and referred to as microbial induced calcite precipitation (MICP). MICP uses naturally occurring bacteria to bind soil particles together (cementation) through calcium carbonate ($CaCO_3$) precipitation, thereby increasing the strength and stiffness of soil. The expected life of MICP treated soil is more than 50 years, which is compatible with the expected service life of many geotechnical structures (DeJong*, et al.*, 2013).

The interest on MICP treated soil triggered when Mitchell and Santamarina (2005) and US National Research Council (NRC, 2006) identified biological processes as an important research topic for the 21st century. Since then more than 100 technical conference and journal papers have been published dedicated to this field (DeJong*, et al.*, 2013). These works include identifying microorganisms (Mitchell and Santamarina, 2005), geometric compatibility between bacteria and pore space (DeJong*, et al.*, 2010) and survivability (Rebata-Landa and Santamarina, 2006), $CaCO_3$ precipitation and its efficiency in MICP (Al Qabany*, et al.*, 2012, Cheng*, et al.*, 2013) and ultimate soil strength improvement (Whiffin*, et al.*, 2007, Burbank*, et al.*, 2011, Burbank*, et al.*, 2013). Only a part of these articles was specific to MICP technique. A search for "MICP" in web of science finds 70 articles in relation to the field of engineering geology and civil engineering. Many of these articles are focused on optimizing MICP in relation to soil bio-chemistry and application processes; however, a part of these literatures studied calcite precipitation and improved soil strength behaviour such as unconfined compressive strength (UCS). The $CaCO_3$ precipitation in MICP treated soils depends on many factors of MICP treatment process such as chemistry and concentrations. Even for the same MICP process, the engineering properties of treated soils depends on soil characteristic and it's states such as particle sizes and their distribution, density, stress etc. The nature and contribution of soil characteristic to UCS for a similar MICP treated soil are not clear as most of the earlier studies were focused on a particular soil. Therefore, this article critically reviewed previously published articles for similar MICP process and put an effort to develop cohesive understanding of soil grading on UCS of MICP treated soil. The demographic statistic of these 70 publications also provided interesting information about the leading institutions and countries for MICP technique and future research direction of this new evolving technique.

2 GENERAL REVIEW OF MICP

2.1 *Methods for MICP*

MICP can be achieved in many ways such as through urea hydrolysis, denitrification, as well as iron and sulphate reduction. However urea hydrolysis is the most energy efficient and ubiquitous method for natural soils.

Sporosarcina pasteurii, which is an alkalophillic soil bacteria with a highly active urease enzyme, is the most commonly used in urea hydrolysis. In the process, urea is hydrolysed to carbamate (NH_2COOH) and ammonia (NH_3) as in Eqn.1. Carbamate is then spontaneously hydrolysed to give carbonic acid (H_2CO_3) and ammonia (NH_3) as in Eqn. 2 which then undergoes hydrolysis according to Eqn. 3 and 4. In the presence of dissolved calcium, this process precipitates $CaCO_3$ (Eqn. 5).

$$CO(NH_2)_2 + H_2O \xrightarrow{urease} NH_3 + NH_2COOH \quad (1)$$

$$NH_2COOH + H_2O \leftrightarrow H_2CO_3 + NH_3 \quad (2)$$

$$H_2CO_3 \leftrightarrow H^+ + HCO_3^- \quad (3)$$

$$NH_3 + H_2O \leftrightarrow NH_4^+ + OH^- \quad (4)$$

$$Ca^{2+} + HCO_3^- + OH^- \leftrightarrow CaCO_3 \downarrow + H_2O \quad (5)$$

The negative charge on the bacteria cell wall attracts the soil particle. Physiochemical properties of the cell and soil particle further help in binding them together where $CaCO_3$ precipitates.

Since 2006, the studies have been focused on treating soil using different MICP application methods. These methods can be broadly classified in two groups: (1) bio-augmentation and, (2) bio-stimulation. In bio-augmentation, external microbes are either injected or percolated into the soil along with nutrient medium to help in their growth and $CaCO_3$ precipitation (DeJong, *et al.*, 2006). In bio-stimulation, indigenous microbes of the soil are stimulated with external nutrient medium thereby inducing growth and $CaCO_3$ precipitation (Burbank, *et al.*, 2013).

2.2 *Demographic statistics of the literature*

Mitchell and Santamariana (2005) was arguably the first publication in main stream geotechnical engineering journals that explicitly discussed the application of biological processes. Then, the US National Research Council (NRC, 2006) identified biological processes as an important research topic for the 21st century. DeJong, *et al.* (2006) was the first publication that was focused on undrained behaviour of MICP treated sand. Since then about 70 journal articles published on MICP. The trajectory of the number of publications by years shows an exponential trend up to 2013 and then remained steady for last 3 years, as shown in Fig. 1. The source countries of these publications are shown in Fig. 2. USA, China, England, Canada, Netherlands and Australia are the source of 26%, 11%, 6%, 5%, 5% and 5% of these publications, respectively. The top two leading institutions for MICP research are University of California, Davis and North Carolina State University and their contribution were 14.29% and 7.14% to these publications. These indicate their leadership and strong research focus on MICP treated soil.

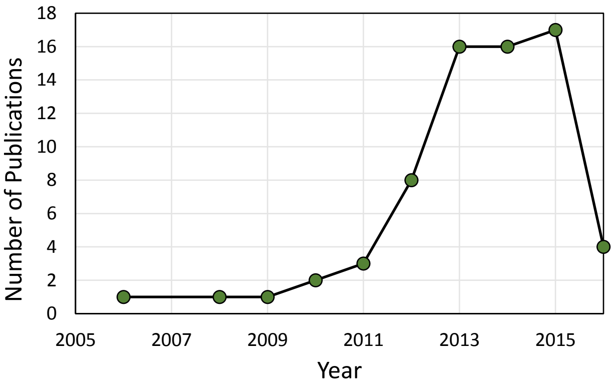

Figure 1. Increasing trend of number of publications for MICP in treating soil (up to March 2016).

3 CRITICAL REVIEW OF IMPROVEMENT OF MICP TREATED SOILS

3.1 *Data selection*

The MICP processes use different chemistry and concentrations for treatment solutions, different application techniques (saturation/unsaturation), different environments, different specimen sizes and soil characteristics which makes it difficult to compare results from different studies. To minimize the influence of the factors that affect $CaCO_3$ precipitation, the amount of precipitate $CaCO_3$ was used, directly, as a parameter in this study. However, the crystal structure of $CaCO_3$ and their formation around the soil particles can also be affected by environment, specimen size, degree of saturation etc. This study only considered small specimens (typical size of 100mm height and 50mm diameter) that was treated with MICP process under laboratory condition in saturated soil and $CaCO_3$ precipitated as calcite crystal structure. Despite the scrutiny of the literature, it may not be possible to eliminate all the influences of the above factors. However, accepting this limitation, this study compile a larger dataset from around the world which was synthesized with statistical analysis to reveal a qualitative trend.

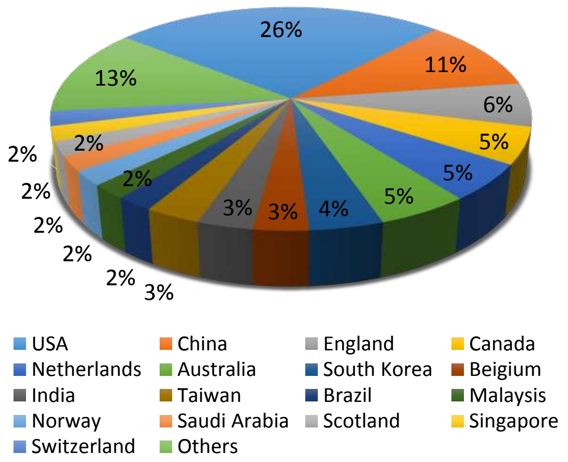

Figure 2. Distribution of source countries of MICP related journal articles (up to March 2016).

3.2 *Soil used for MICP treatment*

A total of 12 different silica sands were found in the literature that were used for the study of unconfined compressive strength, UCS of MICP treated soil. 19 data points for UCS and $CaCO_3$ of these silica sands are extracted from the literature. The distribution of UCS data points with respect to soil types are shown in Fig. 3. Soil particle size and their grading are important for particle arrangement and the void space (throat size) between particles of a soil specimen. Both the arrangement and void space between particles are important for MICP treatment for fluid flow, geometric compatibility between bacteria and pore space and $CaCO_3$ precipitation (DeJong, *et al.*, 2010). Rahman and co-workers (Rahman and Lo, 2008, Rahman, *et al.*, 2008), by analysing a wide range of grading for soil and spherical steel balls, identified that D_{10} (10% or finer on a particle size distribution curve) is a characteristic particle size that has a significant influence on particle arrangement, particularly for the gap (throat size) between particles. Therefore, D_{10} of these soils are also noted in Fig. 3 and will be used in subsequent analyses.

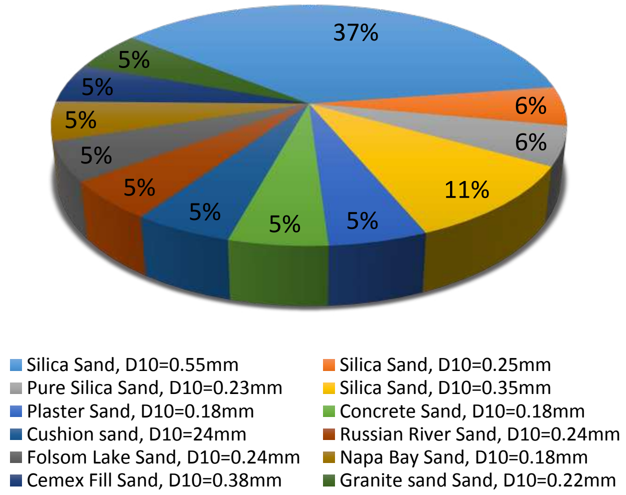

Figure 3. Distribution of UCS data points with respect to their soil type.

3.3 *Unconfined compressive strength of MICP treated soil*

Extreme MICP treatment can turn a soil into a brick-like material (UCS ≈ 20MPa) by applying repeated treatment under very stringent controlled laboratory condition (Cheng and Cord-Ruwisch, 2012) where as a light treatment can have a lower UCS of 0.80MPa (Cheng, *et al.*, 2013). Therefore, the UCS of MICP treated soil cannot be directly comparable without considering fundamental changes in the bonding between soil particles. A crude way of quantifying these bonding would be comparing them with the total percentage $CaCO_3$ precipitation (by mass) during MICP treatment. A comparison of UCS for MICP treated soil with total $CaCO_3$ is presented in Fig. 4. The scatter of the data points does not allow an interpretation of the contribution of $CaCO_3$ to UCS i.e. there is no unique relation. Note how the total $CaCO_3$ precipitates and how it contributes to the effective bonding, depends on particle arrangement and gap between host sand particles for a particular MICP application process. Therefore, it is envisaged that a characteristic parameter for particle size distribution (PSD) curve combined with $CaCO_3$ may give a better correlation

3.4 *Challenges and discussion*

The data points in Fig. 4 were obtained by different testing methods. 15 out of 19 data points were obtained by UCS tests of cylindrical specimens (Cheng, *et al.*, 2013, Gomez, *et al.*, 2014). However, other 4 data points by Cheng and Cord-Ruwisch (2012), Al-Thawadi (2008) and Cheng, *et al.* (2014) were obtained from treated larger sand column into a polyvinyl chloride (PVC) column. These data points were outlier of the scattered data points and therefore, neglected for subsequent analysis. Note that removing these 4 outliers did not improve the interpretation of the contribution of $CaCO_3$ to UCS.

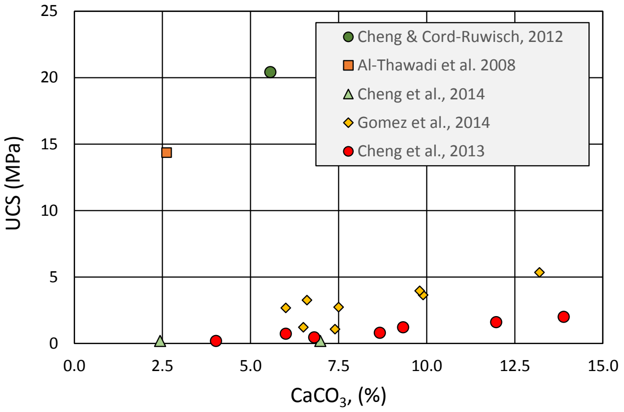

Figure 4. Distribution of UCS vs $CaCO_3$ data points with respect to their soil type.

A 2D plot (UCS vs $CaCO_3$) is not suitable for observing the contribution of MICP treatment on UCS, knowing that the particle arrangement and gap between them significantly influences the bond created by $CaCO_3$. Therefore, the characteristic parameter of PSD curve is added with UCS and $CaCO_3$ in a 3D plot (contour plot) to reveal an observational trend between them. Since the extracted data points were irregular in the grid space, an Inverse Distance to a Power (IDP) gridding method was used for interpolation. In this method data are weighted during interpolation such that the influence of one point relative to another declines with distance from the grid node. Weighting is assigned to the data through the use of a weighting power that controls how the weighting factors drop off as distance from a grid node increases. As the power increases, the grid node value approaches the value of the nearest point. For a smaller power, the weights are more evenly distributed among the neighboring data points. The interpolated value for grid node "*j*" can be calculated by the following equation:

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

where h_{ij} is the effective separation difference between grid node "*j*" and the neighboring point "*i*", $\hat{C}_j$ is the interpolated value for grid node "*j*", C_i are the neighboring points and β is the weighting power (the Power parameter). The details of the statistical method can be found in Davis (2002) and Franke (1982). Normally, Inverse Distance to a Power behaves as an exact interpolator. When calculating a grid node, the weights assigned to the data points are fractions, and the sum of all the weights are equal to 1.0. When a particular observation is coincident with a grid node, the distance between that observation and the grid node is 0.0, and that observation is given a weight of 1.0, while all other observations are given weights of 0.0. Thus, the grid node is assigned the value of the coincident observation. Contour maps were then plotted through these grid points.

3.5 *UCS of MICP and soil grading*

The uniformity coefficient, $Cu=D_{60}/D_{10}$ is often considered to represent soil grading; where D_{60} is particle size at 60% finer on PSD curve. For example, Cu > 4 is well graded sand and Cu < 4 poorly graded sand. The Cu and $CaCO_3$ of the extracted data points are plotted in x and y axis, respectively, in Fig. 5. The UCS is presented by colour contour (z-axis) for an interval of 1MPa. The grid points for this plot were generated by 50 rows and 35 columns i.e. 1750 grid points. Note that a large number of grid points are required for smaller contour interval. For the contour interval of 1MPa, the Fig. 5 would remain same for as low as 360 grid points i.e. contour map is not affected by the finer gird points. However, it may affect by the methods to generate grid points.

Fig. 5 also shows the UCS data points and their values. The contours plot captured the zone of high UCS (in blue) and low UCS (in red). However, this plot shows that Cu does not correlate with UCS and $CaCO_3$.

Since Rahman and coworkers (Rahman, *et al.*, 2008, Rahman, *et al.*, 2014) identified D_{10} as a characteristic particle size for particle arrangement, particularly the gap between particles which influence effective bonding, the contour plotted with D_{10} instead of Cu is presented in Fig. 6. For the same amount of $CaCO_3$, a specimen with smaller D_{10} had higher UCS. The rate of increasing UCS is higher with $CaCO_3$ at lower D_{10}. A mild trend of increasing UCS can be observed with $CaCO_3$ at higher D_{10}.

The coefficient of curvature, $Cc = (D_{30})^2/(D_{10}xD_{60})$ is a characteristic parameter that consider wider range of particle size, including D_{10} for soil grading; where D_{30} is particle size at 30% finer. The contour plot for UCS with $CaCO_3$ and Cc is presented in Fig. 7. Although it shows a general trend of increasing UCS with the increase of $CaCO_3$ and Cc, a maximum increase was obtained at Cc=0.8. This is due to the missing data points in the zone of higher $CaCO_3$ and Cc (0.8 to 1.6). Similar limitation was observed in Fig. 6 with D_{10}, perhaps little vague than in Fig. 7. The Inverse Distance to a Power (IDP) gridding method is suitable to develop an unforeseeable relation among three parameters. However the certainty of the inferred trend is also dependent on the spread of data points in the x-y space.

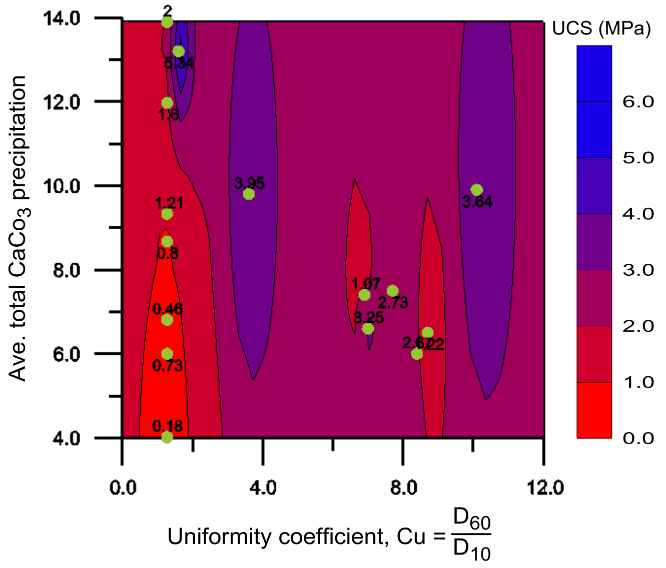

Figure 5. Contour plot for UCS with Cu and $CaCO_3$.

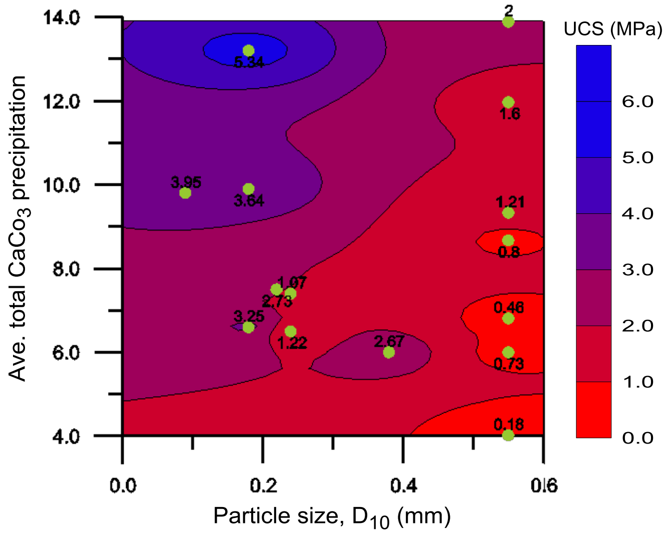

Figure 6. Contour plot of UCS with D_{10} and $CaCO_3$.

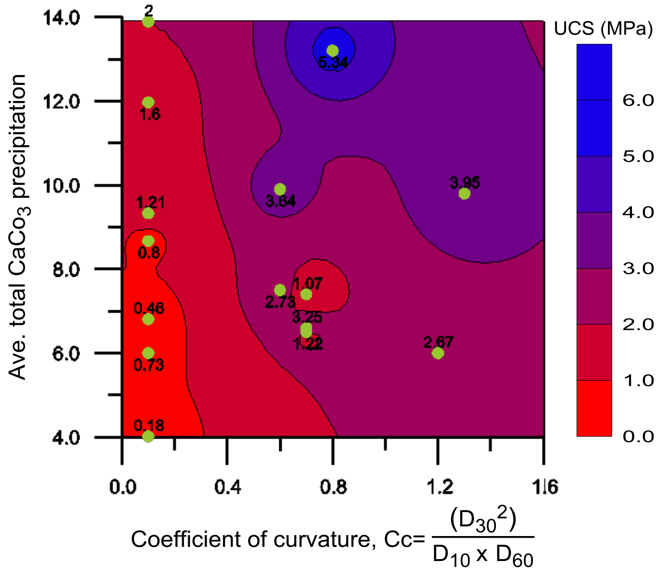

Figure 7. Distribution of UCS vs $CaCO_3$ data points with respect to their soil type.

4 CONCLUSIONS

Microbial induced calcite precipitation (MICP) technique utilizes naturally occurring bacteria to precipitate $CaCO_3$ to bind soil particles together and this increases soil strength. This article reviewed 70 journal articles that have used MICP in the field of civil engineering and engineering geology. A scrutiny of literature revealed that only a few articles reported total $CaCO_3$ precipitation for similar MICP process and engineering properties such as the unconfined compressive strength (UCS) of soil. The major findings are:

- The demographic statistics of those publications showed that the research and publications on MICP increased exponentially from 2005. USA, China, England, Canada, the Netherlands and Australia are the leading countries in terms of MICP research. The University of California, Davis and North Carolina State University are two universities that have particularly focused on MICP techniques.
- A total of 12 different silica sands have been used to compare total $CaCO_3$ with UCS. A compilation of these data points displays a large scatter in terms of the contribution of $CaCO_3$ on UCS. The scatter is due to whether $CaCO_3$ creates an effective bonding between particles. The particle arrangement and gap between host sand particles were considered as major influencing factors for effective bonding.
- Three parameters, namely Cu, D_{10} and Cc, were considered as characteristic parameters which influence particle arrangement and the gaps between them and therefore the effective bonding of $CaCO_3$. A statistical tool known as the Inverse Distance to a Power (IDP) gridding method was used to describe the relation between UCS with $CaCO_3$ and these three parameters. While contour plots with Cu did not produce an inferable trend, other contour plots with D_{10} and Cc did show general trends. D_{10} is embedded in the Cc calculation which indicates a strong influence of D_{10} on overall behaviour. This is consistent with Rahman's earlier work that D_{10} is a characteristic size for the gap between particles.

  The missing data points in the x-y space influence the contour plot in the IDP gridding method which does not provide absolute certainty of the inferred trend. However it does give an overall understanding of the trend.

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