Bio-Mediated Ground Improvement for Fine-Grained Soil

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Bio-Mediated Ground Improvement for Fine-Grained Soil

A Thesis

Submitted to the Graduate Faculty of the
Louisiana State University and
Agricultural and Mechanical College
in partial fulfillment of the
requirements for the degree of
Master of Science

in

The Department of Civil and Environmental Engineering

by

Guantao Cheng
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ABSTRACT

The research explored the use of microbially induced carbonate precipitation (MICP) to improve the mechanical properties of fine-grained soil and rapidly repair soil cracks on embankment slopes. Slope failures are often induced by surface cracks on the embankment slopes. To date, most rapid repair methods for slope failures (e.g., geosynthetics, soil nails, plastic pins, and lime treatment, etc.) involve large earthwork, special installation equipment, and unique construction processes, which may require extended construction time, disturb traffic, or increase the total construction cost. This research explored the feasibility of using bio-cement (MICP) to improve soil mechanical properties, seal the soil cracks, and assess the improvement of MICP on slope stability. Most previous studies on MICP treatment have focused on sandy soils. However, limited research on MICP-treated fine-grained soils were reported, which was investigated in this study. The conducted research tasks include (1) direct shear tests to investigate the mechanical behavior and biogeochemical reactions of low-plasticity silt treated by MICP, (2) cyclic wetting-drying tests to assess the feasibility of using MICP to seal and waterproof the soil cracks, and (3) SLOPE/W modeling of a slope treated by MICP. Direct shear tests were used to evaluate the shear responses of the low-plasticity silt under different overburden pressures (12, 25, and 35 kPa) and different bio-cement treatments. A series of cyclic wetting-drying tests were used to assess the effectiveness of MICP treatment on healing soil cracks. Crack lengths, area, width, and area percentage were measured and compared before and after the MICP treatment. SLOPE/W analysis was performed to assess the factor of safety of a slope under MICP treatment. The direct shear tests results show that the peak shear strengths increased by an average of 30% from the untreated to the MICP-treated
soil samples. The wetting-drying cycle tests results show that MICP treatment can heal
desiccation cracks, reducing crack length, crack width, and crack area. The results of the
SLOPE/W modeling show that the MICP treatment had a positive effect on the improvement
of slope stability, but more field tests are needed for optimizing the treatment solutions and
procedures and assessing the long-term effect and ecological impacts.
CHAPTER 1. INTRODUCTION

1.1. Overview

Highway embankment slope failures result in road closures, damage public and private properties, and pose serious safety hazards. Many slope failures happened due to desiccation cracks induced by wetting and drying cycles (Yang et al. 2020; Smethurst and Clarke 2010). Wang et al. (2020) explored the influence of cracks on the stability of embankment slopes subjected to rainfall infiltration. Results showed that the pore water pressure distributions in the slope and the factor of safety of the slopes were affected by the presence of soil cracks. When cracks were shallow, the pore water pressure profile and factor of safety of the slopes experienced small changes. When deep cracks existed, however, pore water pressures increased significantly, and the factor of safety of the slopes decreased rapidly. To remediate embankment cracks and restore embankment slopes, several slope repair methods have been used, including geosynthetics, soil nails, retaining structures, plastic pins, surface water management, and lime treatment. Most of these methods involve large earthwork, special installation equipment, and special construction processes, which may extend the construction timeline, cause road closure, and increase project costs.

The research described in this thesis investigated an innovative slope repair method using bio-cement. Bio-cement utilizes a low-viscosity and eco-friendly bio-grout that can be easily percolated into the cracks on the slopes without the need for a pressurized pump. Bio-cement can seal, waterproof, and cement slope cracks in a
relatively short time (e.g., 12 hours) due to its fast reaction rate. Thus, no special installation equipment and no special construction process are required, potentially saving construction time and cost. It is envisioned that *in-situ* slope repair using bio-cement could be simply achieved by percolating bio-grout into the cracks at the slope surface using several buckets of bio-grout solutions.

The bio-cementation process involves the use of microbially induced carbonate precipitation (MICP). The overall MICP reaction can be written as shown in Equation 1 (Whiffén 2004; DeJong et al. 2006; Chu et al. 2012; Whiffén et al. 2007; Won et al. 2020; Wang et al. 2020).

\[
\text{CO(NH}_2\text{)}_2 + 2\text{H}_2\text{O} + \text{CaCl}_2 \rightarrow \text{CaCO}_3 \text{(precipitation)} + 2\text{NH}_4\text{Cl} \quad [1]
\]

MICP treatment promotes calcium carbonate (CaCO$_3$) precipitation in the soil matrix, inducing the cementation bond formation between soil particles (Chou et al. 2011; Chu et al. 2012). In comparison to untreated soil samples, MICP-stabilized sands display greater strength (Dejong et al. 2010; Whiffín et al. 2007; Al Qabany and Soga 2013), higher stiffness (van Paassen et al. 2010; Mortensen et al. 2011), lower porosity (Whiffín et al. 2007), and lower hydraulic conductivity (Chou et al. 2011; Al Qabany and Soga 2013). Most studies on MICP have focused on sandy soils (DeJong et al. 2006; Whiffín et al. 2007; Burbank et al. 2013; Martinez et al. 2013). However, the effects of the MICP treatment on fine-grained soils remain largely unexplored due to the small pore-throat size among fine-grained soil particles (DeJong et al., 2010). Here, an experimental study was conducted to investigate the effect of MICP treatment on the fine-grained soils using direct shear tests. Direct shear tests were used to investigate the
shear responses of the low-plasticity silt under different overburden pressures (12, 25, and 35 kPa) and different types of MICP treatment media. Moreover, a series of cyclic wetting-drying tests were performed to evaluate the healing capability of the MICP treatment for desiccation cracks of the low-plasticity silt. Lastly, the SLOPE/W modeling was used to assess the feasibility of using MICP treatment to enhance the factor of safety of an embankment slope model.

1.2. Problem Statement

Although many researchers have investigated MICP treatment in sand, limited studies focused on the bio-cement improvement for fine-grained soils. Also, bio-cement treatment for healing soil cracks and for enhancing slope stability are novel methods that remain unexplored. These unexplored areas were partially investigated in this thesis.

1.3. Objectives and Scope

1. Direct shear tests to investigate the mechanical behavior and biogeochemical reactions of the low-plasticity silt treated by bio-cement (MICP): Low-plasticity silt samples were treated by different types of MICP solutions and sheared under consolidated drained direct shear test condition, which was compared to the untreated silt samples. All direct shear test samples were 63.5 mm in diameter and 31.8 mm in depth. The soil was air-dried at 100°C for 24 hours, followed by mixing with the calculated amount of
deionized water to achieve the optimum water content of 9.7%. The soils were then sealed and homogenized for 18 hours. Three types of samples using different treatment solutions were investigated, including untreated, UB-treated (urea medium and bacteria), and UBC-treated (urea medium, bacteria, and cementation medium) tests. Various engineering properties, including shear stress versus horizontal displacement, vertical displacement versus horizontal displacement, equivalent calcium carbonate contents, and micro-scale structure characteristics using scanning electron microscope (SEM) and the energy-dispersive X-ray spectroscopy (EDS), were measured. Raman spectroscopy was also used to investigate the chemical changes in the silt samples after MICP treatment.

2. **Cyclic wetting-drying tests to assess the feasibility of using bio-cement to seal and waterproof soil cracks**: To investigate the healing capability of the MICP treatment on the desiccation cracks, a series of cyclic wetting-drying tests were conducted. The silt was air-dried and passed through sieve No. 16 and then mixed with deionized water to achieve the liquid limit (water content = 42%). The prepared silt was poured into 150 mm diameter Petri dishes, compacted, and carefully leveled to a uniform thickness of 5 mm. The high-definition camera was used to capture the morphology of the silt surface. Three identical samples were tested simultaneously to assess the variability of the results.
3. **SLOPE/W modeling of an embankment slope treated by MICP:**

A preliminary study was performed to investigate the effect of MICP treatment on improving the slope stability of an embankment slope model. SLOPE/W modeling was conducted using the geometry of the embankment slope reported by Stark et al. (2017) and soil properties of the silt measured in the direct shear tests. The results of the direct shear tests on MICP-treated samples were used to provide the improved soil parameters for MICP treated embankment slope model.

1.4. **Outline**

This thesis includes six chapters. The first chapter is an introduction. Chapter two presents a literature review on MICP treatment, soil cracks, and embankment slope stability. Chapter three discusses direct shear tests on the low-plasticity silt with MICP treatment. Chapter four presents the lab-scale cyclic wetting-drying testing of silt samples with and without MICP treatment. Chapter five describes a preliminary SLOPE/W analysis to assesses the feasibility of MICP treatment to improve the factor of safety of an embankment slope model. Chapter six presents overall conclusions.
CHAPTER 2. LITERATURE REVIEW

2.1. MICP Treatment

Ground improvement techniques are widely used in the field to fulfill the construction criteria. Compared to traditional techniques such as vibro-compaction and grouting, bio-cementation for ground improvement has been attracting increased research interest in the last decade. Bio-cementation increases soil shear strength by generating particle-binding materials (e.g., CaCO$_3$) through microbial processes (Volodymyr and Chu, 2008). One primary bio-cementation technique is microbially induced carbonate precipitation (MICP), which utilizes urea hydrolysis to increase the pore fluid's alkalinity and induce calcium carbonate precipitation (Fujita et al. 2008). MICP can significantly improve the engineering properties of sands. Harkes et al. (2008) injected $S$. pasteurii into a column of sandy soil and measured the unconfined compression strength (UCS) ranged from 0.2 to 20 MPa with 30 to 600 kg/m$^3$ calcium carbonate precipitation. Van Paassen et al. (2009) performed MICP treatment on sand samples and reported UCS ranging from 1 to 12 MPa with calcium carbonate content ranged from 0 to 24% by weight. DeJong et al. (2006) injected $S$. pasteurii into a sand column for MICP treatment and reported that the shear stress ratio increased from 1.0 to 3.5 compared to untreated sand at 1% axial strain.

Most research so far focuses on sandy soils treated by MICP, whereas few studies have investigated MICP-treated fine-grained soils. This is because the small pore-throat size among fine-grained soil restrains bacterial transport (DeJong et al.,
2010). Furthermore, most MICP studies are limited to laboratory-scale tests. Field-scale applications involve the *in-situ* injection of bacteria and cementation solutions, which could encounter significant heterogeneous treatment and is probably not applicable for fine-grained soil. Sharma and Ramkrishnan (2016) applied MICP treatment to two types of clays (i.e., intermediate compressible clay and highly compressible clay). Their results show that both clays obtained considerable improvement in the UCS with 1.5 to 2.9 times increments. Also, the amount of the strength increment was proportional to the duration of the MICP treatment. Won et al. (2020) investigated the effect of kaolinite on MICP treated sand samples. The results showed that the kaolinite particles worked as nucleation sites and facilitated the heterogeneous nucleation of calcium carbonate. Meanwhile, the well-predicted deposition profile of kaolinite correlated well with the deposited CaCO$_3$ profile.

### 2.2. Soil Cracks and Embankment Slope Stability

Desiccation cracking can degrade the mechanical and hydraulic properties of soil. Traditional remediation methods are associated with high maintenance and operation costs or the usage of non-eco-friendly chemicals. Microbially induced calcite precipitation (MICP) has arisen as a green and sustainable soil improvement technique, which may provide an efficient way of crack remediation. Vail et al. (2019) used a series of cyclic wetting-drying tests and showed that MICP significantly delayed the initiation of desiccation cracks in the high plasticity clay (bentonite). Both surface cracking ratio and average crack width were less than the untreated groups.
Cementation has been used in crack healing. Ayra et al. (2018) conducted experimental tests to evaluate the effectiveness of cement in improving slope stability. By comparing the shear strength between an untreated slope and a slope with cement injection, the internal friction angle of the embankment slope increased from 32° to 47.6°, and the factor of safety of the slope increased from 0.78 (before cementation) to 1.17 (after cementation).

Similarly, enhancing embankment slopes using bio-cementation could be a potential solution. Wang et al. (2020) conducted laboratory experiments and finite element modeling to investigate MICP-treated sand slope failure under rainfall conditions. They concluded that MICP treatment groups significantly improved the erosion resistance and the stability of the embankment slope. Wang et al. (2011) presented how cracks affected the soil slope stability by infiltration of rainwater using SEEP/W and SLOPE/W. They concluded that soil cracks could affect the pore water pressure distributions and the factor of safety of the slope. The safety factor would have a more significant decrease if the cracks happened in the crest of the slope than the cracks happened in the middle of the slope.
CHAPTER 3. DIRECT SHEAR TESTS ON MICP-TREATED SILT

3.1. Introduction

Microbially induced carbonate precipitation (MICP) has been studied as a novel soil improvement technique for almost two decades (Mitchell and Santamarina 2005; DeJong et al. 2006; Whiffin et al. 2007; Van Paassen 2009; DeJong et al. 2014; San Pablo et al. 2020). Previous studies show that MICP can induce calcium carbonate (CaCO$_3$) precipitation in the soil matrix through microbial-catalyzed hydrolysis of urea (ureolysis) (Ferris et al. 1997; Ivanov and Chu 2008; DeJong et al. 2010; Terzis and Laloui 2019b). The bacteria (e.g., Sporosarcina pasteurrii, ATCC 11859) produce urease to hydrolyze urea into ammonium and carbonic acid, which is accompanied by an increase of alkalinity (pH of ~9) and the increasing availability of the carbonate ion (Mortensen et al. 2011; Al Qabany et al. 2012). The addition of calcium chloride and the increasing availability of the carbonate ion shift the equilibrium of calcium carbonate (CaCO$_3$) precipitation/dissolution toward precipitation (Stocks-Fischer et al. 1999; Ebigo et al. 2012). The precipitated CaCO$_3$ can coat soil particles, cement soil particles, and fill soil void space (Martinez and DeJong 2009; Terzis and Laloui 2018; Wang et al. 2019; Lin et al. 2020), increasing the strength, stiffness, and dilatancy and reducing the hydraulic conductivity of the soil matrix (Van Paassen et al. 2009; Cheng et al. 2013; Al Qabany and Soga 2014; Montoya and DeJong 2015; Feng and Montoya 2016; Lin et al. 2016a; Nafisi et al. 2020). Most studies investigated the mechanical properties of sands treated by MICP and their geotechnical applications in sandy soils.
(e.g., liquefaction mitigation, stabilizing coastal sand dunes and fugitive dust, and improving pile capacities by bio-grouting) (Whiffin et al. 2007; DeJong et al. 2010; Cheng and Cord-Ruwisch 2014; Montoya et al. 2014; Lin et al. 2016b; Lin et al. 2018; Terzis and Laloui 2019a; Liu et al. 2021). However, limited studies have been conducted on MICP-treated fine-grained soils (Soon et al. 2014; Li 2015; Sharma and Ramkrishnan 2016; Islam et al. 2020), which will be further investigated in this study.

Since the pore size of fine-grained soils is significantly smaller than that of sandy soils, bacteria transport and colonization in the fine-grained soils encounter difficulties (Mitchell and Santamarina 2005; Al Qabany and Soga 2014). The percolation and injection of MICP treatment solutions used in sandy soils may not apply to fine-grained soils due to their low permeability (Li 2015). Thus, different MICP treatment methods for fine-grained soils were investigated, such as kneading (i.e., thin-layer by thin-layer mixing of soil and MICP solutions) (Li 2015), mixing (i.e., bulk mixing of soil and MICP solutions) (Sharma and Ramkrishnan 2016; Teng et al. 2020), mixing and pressure-injection (i.e., mixing soil with a medium containing the bacteria suspension and then injecting the cementation medium under pressure) (Soon et al. 2014; Arpajirakul et al. 2021), and bioencapsulation (i.e., forming CaCO$_3$ precipitation shells around clay balls, Li 2015). Sharma and Ramkrishnan (2016) applied MICP treatment to two types of clays (i.e., intermediate compressible clay and highly compressible clay). The results showed that both clays obtained noticeable improvement in the unconfined compressive strength with 50% to 190% increments. Li (2015) conducted several feasibility studies on the MICP-treated kaolin, marine clay,
and bentonite samples using unconfined compression, triaxial, oedometer, and direct simple shear tests. The experimental results showed that a higher shear strength was observed for all soil types treated by MICP as compared to untreated soils under the same water content. Soon et al. (2014) explored the feasibility of using MICP for improving the engineering properties of a tropical residual soil (ML). The obtained shear strength increased by 69% and hydraulic conductivity reduced by 90%. Islam et al. (2020) investigated the applicability of biostimulation (i.e., utilizing natural microbes existing in clayey soils to precipitate calcium carbonate) to stabilize clayey soils. The clay samples were first injected with 1 pore volume of the enrichment solution to stimulate the growth of bacteria. Then, 1 pore volume of the cementation solution was injected to precipitate calcium carbonate. The unconfined compressive strength (UCS) increased for all clayey soils after MICP treatment. The increase in strength was attributed to the formation of calcium carbonate within the soil pore. However, the possible biogeochemical reactions in the fine-grained soils during MICP treatment (e.g., the soil minerals may react with MICP solutions due to the increasing pH and the presence of carbonate ions) is not fully investigated (Cardoso et al. 2018), which will be partially investigated in this study.

The experiments described in this paper aimed to investigate the mechanical properties and biogeochemical reactions of low-plasticity silt treated by two types of MICP treatments, (1) urea medium and bacteria without cementation medium (named UB treatment) and (2) urea medium, bacteria, and cementation medium (named UBC treatment), which were compared to those of untreated silt samples. Direct shear tests
were used to investigate the mechanical properties of the silt samples at three confining pressures (12, 25, and 35 kPa). After the direct shear tests, silt samples were saved for CaCO₃ content measurements and were subjected to scanning electron microscopy (SEM) imaging, energy dispersive X-ray spectroscopy (EDS), X-ray Powder Diffraction (XRD), and Raman spectroscopy analysis. The results of shear stress versus horizontal displacement, compression displacement versus horizontal displacement, CaCO₃ contents and distributions, chemical element and mineral compositions, and micro-scale structure characteristics of the silt samples are reported and discussed.

3.2. Materials

3.2.1. Bacteria Cultivation and MICP Treatment

Table 1 presents the solutions used for growing the bacteria cells (e.g., tris buffer and growth medium) and for MICP treatment (i.e., urea medium and cementation medium). The gram-positive bacteria *Sporosarcina pasteurii* strain ATCC 11859 (obtained from American Type Culture Collection, ATCC) was used in this study. The frozen stocks of the bacteria were prepared according to Lin et al. (2016a). To prepare bacteria cells for MICP treatment, bacteria from frozen stocks were cultivated in the growth medium (Table 1) inside a shaking incubator at 30°C for about 24 hours. The bacteria cells were then harvested at OD₆₀₀ = 0.8~1.2 (OD₆₀₀: optical density of a sample measured at a wavelength of 600 nm), centrifuged at 5000 rpm for 20 min (Refrigerated centrifuge for 3 L centrifugation) and 4000 rpm for 30 min (benchtop centrifuge for 200 mL centrifugation) to a targeted bacteria density of 1×10⁸ cells/mL.
The bacteria cells were then stored in the 4°C fridge (two weeks maximum) before use. The MICP treatment media, including urea medium and cementation medium, are also shown in Table 1. Urea medium was used for urea hydrolysis by bacteria cells. The cementation medium was used to induce CaCO₃ precipitation in the soil matrix.

Table 3.1. Summary of Media Employed to Grow Cells and Conduct Microbially Induced Carbonate Precipitation (MICP)

<table>
<thead>
<tr>
<th>Solution</th>
<th>Constituents</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tris Buffer</td>
<td>7.6 g Tris hydrochloric acid</td>
</tr>
<tr>
<td></td>
<td>54.7 g Tris base</td>
</tr>
<tr>
<td></td>
<td>in 500 mL deionized water</td>
</tr>
<tr>
<td></td>
<td>20 g Yeast extract</td>
</tr>
<tr>
<td></td>
<td>10 g Ammonium sulfate</td>
</tr>
<tr>
<td></td>
<td>In 1 L of 0.13 M Tris buffer (pH = 9), sterilized by filter</td>
</tr>
<tr>
<td></td>
<td>20 g/L Urea</td>
</tr>
<tr>
<td></td>
<td>2.12 g/L NaHCO₃</td>
</tr>
<tr>
<td></td>
<td>20 g/L NH₄Cl</td>
</tr>
<tr>
<td></td>
<td>3 g/L Bacto nutrient broth</td>
</tr>
<tr>
<td></td>
<td>Adjust pH to 5.5 with 5 M HCl</td>
</tr>
<tr>
<td></td>
<td>sterilized by filter</td>
</tr>
<tr>
<td>Urea Medium</td>
<td>Same as Urea Medium but additionally supplemented with</td>
</tr>
<tr>
<td></td>
<td>147 g/L CaCl₂·2H₂O</td>
</tr>
<tr>
<td>Cementation</td>
<td>#The growth medium is the ATCC medium 1376 that is recommended for growing the bacteria strain.</td>
</tr>
<tr>
<td>Medium</td>
<td></td>
</tr>
</tbody>
</table>

3.2.2. Soil Type and Properties

The soil was collected near the Accelerated Loading Facility of the Louisiana Department of Transportation and Development (LA DOTD). According to the unified soil classification system (USCS), the soil is classified as low-plasticity silt with some
sand and clay (ML). The grain size distribution is analyzed using sieve analysis and PARIO hydrometer test (Meter Company, Pullman, WA), which is shown in Figure 3.1. The liquid and plastic limits are 33% and 26%, respectively. The optimum moisture content and the maximum dry unit weight are 9.7% and 14.7 kN/m$^3$, respectively. Based on the XRD analysis (discussed later in Results), the silt consists of quartz, albite, muscovite, and glauconite. Albite is a feldspar mineral. Muscovite is a mica mineral. Both albite and muscovite are nonclay minerals. Glauconite is an iron-rich illite mineral, which is the most commonly found clay mineral in soils (Mitchell and Soga 2005).

Figure 3.1. Particle size distribution of the silt.
Figure 3.2. Revised Soil Classification System (RSCS) results: (a) soil-specific triangular chart and (b) fines classification chart.

The soil was also classified using the revised soil classification system (RSCS) (Jang and Santamarina 2016; Park and Santamarina 2017). Compared to the USCS, RSCS can better capture the fines threshold fractions that begin to control the...
mechanical and hydraulic properties of the soil matrix and can reflect the role of pore-fluid chemistry (i.e., different pore-fluids that have contrasting permittivity and electrical conductivity) in the behavior of fines (Park and Santamarina 2017). The input parameters for RSCS include the particle size distribution, uniformity coefficient ($C_u$), coarse grain roundness ($R$), and liquid limits of soil passing sieve No. 200 with different types of pore fluids. The sand grain roundness ($R$) was determined visually using an optical microscope (SWIFT Pro Digital Compound Microscope) by referencing the particle shape charts in Cho et al. (2006). Fall cone tests using three types of pore fluids, including deionized water, kerosene (low permittivity), and 2M NaCl brine (high ionic concentration), were used to determine the liquid limits of soil passing sieve No. 200 following Jang and Santamarina (2016). The liquid limits in deionized water, kerosene, and 2M NaCl brine are 42%, 37%, and 39%, respectively. The accompanying RSCS Excel sheet provided by Park and Santamarina (2017) was used to classify the soil using RSCS. The classification charts are shown in Figures 2a and b. Figure 3.2a shows that the test soil has 79% of fines (passing sieve No. 200) and 21% of sand (between sieve Nos. 4 and 200). The soil is in the F(F) region, indicating that the fines fraction controls the mechanical properties and fluid flow of the soil matrix. Figure 3.2b shows that the soil has a low plasticity and a low electrical sensitivity to pore fluid chemistry ($S_E=0.13$). The electrical sensitivity $S_E$ is defined to capture the changes in liquid limit with pore fluids that have different permittivity and electrical conductivity (e.g., deionized water, kerosene and 2M NaCl brine). More information about the calculation of electrical sensitivity can be found from Jang and Santamarina (2016).
3.3. Experimental Procedures

3.3.1. Test Types

Three types of direct shear tests were performed in this study using three different treatment solutions, including (1) deionized water (named untreated), (2) urea medium suspended with bacteria cells (named UB), and (3) urea medium, bacteria cells, and cementation medium (named UBC) as shown in Table 2. Also, three different confining pressures were used to investigate the effect of confining pressures on soil behavior (Table 2). Three types of treatment solutions used the same volume (total of 30 mL as shown in Table 2) and same density of bacteria cells (i.e., $1 \times 10^8$ cells/mL). Untreated tests were served as control by adding 30 mL of deionized water to investigate the mechanical behavior of the silt without MICP treatment. The UB treatment includes a urea medium (30 mL) mixed with bacteria, which was used to investigate the mechanical behavior of the UB-treated silt samples without adding cementation medium (i.e., without adding calcium chloride). The UBC treatment has been widely used for MICP treatment in the literature, including urea medium (10 mL), bacteria cells, and cementation medium (20 mL). It is important to note that all tests were successfully duplicated to verify repeatability and validate the results.
Table 3.2. Test Types of Direct Shear Tests

<table>
<thead>
<tr>
<th>Test Type</th>
<th>Confining Pressure (kPa)</th>
<th>Urea Medium Volume (mL)</th>
<th>Cementation Medium Volume (mL)</th>
<th>Deionized Water Volume (mL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Untreated</td>
<td>12</td>
<td>0</td>
<td>0</td>
<td>30</td>
</tr>
<tr>
<td>Untreated</td>
<td>25</td>
<td>0</td>
<td>0</td>
<td>30</td>
</tr>
<tr>
<td>Untreated</td>
<td>35</td>
<td>0</td>
<td>0</td>
<td>30</td>
</tr>
<tr>
<td>UB</td>
<td>12</td>
<td>30</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>UB</td>
<td>25</td>
<td>30</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>UB</td>
<td>35</td>
<td>30</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>UBC</td>
<td>12</td>
<td>10</td>
<td>20</td>
<td>0</td>
</tr>
<tr>
<td>UBC</td>
<td>25</td>
<td>10</td>
<td>20</td>
<td>0</td>
</tr>
<tr>
<td>UBC</td>
<td>35</td>
<td>10</td>
<td>20</td>
<td>0</td>
</tr>
</tbody>
</table>

Note: Untreated tests used deionized water only; UB tests used urea medium and bacteria cells; UBC tests used urea medium, bacteria cells, and cementation medium.

3.3.2. Sample Preparation and MICP Treatment Procedures

Since the soil failure surface in the direct shear tests is located at the shear interface between the direct shear split boxes, we designed a MICP treatment procedure to target for treating the soil at the shear interface that controls the mechanical behavior of the direct shear samples. Vacuum grease (Dow Silicones Corporation) was used to seal the small gap between the top and bottom split boxes to prevent leakage of the MICP treatment solutions and to reduce the friction resistance between the two shear boxes. The silt was first dried in an oven at 100°C for 24 hours. After drying, the silt was mixed with deionized water to achieve the optimum water content of 9.7%. The mixture was then sealed and equilibrated for 18 hours. After homogenization, the silt was first compacted to fill the bottom split box (Figure 3.3a), followed by filling 30 mL.
of the MICP solutions (for UB-and UBC-treated samples) or deionized water (for untreated samples) into the split box (Figures 3b and c). Stored bacteria cells were suspended in the targeted volumes (10 or 30 mL) of urea medium (Table 1), stirred, and introduced into the direct shear box (Figure 3.3b). Then, the targeted volume (20 mL) of cementation medium (Table 1) for UBC-treated samples was introduced into the direct shear box (Figure 3.3c). Immediately after the inoculation of the treatment solutions, additional silt was compacted into the top split box to achieve the dry density of 14.7 kN/m$^3$ (Figure 3.3d). The final size of the direct shear test samples was 63.5 mm in diameter and 31.8 mm in depth. Porous stones and filter papers were installed at the top and bottom of the silt samples for water drainage and soil retention.

Figure 3.3. Direct shear sample preparation: (a) compacted silt in the bottom split box, (b) urea medium suspended with bacteria cells or deionized water filled in the split box, (c) cementation medium added into the split box, and (d) compacted silt added into the top split box.
3.3.3. Direct Shear Tests

The Geotac Automated Direct Shear System was used to investigate the mechanical behavior of UB-and UBC-treated and untreated silt samples. The direct shear tests were performed following the ASTM standard D3080 (ASTM 2003). After sample preparation and MICP treatment, the samples were saturated with water. The samples were then subjected to consolidation for 24 hours under three consolidation pressures (12, 25, and 35 kPa, Table 2). After consolidation, direct shear tests were performed using a displacement rate of 0.032 mm/min to achieve a consolidated drained test condition.

3.3.4. Equivalent CaCO₃ Content Measurements

After the direct shear tests, three specimens were collected from each direct shear sample at the depths of 11, 17 (at the shear interface), and 23.5 mm and were then oven-dried for CaCO₃ content measurements (defined as the mass of CaCO₃ divided by the mass of dry soil without CaCO₃). The CaCO₃ contents of the specimens were quantified in accordance with the ASTM standard D4373 (ASTM 2014). Silt specimens (about 25 g) were placed in a sealed test chamber and reacted with hydrochloric acid (1M, 30 mL) to generate carbon dioxide gas. The generated carbon dioxide gas could increase the air pressure in the test chamber, which was monitored by a pressure gauge. The final readings (air pressure in kPa) of the pressure gauge were recorded after 2 hours of the reaction. The relationship between pressure reading and mass of CaCO₃ was calibrated by measuring the corresponding pressure reading under the defined mass.
of CaCO$_3$ (0, 0.2, 0.4, 0.6, 0.8, and 1 g, reagent grade). The calibrated relationship between the pressure readings and CaCO$_3$ masses was used to determine the CaCO$_3$ contents of the silt specimens from the measured pressure readings.

It is important to note that soil minerals may react with MICP media due to increasing pH and the presence of carbonate ions (Ivanov and Chu 2008; Naeimi et al. 2016). Thus, other precipitation compounds (e.g., iron carbonate) could be produced during MICP treatment (discuss later in the Discussion section). This means that the CaCO$_3$ content measurements in this study are, in fact, equivalent CaCO$_3$ contents of the silt samples. The original equivalent CaCO$_3$ content of the untreated silt was first measured (about 2%), which serves as a baseline. The equivalent CaCO$_3$ contents of the UB-and UBC-treated samples were calculated by subtracting the baseline equivalent CaCO$_3$ content (2%) from the measured CaCO$_3$ contents.

### 3.3.5. SEM, EDS, XRD, and Raman Spectroscopy

After direct shear tests, additional specimens were collected from the shear interface of the direct shear samples for SEM imaging, EDS, XRD, and Raman spectroscopy analysis. The Quanta 3D Dual Beam SEM was used for investigating the morphology and structure of the silt specimens. The EDS system was integral to the SEM device and was used to analyze the elemental compositions of the specimens and to conduct calcium cation mapping on the specimens. The mineral compositions of the soil specimens were characterized by a Panalytical Empyrean X-ray diffractometer (XRD). The XRD scans were recorded with a Cu K$_\alpha$ radiation ($\lambda=1.54$ Å, 45 kV, and
inVia Reflex Raman microscope/spectroscope was utilized to identify the chemical signatures of changes in the silt specimens before and after the MICP treatments. The 633 nm laser was chosen as the excitation source for the measurements on the silt samples. The Raman spectrum was carried out using the synchro mode from 200 to 3000 cm\(^{-1}\) with an exposure time for each scan of 10 s. All the spectra were obtained at a 20X magnification. Before the Raman scanning tests, calibrations were done using a 520.5 cm\(^{-1}\) line of a silicon wafer.

### 3.4. RESULTS

#### 3.4.1. Shear Stress versus Horizontal Displacement

The relationships between shear stress and horizontal displacement of the silt samples under 12 kPa confining pressure (Figure 3.4a) show strain-softening behavior due to relatively low confining pressure. However, the shear stresses versus horizontal displacements of the silt samples under 25 and 35 kPa confining pressures reveal strain hardening behavior (Figure 3.5a and 6a). A comparison of untreated, UB-treated, and UBC-treated samples indicates that the peak shear strengths increased by an average of 12% for the UB-treated samples and 30% for the UBC-treated samples compared to the peak shear strengths of the untreated samples. When compared to the ultimate shear stresses of the untreated samples (defined as the shear stress at the horizontal displacement of 15 mm in this study), the ultimate shear stresses increased by an average of 30% for the UB-treated samples and 55% for the UBC-treated samples. The
initial slopes between the shear stress and horizontal displacement were also calculated. As compared to the untreated samples, the initial slopes increased by an average of 24% for UB-treated samples and 80% for UBC-treated samples.

![Figure 3.4](image-url)

Figure 3.4. Direct shear test results of the silt samples at the confining pressure of 12 kPa: (a) shear stress versus horizontal displacement and (b) compression displacement versus horizontal displacement.
Figure 3.5. Direct shear test results of the silt samples at the confining pressure of 25 kPa: (a) shear stress versus horizontal displacement and (b) compression displacement versus horizontal displacement.
Figure 3.6. Direct shear test results of the silt samples at the confining pressure of 35 kPa: (a) shear stress versus horizontal displacement and (b) compression displacement versus horizontal displacement.

These results demonstrate that the peak and ultimate shear strengths were improved by UB and UBC treatments. The improvements of the peak and ultimate shear strengths of the UB-and UBC-treated samples are mainly attributed to the carbonate precipitations (e.g., calcium carbonate and iron carbonate) at the shear interface, cementing the soil particles together. Higher equivalent CaCO$_3$ contents at the shear interface were achieved in the UBC-treated samples (discussed later in the
equivalent CaCO$_3$ content measurement section), leading to the highest shear strengths of the UBC-treated samples. For UB-treated samples, since cementation medium (i.e., calcium chloride) was not used, CaCO$_3$ precipitation should be minimal. It is indicated that other precipitation compounds were generated during the UB treatment, which will be discussed later in the Discussion section. It is also important to note that the direct shear test treated by the urea medium only (i.e., without bacteria cells and cementation medium) was also conducted. While its relationship of the shear stress versus the horizontal displacement was similar to the untreated samples, showing that the urea medium can not improve the mechanical behavior of the silt samples.

### 3.4.2. Volumetric Behavior

Figures 4b, 5b, and 6b present the relationships of the compression displacement versus horizontal displacement for untreated, UB-and UBC-treated silt samples under 12, 25, and 35 kPa confining pressures. Untreated samples showed the highest vertical compression displacements compared to the UB-and UBC-treated samples except for the untreated samples under the confining pressure of 35 kPa. UB and UBC treatments can be seen to reduce the vertical compression displacements of the treated samples. UB-treated samples generally showed less settlements as compared to the UBC-treated samples. The different compression displacements between untreated and UB-and UBC-treated samples are controlled by the equivalent CaCO$_3$ contents and their distributions in the samples (discussed next).
3.4.3. Equivalent CaCO\(_3\) Contents and Distributions

Figures 7a, b, and c present the measured equivalent CaCO\(_3\) contents along with the sample depth for the UB-and UBC-treated samples. It is important to note that the reported equivalent CaCO\(_3\) contents of the UB-and UBC-treated samples as shown in Figure 3.7 were calculated by subtracting the baseline CaCO\(_3\) content of natural silt (2\%) from the measured CaCO\(_3\) contents. The y-axis represents the depth from the sample top (0 mm) to the sample bottom (31.8 mm). Soil specimens were collected at three different depths (11, 17, and 23.5 mm) for equivalent CaCO\(_3\) content measurements in accordance with the ASTM standard D4373 (ASTM 2014). The equivalent CaCO\(_3\) content distributions of the UB-treated samples under 12 and 35 kPa confining pressures show a gradient along the sample height. The highest equivalent CaCO\(_3\) contents are near the bottom (0.7\%) and near the top (0.7\%) for 12 and 35 kPa confining pressures, respectively. However, the equivalent CaCO\(_3\) content is the highest at the shear interface (0.2\%) for the UB-treated sample at 25 kPa confining pressure. For the UBC-treated samples under different confining pressures, the equivalent CaCO\(_3\) contents were the highest at the shear interface (sample depth = 17 mm). The equivalent CaCO\(_3\) contents are 0.9\%, 0.5\%, and 0.8\% at the shear interface at confining pressures of 12, 25, and 35 kPa, respectively. However, the equivalent CaCO\(_3\) contents at the depths of 11 and 23.5 mm of the UBC-treated samples were around 0\%. 
Figure 3.7. Equivalent CaCO$_3$ content distributions along the sample depth at confining pressures of: (a) 12 kPa, (b) 25 kPa, and (c) 35 kPa.
The highest equivalent CaCO$_3$ contents at the shear interface (i.e., depth of 17 mm) of the UBC-treated samples may be attributable to the fast ureolysis and CaCO$_3$ precipitation rates after adding cementation medium (i.e., adding CaCl$_2$ promoted fast precipitation of CaCO$_3$). In contrast, since no cementation medium was added in the UB-treated samples, the precipitation rates of other carbonate compounds (e.g., iron carbonate) were lower than that of the UBC-treated samples. This means that the UB treatment solutions could permeate in the silt samples during sample preparation, which induced higher equivalent CaCO$_3$ contents at the sample top and bottom (i.e., at depths of 11 and 23.5 mm).

The relationships of the shear stress and horizontal displacement (Figures 4a, 5a, and 6a) are controlled by the equivalent CaCO$_3$ contents at the shear interface. It can be seen from Figures 7a, b, and c that the equivalent CaCO$_3$ contents at the shear interface of the UBC-treated samples ranged from 0.5% to 0.9%, which are an average of 70% higher than those of the UB-treated samples (ranged from 0.2% to 0.65%) under the same confining pressure. Therefore, the UBC-treated samples with higher equivalent CaCO$_3$ contents at the shear interface showed higher peak and ultimate shear strengths than those of UB-treated samples. Furthermore, the distributions of the equivalent CaCO$_3$ contents affected the measured compression displacements, as shown in Figures 4b, 5b, and 6b. Since the UB-treated samples showed larger distributions of the equivalent CaCO$_3$ contents as compared to the UBC-treated samples (equivalent CaCO$_3$ contents concentrated at the shear interface only), the compression displacements of the UB-treated samples were lower than the UBC-treated samples.
3.4.4. Failure Envelopes

The Mohr-Coulomb failure envelopes were produced using the direct shear test results. Figure 3.8 shows the peak failure envelopes of the untreated, UB-and UBC-treated samples. The friction angles and cohesions were calculated from the fitted failure envelopes. The peak friction angles of untreated, UB-treated, and UBC-treated samples are 28.8°, 33.9°, and 37.6°, respectively. The cohesions of the untreated, UB-treated, and UBC-treated samples are 5.9, 5.4, and 7.1 kPa, respectively. The increasing friction angles of untreated, UB-treated, and UBC-treated samples may be attributed to the precipitation of CaCO$_3$ and other precipitation minerals at the shear interface (Figure 3.7), which modified the frictional resistances of the soil matrix. The higher cohesion (7.1 kPa) of the UBC-treated samples is due to the higher equivalent CaCO$_3$ contents achieved at the shear interface than the UB-treated samples (Figure 3.7).

![Figure 3.8. Peak failure envelopes of untreated, UB-treated, and UBC-treated samples.](image-url)
3.4.5. SEM Imaging and EDS Analysis

The SEM imaging and EDS analysis on silt samples are shown in Figure 3.9. The comparisons of the SEM images (Figures 9a, b, and c) between different samples show that the untreated sample has better-defined particles, while the particles in the UB- and UBC-treated samples are not well defined, which is possibly attributed to the CaCO$_3$ and other minerals precipitation. It was reported that CaCO$_3$ precipitation could form cementation bonds and coating on soil particles during MICP treatment (Martinez and DeJong 2009; Li 2015; Naeimi et al. 2016; Terzis and Laloui 2018; Wang et al. 2019; Lin et al. 2020). The elemental compositions of the untreated and UB-treated samples show the existence of calcium cation (0.8 and 1.8 %, respectively), indicating the existence of CaCO$_3$ in the natural silt. However, the calcium content of the UBC-treated sample is 4.7%, which is significantly higher than those of untreated and UB-treated samples. The calcium mapping (light green color shown in Figure 3.9d) from the EDS analysis demonstrates a large distribution of calcium element in the UBC-treated samples. This means that a large amount of CaCO$_3$ precipitation happened in the UBC-treated samples. In addition, EDS analyses show iron cation (5.1% to 9.9%) existing in the silt, which may lead to the precipitation of iron carbonate and iron hydroxide during MICP treatment (will be further discussed in the Discussion section).
Figure 3.9. SEM imaging and EDS results of (a) untreated, (b) UB-treated, and (c) UBC-treated samples; and (d) calcium element mapping of the UBC-treated sample.

3.4.6. XRD and Raman Spectra

The XRD spectra in Figure 3.10 present the mineral compositions of the silt samples without treatment and with UBC treatment. The XRD pattern of the untreated silt sample shown in Figure 3.10a indicates a high mass percentage of quartz and relatively small amounts of albite, muscovite, and glauconite. The XRD pattern of the UBC-treated sample demonstrates a similar pattern as the untreated silt sample, including quartz, albite, muscovite, and glauconite. It can be seen that XRD can not detect the mineral changes after the UBC treatment since the XRD has a detection limit of about 2% to 3% mass percentage of a mineral (Moore and Reynolds Jr 1989; Newman et al. 2015). Since the amount of equivalent CaCO$_3$ precipitation is below 1%
in this study, the XRD analysis could not detect the mineral changes in the silt samples after MICP treatment.

Figure 3.10. X-Ray Diffraction (XRD) patterns of (a) untreated and (b) UBC-treated samples.
Figure 3.11. Raman spectra of (a) untreated, (b) UB-treated, and (c) UBC-treated samples.
Figure 3.11 shows the Raman spectra of the untreated, UB-treated, and UBC-treated samples. The Raman spectrum of the untreated sample (Figure 3.11a) shows a high-intensity peak at 460 cm$^{-1}$, indicating quartz in the silt (Goienaga et al. 2011), which is also confirmed by the XRD spectra shown in Figures 10a and b. The peaks in the range of 90 to 430 cm$^{-1}$ of the Raman spectrum of the untreated sample correspond to many other minerals (containing magnesium and iron) in the soil. However, it is impossible to define their corresponding minerals due to the complexity of the measured peaks and soil minerals. As compared to the Raman spectrum of the untreated sample, the Raman spectra of the UB-treated and UBC-treated samples show several additional peaks. The peaks located at 296 cm$^{-1}$ indicate carbonate, which matches the typical Raman spectra of carbonate (Steele et al. 2007; Zhao et al. 2020). A broad peak covering from 580 to 850 cm$^{-1}$ corresponds to the minerals of iron hydroxide, iron carbonate, and calcium carbonate in the literature studies (De Faria et al. 1997; Hanesch 2009; De La Pierre et al. 2014; Spivak et al. 2014; Dufresne et al. 2018). These results confirm the precipitation of calcium carbonate, iron hydroxide, and iron carbonate in the silt samples during MICP treatment. In addition, the peak observed at the 1340 cm$^{-1}$ is related to the bacteria cells added in the silt in accordance with previous literature studies (Parikh et al. 2014). The results of the Raman spectra demonstrate that there were iron hydroxide, iron carbonate, and calcium carbonate precipitations in the silt samples during the UB and UBC treatments. The calcium carbonate precipitation may be limited in the UB-treated samples as no cementation medium (i.e., calcium chloride) was added.
3.5. DISCUSSIONS

Most research on MICP used calcium cation (e.g., calcium chloride) to induce CaCO$_3$ precipitation for cementing soil matrix (Rebata-Landa 2007; Mortensen et al. 2011; DeJong et al. 2014). However, other types of cementation compounds could also be produced from the MICP treatment, such as ferrous carbonate (FeCO$_3$), ferric hydroxide (Fe(OH)$_3$), and ferric carbonate (Fe$_2$(CO$_3$)$_3$) (Ivanov and Chu 2008; Naeimi 2014). Naeimi et al. (2016) used the ferrous cations (provided by ferrous sulfate) to replace calcium cation in the MICP treatment to precipitate ferrous carbonate (FeCO$_3$) in a poorly graded medium-grained clean sand. The results showed that the unconfined compressive strength increased up to 402 kPa at the ferrous carbonate content of 6%. The precipitated ferrous carbonates were found cementing sand grains in the SEM imaging. Ivanov et al. (2014) used the iron-based biogROUT that consists of urease-producing bacteria, ferric cations (provided by ferric chelate), and urea to precipitate ferric hydroxide (Fe(OH)$_3$) for improving the strength and reducing the permeability of a rounded-grain silica sand. The unconfined compressive strength increased with the increasing ferric hydroxide content and reached 240 kPa at the ferric hydroxide content of 3%.

Since iron exists in the test silt as evidenced by the EDS analysis (ranged from 5.1 to 9.9% shown in Figure 3.9), it is possible that several iron precipitations (e.g., iron carbonate and iron hydroxide) were formed in the silt samples during the UB and UBC treatments. This possibility was also confirmed by the Raman spectra (Figure 3.11), which shows a new peak (from 580 to 850 cm$^{-1}$) that indicates the presence of iron
hydroxide, iron carbonate, and calcium carbonate generated in the UB-and UBC-treated samples. Because of the generation of the iron precipitation compounds, the UB-treated samples had higher shear strength than those of the untreated silt samples in the direct shear tests. When adding cementation medium in the UBC-treated samples, the precipitations of CaCO3 and iron compounds lead to higher shear strengths than those of UB-treated samples. Thus, the CaCO3 content measurements in Figure 3.7 are measurements of the equivalent CaCO3 contents as the iron carbonate was precipitated in the silt samples. In addition, the increasing shear strengths of the UB-and UBC-treated samples may also be attributed to the increasing pH, which may result in osmotic effects in the clay portion of the silt samples (Calvello et al. 2005; Spagnoli et al. 2012).

3.6. SUMMARY AND CONCLUSIONS

This paper investigates the mechanical behavior of a fine-grained soil (low-plasticity silt) treated by two types of MICP treatments, (1) urea medium suspended with bacteria cells (named UB treatment) and (2) urea medium, bacteria cells, and cementation medium (named UBC treatment), and discusses their possible biogeochemical reactions. The silt samples were treated by UB and UBC treatments and were subjected to the direct shear tests at different confining pressures (12, 25, and 35 kPa). The equivalent CaCO3 contents and their distributions in the samples were measured. To investigate the micro-scale soil structure, elemental and mineral compositions, scanning electron microscopy (SEM) imaging, energy dispersive X-ray spectroscopy (EDS), X-ray Powder Diffraction (XRD), and Raman spectroscopy
analysis were performed. The test results, including shear stresses versus horizontal displacements, compression displacements versus horizontal displacements, CaCO$_3$ contents and distributions, chemical element and mineral compositions, and micro-scale structure characteristics of the samples, were reported. Based on the results presented in this paper, the following conclusions are drawn.

1. The peak and ultimate shear strengths of the silt samples were improved by the UB and UBC treatments. The peak shear strengths increased by an average of 12% for the UB-treated samples and 30% for the UBC-treated samples than the untreated samples.

2. UB-and UBC-treated samples showed lower vertical compression displacements than the untreated samples. UB-treated samples generally showed less settlements as compared to the UBC-treated samples. The different compression displacements between different treatments are controlled by the distributions of equivalent CaCO$_3$ contents in the samples.

3. The peak friction angles for the untreated, UB-treated, and UBC-treated samples are 28.8$^\circ$, 33.9$^\circ$, and 37.6$^\circ$, respectively. The cohesions of the untreated, UB-treated, and UBC-treated samples are 5.9, 5.4, and 7.1 kPa, respectively.

4. The improvements of the mechanical properties of the UB-and UBC-treated samples are mainly attributed to the precipitations of calcium carbonate, iron carbonate, and iron hydroxide at the shear interface. Higher equivalent CaCO$_3$ contents at the shear interface were measured in the UBC-treated samples, leading to higher shear strengths than the UB-treated samples.
5. Since iron exists in the silt as evidenced by the EDS analysis, several iron precipitations (e.g., iron carbonate and iron hydroxide) were formed in the silt samples during the UB and UBC treatments. The precipitations of iron carbonate and iron hydroxide were also confirmed by the Raman spectra of the UB-and UBC-treated samples.
CHAPTER 4. WETTING & DRYING CYCLE TESTS

4.1. Introduction

Desiccation cracking is common in soil, which degrades the mechanical and hydraulic properties of soil. Desiccation cracking is initiated by moisture evaporation or volumetric shrinkage. The cracks undermine the soil structure and weaken the soil strength (Tang et al., 2010; Hallett et al., 2013). The degradation of soil properties induced by the presence of desiccation cracks due to wetting and drying cycles is responsible for various geohazards, such as slope failures (Alonso et al., 1995), road embankment failures (Groenevelt and Grant, 2004), as well as foundation and dam failures (Osinubi and Nwaiwu, 2008).

Numerous lab and in-situ tests have investigated the potential formation of desiccation cracking in recent decades. It is known that the surface layer of soil starts drying first during evaporation, followed by further drying in deep soil layers. The capillary suction in the deeper layer causes the meniscus surface tension effect. In the drying process, the soil's progressive volumetric shrinkage is induced by capillary suction through moisture loss (Morris et al., 1992; Tang et al., 2010). However, natural soils usually have concentrated local tensile stress and anisotropic volumetric shrinkage due to intrinsic heterogeneity. Desiccation cracking occurs after tensile stress exceeds the soil strength.

Microbially induced calcite precipitation (MICP) has been considered as an environmentally friendly soil improvement technique, which may reduce desiccation
cracking. In this chapter, a series of cyclic wetting-drying tests were performed to evaluate the effect of MICP treatment on the desiccation cracking behavior of low-plasticity silt. Three similar low-plasticity silt samples were treated by MICP media. The urea medium suspended with bacteria cells were dribbled in the cracks using 5mL syringes, followed by the cementation medium. Morphologies of soil desiccation cracks were captured by a high-resolution optical camera, then transformed into 8-bit binary figures through MATLAB. The images of the cracks were cropped and adjusted to same greyscale through Adobe Photoshop. The image scale and the detailed length of each crack were defined by ImageJ. Freehand lines in ImageJ were used to measure the crack length and area, under 800x magnification. Other parameters featuring the crack patterns, including the averaged crack width and crack area percentage, are reported.

4.2. Materials and Methods

4.2.1. Soils and MICP recipe

The silt used in the direct shear tests (Chapter 3) was used in this study. The MICP treatment solutions were the same as those used in the direct shear tests.

4.2.2 Sample preparation

The silt was air-dried for 24 hours and passed through sieve No. 16 (opening size=1.18 mm). The passing silt was then mixed with deionized water to achieve a water content at liquid limit (around 42% water content). After homogenization, the silt was poured into the 150-mm diameter Petri dishes, lightly compacted, and carefully leveled
to a uniform thickness of 5 mm as shown in Figure 4.1. Three similar samples were tested simultaneously to check the variability of the results.

![Samples prepared in the Petri dishes](image)

Figure 4.1. Setup of the cyclic wetting and drying tests.

**4.2.3. Testing procedure**

Three similar samples were prepared and tested using the same procedure. Three silt samples were subjected to two initial wetting-drying cycles (denoted as Treatments 0 and 1) and two subsequent wetting-drying cycles (denoted as Treatments 2 and 3). Each cycle lasted about 96 hours and contained two stages, including the drying stage followed by the wetting stage. In the drying stage, samples were exposed to thermal heating using two light bulbs for 48 hours. The soil surface temperature was measured by a thermal gun (ETEKCITY lasergrip 774). The soil surface temperature was constant at 60±1°C. In the wetting stage, the light bulbs were turned off and the temperature was cooled down to 20 ± 1°C (lab temperature, checked by the thermal gun). Deionized water was dribbled to the surface of the silt samples using the 5mL
syringe until the total sample weight returned to the original sample weight (i.e., the weight before the first wetting-and-drying treatment) followed by a retention time of 48 hours. To apply MICP treatment, MICP treatment media were applied on the samples instead of deionized water for the wetting stage of Treatment 2. The bacteria cells and urea medium (9 mL) were dribbled into the cracks of samples using 5mL syringes, followed by cementation medium (9 mL). After each treatment cycle, the crack patterns of each sample were captured by a high-resolution camera mounted above the Petri dishes for image-based quantitative analysis.

To quantitatively compare the effects of the MICP treatment on the desiccation cracks of silt samples at different wetting-drying cycles, MATLAB and ImageJ software were used in this study. Figure 4.2 shows the processing procedure of a silt sample. Photos captured in different treatment cycles were first transformed into 8-bit binary figures in MATLAB with the same grayscale (Figure 4.2a). The binary figure was trimmed to remove the boundary of the Petri dish (Figure 4.2b) and then imported into ImageJ. In ImageJ, the figure was defined with the correct scale (Figure 4.2c). According to the definition of the crack length defined by Liu et al (2013), the crack length in this study is defined as the distance between two adjacent intersection nodes, as shown in Figure 4.2d. Also, the crack length of those cracks without intersections was defined as the distance between two “Node_0”. The size of the “Node_0” should have three pixels that have the same color and grayscale (adjusted through palette in Adobe Photoshop). Freehand lines were drawn in the binary figures to represent the crack lengths under 800x magnification (Figure 4.2e). In order to calculate the total
crack area of a sample, several freehand curves were drawn to cover a single crack area, under 800x magnification (Figure 4.2f). Following the similar procedures as shown in Figure 4.2f, other crack areas were found. The summation of all single crack areas was equal to the total crack area of the sample. The labelled crack areas are displayed in Figure 4.2g. In Figure 4.2g, the inverted colors between the cracks and soil sample were for illustration with a better contrast. The summation of the white area (intact soil surface) and the crack area (black area) was equal to the area of the Petri dish. The averaged crack width was then calculated by dividing the total crack area by the total crack length. The crack area percentage was calculated by dividing the crack area (black area as shown in Figure 4.2g) by the total area of the Petri dish (white and black areas together in Figure 4.2g).

Thus, the following parameters of the crack patterns were determined: (1) statistical data of crack length (determined by ImageJ), (2) total crack area (determined by ImageJ), (3) averaged crack width (total crack area divided by the total crack length); (4) crack area percentage (total crack area divided by the total sample surface area). The measurements of the cracking depths were not performed because the camera can only capture the two-dimensional information of the surface cracks.
Figure 4.2. Image processing: (a) binary photo processed by MATLAB, (b) boundary of the Petri dish was removed, (c) define the scale of the photo, (d) define a crack length, (e) draw a curve to represent the crack length, (f) define a crack area, and (g) mark all crack areas and calculate the total crack area.

(figure continued)
(figure continued)
(figure continued)
4.3. Results and Discussions

Figure 4.3 shows the binary photos of cracks of each sample. Figures 4.3a to c show the cracks generated in each sample during Treatment 0. Figures 4.3d to 4.3f show the cracks of each sample during Treatment 1. Figures 4.3g to 4.3i show the cracks of each sample during Treatment 2 (performed MICP treatment). Figures 4.3j to 4.3l show the cracks of each sample during Treatment 3. Figures 4.3a to 4.3f shows that Treatment 1 wetting-drying cycle induced new branches of cracks along the existing cracks as compared to Treatment 0. Comparing the treated (Figures 4.3g to i) with untreated samples (Figures 4.3d to f), it can be observed that the crack width of certain cracks and crack areas decreased. From Treatment 2 to Treatment 3, the number of cracks and crack areas of Figures 4.3j to l (Treatment 3) increased compared to Figures 4.2g to i (Treatment 2). This demonstrates that the number of cracks and areas after MICP treatment can still increase to some extent if wetting-drying cycles continued, which needs further investigation in future studies.
Figure 4.3. Photos of the soil cracks: (a) Sample 1 at Treatment 0, (b) Sample 2 at Treatment 0, (c) Sample 3 at Treatment 0, (d) Sample 1 at Treatment 1, (e) Sample 2 at Treatment 1, (f) Sample 3 at Treatment 1, (g) Sample 1 at Treatment 2, (h) Sample 2 at Treatment 2, (i) Sample 3 at Treatment 2, (j) Sample 1 at Treatment 3, (k) Sample 2 at Treatment 3, (l) Sample 3 at Treatment 3.
Figure 4.4. Statistical results of the crack length of Sample 1 at each treatment cycle.

Figure 4.5. Statistical results of the crack length of Sample 2 at each treatment cycle.
The distributions of the measured crack lengths at different treatment cycles were summarized in Figures 4.4 to 4.6. The y-axis (frequency) corresponds to the number of cracks generated in the designated crack length range (defined on the x-axis). The crack length and frequency in each sample were slightly increased from Treatment 0 to Treatment 1, respectively (Figures a to b in Figures 4.4, 4.5, and 4.6). Comparing the distribution of crack lengths between Treatment 1 (before MICP treatment, Figures 4.4b, 4.5b, and 4.6b) and Treatment 2 (after MICP treatment, Figures 4.4c, 4.5c, and 4.6c), the frequencies of the cracks in most crack length ranges were significantly reduced. These reductions are mainly attributed to the CaCO$_3$ precipitation during MICP treatment that healed the desiccation cracks.
Figure 4.7. (a) Box plots of crack length versus treatment, (b) box plot legend.
Figure 4.8. (a) average crack area versus treatment, (b) average crack width versus treatment, and (c) average crack percentage versus treatment.
Figure 4.7 summarized the statistical data of crack lengths of three samples during different treatment cycles. In Figure 4.7a, it seems that the mean values of the crack length did not show a significant decrease after MICP treatment (comparison between Treatment cycle 1 and Treatment cycle 2). However, as shown in Treatment cycles 2 and 3, the number of outliers were significantly reduced compared to Treatment cycles 0 and 1, demonstrating that MICP treatment can reduce the crack length, especially those long cracks. Figure 4.7b shows the box plot legend of Figure 4.7a. As shown in Figures 4.8a, b, and c, there are decreasing trends of total crack area, averaged crack width, and crack area percentage from Treatment 0 to Treatment 2. It is unclear why the total crack area, averaged crack width, and crack area percentage decreased from Treatment 0 to Treatment 1. This may be due to the erosion induced by deionized water application during wetting stage, which eroded the surface soil to fill the cracks. For the trends from Treatments 1 to 2 (from untreated cycle to MICP-treated cycle) in Figures 4.8a, b, and c, the decreases of the total crack area, averaged crack width, and crack area percentage are due to carbonate precipitation (evidenced by the white CaCO$_3$ shown in the cracks). After the MICP treatment, there was an increasing trend from Treatment 2 to Treatment 3. This trend also confirms the previous observations of the crack length (increasing for Treatment 2 to Treatment 3) in Figures 4.4 through 4.6. It can be concluded that the MICP treatment can heal the desiccation cracks of low-plasticity silt in a relatively short period. It is also important to note that the cracks could regenerate after MICP treatment, as evidenced by the increasing crack parameters from Treatment 2 to Treatment 3 (Figures 4.8a to c). Future studies will
focus on optimizing MICP treatment solutions and schedule to reduce the formation of cracks after MICP treatment.

4.4. Conclusions

The results of the cyclic wetting-drying tests proved that the MICP treatment has potential to heal desiccation cracks. MICP treatment can reduce the crack length. Meanwhile, total crack area, averaged crack width, and crack area percentage decreased by 32%, 15%, and 36%, respectively. Since the cracks created in the Petri dishes were quite different from the actual environment, further studies are required and will focus on optimizing the MICP injection method and conducting large scale in-situ tests to investigate the treatment methods, quality assessment, long-term effects, and ecological impacts.
CHAPTER 5. PRELIMINARY SLOPE STABILITY MODELING

5.1. Introduction

A preliminary study was performed to investigate the effect of MICP treatment on improving the slope stability of an embankment slope model. SLOPE/W analysis was conducted using the geometry of the embankment slope reported by Stark et al. (2017). However, the soil stratigraphy and properties reported by Stark et al. (2017) were not used in the study. Instead, it was assumed that the slope model is made of the low-plasticity silt used in Chapters 3 and 4. The mechanical properties of the silt obtained from the direct shear tests were used to provide the input parameters of soil cohesions and friction angles for untreated and MICP-treated embankment slope models. The results of the SLOPE/W analysis were used to assess the effectiveness of MICP treatment on the improvement of safety factor of the embankment slope.

To define the silt properties after MICP treatment in SLOPE/W models, the cohesions and friction angles of the silt samples after MICP treatment from direct shear test results were used.
Table 5.1 SLOPE/W Input Parameters

<table>
<thead>
<tr>
<th>Treatment Types</th>
<th>Unit Weight (kN/m$^3$)</th>
<th>Cohesion (kPa)</th>
<th>Friction Angle (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Untreated</td>
<td>14.7</td>
<td>5.9</td>
<td>28.8</td>
</tr>
<tr>
<td>UB-treated</td>
<td>14.7</td>
<td>5.4</td>
<td>33.9</td>
</tr>
<tr>
<td>UBC-treated</td>
<td>14.7</td>
<td>7.1</td>
<td>37.6</td>
</tr>
</tbody>
</table>

Figure 5.1. Geometry of the embankment slope in SLOPE/W.

5.2. Parameters and Methods

Three SLOPE/W models were prepared under different treatment conditions. The untreated slope served as the control. Two types of MICP treatments were used to treat the slope models and investigate their stabilities, including UB-treated and UBC-treated models. The soil properties measured from Chapter 3 were used for each of the three models as shown in Table 5.1. In the untreated slope model, the cohesion and friction angle of the silt are equal to 5.9 kPa and 28.8°. The cohesion and friction angle of the silt in the UB-treated slope are 5.4 kPa and 33.9°. The cohesion and friction angle of the silt in the UBC-treated slope are 7.1 kPa and 37.6°. Figure 5.1 shows the slope
geometry defined in the SLOPE/W. Soil properties in the SLOPE/W model have the same soil properties as the low-plasticity silt in Table 5.1. The slope stability analysis was performed using the Morgenstern and Price (1965) method under drained condition. The blue dashed line is the defined groundwater table. The red solid lines represent the slip surfaces (Point 8 to 9 is the entrance slip surface and Point 5 to 6 is the exit slip surface).

5.3. Results and Discussions

The results of the SLOPE/W analysis are shown in Figure 5.2. When comparing the failure surfaces among Figures 5.2a, b, and c, the affected soil areas (green areas in Figure 5.2) are almost identical. The factor of safety of the original untreated embankment slope is 1.708 as shown in Figure 5.2a. Figures 5.2b and c show the results of the UB-treated and UBC-treated slopes, respectively. The factor of safety of the UB-treated slope is 1.893, which is 12% higher than the untreated slope as shown in Table 5.2. When compared to the UB-treated slope, the factor of safety of the UBC-treated slope is 2.267 (21% higher). Also, the factor of safety of the UBC-treated slope is 33% higher than untreated slope.
Figure 5.2. SLOPE/W analysis results: (a) untreated slope, (b) UB-treated slope, and (c) UBC-treated slope.
Table 5.2 SLOPE/W Results

<table>
<thead>
<tr>
<th>Treatment Types</th>
<th>Factor of Safety</th>
<th>Increment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Untreated</td>
<td>1.7</td>
<td></td>
</tr>
<tr>
<td>UB-treated</td>
<td>1.9</td>
<td>+12%</td>
</tr>
<tr>
<td>UBC-treated</td>
<td>2.3</td>
<td>+21%</td>
</tr>
</tbody>
</table>

5.4. Conclusions

The results reveal that the MICP treatment methods can enhance the slope stability by increasing the factor of safety up to 33%. It is important to note that the slope stability analysis is a preliminary study. The results of the analysis indicate that MICP treatment has potential to improve the slope stability of the embankment slopes. However, additional experimental studies in the laboratory and in the field are needed to investigate the treatment methods, quality assessment, long-term effects, and ecological impacts.
CHAPTER 6. CONCLUSIONS

Through a combination of experimental studies and SLOPE/W analysis, the research described in this thesis evaluated the potential effectiveness of MICP treatment for improving the mechanical properties of low-plasticity silt, healing desiccation cracks, and enhancing the stability of embankment slopes. Geotechnical laboratory tests included direct shear tests and cyclic wetting-drying tests. A preliminary slope stability analysis was conducted using SLOPE/W. Scanning electron microscopy (SEM) imaging, energy-dispersive X-ray spectroscopy (EDS), X-ray Powder Diffraction (XRD), and Raman spectroscopy analysis were used to investigate the soil morphology and the elemental compositions of the soil. Based on the results presented in this thesis, the following conclusions are drawn.

The peak and ultimate shear strengths of the silt samples were improved by the UB and UBC treatments. The peak shear strengths increased by an average of 12% for the UB-treated samples and 30% for the UBC-treated samples compared to the peak shear strengths of the untreated samples.

UB-and UBC-treated samples showed lower vertical compression displacements than the untreated samples. UB-treated samples generally showed less settlements as compared to the UBC-treated samples. The different compression displacements between different treatments are controlled by the distribution of equivalent CaCO$_3$ contents in the samples.

The peak friction angles of the untreated, UB-treated, and UBC-treated samples are 28.8°, 33.9°, and 37.6°, respectively. The cohesions of the untreated, UB-treated,
and UBC-treated samples are 5.9, 5.4, and 7.1 kPa, respectively.

The improvements of the mechanical properties of the UB-and UBC-treated samples can likely be attributed to the precipitations of calcium carbonate, iron carbonate, and iron hydroxide at the shear interface. Higher equivalent CaCO$_3$ contents at the shear interface were measured in the UBC-treated samples, leading to higher peak shear strengths of the UBC-treated samples.

Since iron exists in the silt as evidenced by the EDS analysis, it is possible that several iron precipitations (e.g., iron carbonate and iron hydroxide) were formed in the silt samples during the UB and UBC treatments. The precipitations of iron carbonate and iron hydroxide were also confirmed by the Raman spectra of the UB-and UBC-treated samples.

The MICP treatment has potential to heal desiccation cracks as evidenced by the cyclic wetting-drying tests. In the preliminary tests reported here, MICP treatment can reduce the crack length, especially those long cracks. Also, total crack area, averaged crack width, and crack area percentage decreased by 32%, 15%, and 36%, respectively.

The results of the SLOPE/W analysis show that MICP treatment could potentially enhance slope stability by increasing the factor of safety from 1.7 to 2.3 for the test case considered. The MICP treatment had a positive effect on the improvement of slope stability; however, further investigation is needed. A future large-scale experimental or field-scale study is recommended to optimize the treatment solutions and procedures, assess the improvement quality, and investigate long-term effect of
Collectively, the research reported in this thesis suggests that MICP treatment can improve the engineering properties of low-plasticity silt, heal desiccation cracks, and enhance slope factor. It is recommended that future studies should focus on the optimization of MICP treatment for \textit{in-situ} slope stabilization and ground improvement.
REFERENCES


ASTM (2007). "Standard test methods for laboratory compaction characteristics of soil using standard effort (12,400 ft-lbf/ft3 (600 KN-m/m3))." *ASTM D698*, West Conshohocken, PA.


Li, B. (2015). "Geotechnical properties of biocement treated sand and clay." *School of Civil and Environmental Engineering, Nanyang Technological University*.


Photoshop [Computer software]. Adobe System, San Jose, United States of America.


SLOPE/W [Computer software]. Geo-Slope International, Calgary, Canada.


Guantao Cheng was born in China in February 1996. He finished his bachelor's degree in Civil Engineering – Valparaiso University – Valparaiso – United States (2016-2018). In August 2018, he joined Louisiana State University to pursue master's degree and planned to finish in August 2021. Since then, he has worked as a graduate research assistant at the Department of Civil and Environmental Engineering. He worked on utilizing microorganisms to improve the engineering properties of soil during this time.