



**RESEARCH & DEVELOPMENT**

# **Reducing Erosion Susceptibility of Coastal Highways using Biologically-Based Methods**

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16. Abstract Roadbeds supporting coastal highways in North Carolina (e.g., Highway 12) are susceptible to erosion during large storm events. Reinforcing vulnerable coastal subgrades and slopes can reduced the erosion potential and the coastal infrastructure can be maintained. Bio-mediated soil improvement methods can be used to stiffen sandy subgrade and slopes and reduce the soil's susceptibility to erosion. Microbial induced carbonate precipitation (MICP) treatment methods utilize natural soil bacteria to hydrolyze urea as a nutrient source and produce calcite cementation within the soil matrix. This bio-cementation process can be used to mitigate damage to highway subgrades and slopes by implementing the process in situ. The overarching goal of this project is to implement a bio-mediated soil improvement method in situ and monitor its performance when exposed to natural conditions (e.g., weather fluctuations, precipitation, surface water, etc.). In order to implement field trials, a laboratory program was performed to develop the appropriate treatment method (e.g., level of cementation) to reduce erosion and increase shear strength. Furthermore, the ability of vegetation to take root post-treatment was evaluated. MICP was successfully implemented in an Ahoskie, NC field site as a soil improvement method for shallow depths. Multiple treatment application techniques were assessed, and the surface spraying technique demonstrated the highest level of cementation near surface, and more uniformly covered a larger area of the slope. Dynamic cone penetration (DCP) tests were performed to have an assessment of soil improvement along the soil profile. All test plots exhibited a significant penetration resistance improvement either in depth or surface. Impinging jet tests, pocket penetrometer, and initial penetration depth measurements were completed to evaluate the surficial soil improvements and erodibility resistance. Surficial strength and erodibility parameters significantly improved with increase in mass of calcium carbonate. A higher erosion resistance compared to the values reported in literature for saturated soil treatment is the results of the unsaturated MICP-treatment and a more efficient cementation bond. Strength values measured with pocket penetrometer were also shown to be consistent with laboratory unconfined compression tests with varying cementation levels. The permanence of the stabilized soil was confirmed by monitoring the treated soil with time and after extreme environmental conditions. MICP treatment experiments with vegetation indicate that up to a certain level of cementation, both MICP soil improvement and plant growth can coexist.			
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## Executive Summary

Roadbeds supporting coastal highways in North Carolina (e.g., Highway 12) are susceptible to erosion during large storm events. During large storms, such as hurricanes and nor'easters, storm surge and waves are able to erode the soil and undermine the highway. Coastal highways in North Carolina have experienced over-washing due to coastal storm surges, which led to pavement damage and highway closure. By reinforcing vulnerable coastal subgrades and slopes, erosion potential can be reduced and the coastal infrastructure can be maintained.

Bio-mediated soil improvement methods can be used to stiffen sandy subgrade and slopes and reduce the soil's susceptibility to erosion. Natural biological processes have been shown to improve the behavior of sand deposits by increasing the sand's strength, stiffness, and erosion resistance. Microbial induced carbonate precipitation (MICP) treatment methods utilize natural soil bacteria to hydrolyze urea as a nutrient source and produce calcite cementation within the soil matrix. This bio-cementation process can be used to mitigate damage to highway subgrades and slopes by implementing the process in situ. Reinforced sand deposits via bio-cementation would improve the resiliency of the coastal infrastructure by reducing the susceptibility to erosion in an innocuous, natural, and cost-effective manner.

The overarching goal of this project is to implement a bio-mediated soil improvement method in situ and monitor its performance when exposed to natural conditions (e.g., weather fluctuations, precipitation, surface water, etc.). In order to implement field trials, a laboratory program was performed to develop the appropriate treatment method (e.g., level of cementation) to reduce erosion and increase shear strength. Furthermore, the ability of vegetation to take root post-treatment was evaluated.

An experimental program was performed to investigate the effect of MICP treatment solutions with varying ratios of urea to calcium chloride on unconfined compressive strength (UCS) and erodibility parameters of two types of soil. All specimens were treated up to the target shear wave velocity of about 1100-1300 m/sec. Different numbers of treatments were required to reach the target shear wave velocity using varying treatment concentrations, and the results of the UCS indicated that different types of soil treated with the same treatment solution can show different stress-strain behavior depending on the grain size distribution of the particles. In addition, higher calcium carbonate can lead to higher shear strength of the specimen. All specimens displayed significant improvement in erodibility parameters. Improvement of the erodibility parameters and strength of the specimens revealed that in addition to the mass of calcium carbonate, the chemical concentration used for MICP treatment can be effective in the level of improvement.

MICP was successfully implemented in the field as a soil improvement method for shallow depths. Treatment was applied to a coastal sandy slope through three solution delivery systems known as surface spray method, use of PVDs, and shallow trenches. Mechanical soil improvement achieved with the use of lower grade chemicals and performing treatment under inclement weather condition. Pond water was used as a source of water for solution preparation during the treatment and its compatibility with MICP process was verified using UCS tests prior to the field experiment.

Dynamic cone penetration (DCP) tests were performed to have an assessment of soil improvement along the soil profile. All test plots exhibited a significant penetration resistance improvement either in depth or surface. The level of improvement followed the overall trend of the precipitation pattern. Impinging jet tests, pocket penetrometer, and initial penetration depth measurements were completed to evaluate the surficial soil improvements and erodibility resistance. Surficial strength and erodibility parameters significantly improved with increase in mass of calcium carbonate. A higher erosion resistance compared to the values reported in literature for saturated soil treatment is the results of the unsaturated MICP-treatment and a more efficient cementation bond. Strength values measured with pocket penetrometer were also shown to be consistent with laboratory unconfined compression tests with varying cementation levels.

The surface spray method created a wider treated zone with the maximum soil improvement on the surface. Implying that the method can be used as an easy and effective method for surficial improvement applications such as sand dune protection, dust control, erosion and scour mitigation, etc. PVD method is capable of providing a deeper treated zone from surface to the depths of interest. The maximum improvements in the deeper depths suggested that this method is better suited for deep soil applications such as slope stability. The application of MICP with PVDs method can be a cost-effective technique in large-scale projects to create a large number of cemented columns in depth. Trenches method improved both surficial and deeper soil properties, however, in a more localized manner.

The permanence of the stabilized soil was confirmed by monitoring the treated soil with time and after extreme environmental conditions. Monitoring the field indicated that severe weather conditions such as freeze and thaw, heavy rainfall, and a hurricane had no significant adverse effect on the strength of MICP-treated soil.

Bermuda grass was evaluated to assess its ability to rebound after MICP treatments. The grass was treated separately with ingredients and byproducts of MICP-solution to assess the compatibility of the chemicals with plants. Compared to ammonium, urea and  $\text{CaCl}_2$  effected plant health in earlier stages of treatment. Lower urea and ammonium concentrations promoted plants health and growth, however in 50 mM concentrations or higher, younger seedlings did not survive. Results indicated that regular MICP-treatment concentrations are higher than the tolerance range of plants. It is recommended to apply treatment solutions with concentrations lower than 50 mM and on fully grown plants. Addition of phosphate to cementation solution and also rinsing specimens three hours after the treatment slightly alleviated the adverse effects of chemicals on plants. In addition, applied concentrations of phosphate exerted no changes in formed morphology of precipitated calcite. Seed germination and growth of Bermuda grass was assessed through specimens treated to different levels of cementation. After 19 days, seeds planted in untreated, lightly cemented and moderately cemented soils indicated similar seedling growth and coverage. Conversely, sparse seedlings grew in heavily cemented sand. This indicates that up to a certain level of cementation, both MICP soil improvement and plant growth can coexist.

## **Introduction**

Roadbeds supporting coastal highways in North Carolina (e.g., Highway 12) are susceptible to erosion during large storm events. During large storms, such as hurricanes and nor'easters, storm surge and waves are able to erode the soil and undermine the highway. Coastal highways in North Carolina have experienced over-washing due to coastal storm surges, which led to pavement damage and highway closure. By reinforcing vulnerable coastal subgrades and slopes, erosion potential can be reduced and the coastal infrastructure can be maintained.

As an example, if the sandy material supporting coastal highways, such as Highway 12 in the Outer Banks, is strengthened to minimize their erodibility during storm events, then the highway may not experience as much undermining, and more of the lifeline would remain open for emergency work. Erosion at the interface of pavement and sand can lead to collapse of pavement and development of channelization for flow across or along the barrier island. Preventing the erosion of the subgrade soils and slopes will reduce the damage to the coastal highways, and help maintain open and connected highways during the recovery period after storm events.

Additionally, the Department currently designs slopes supporting roadways in sandy material with a shallow slope (i.e., 3:1 horizontal:vertical) due to the erodibility and stability of the material. The shallow slope leads to a wider right-of-way extent and sometimes requires additional measures, such as retaining walls, when the large right-of-way extent is not available. More competent material may be designed with a 2:1 slope, thereby reducing the right-of-way extent. By reinforcing vulnerable coastal subgrades and slopes, erosion potential can be reduced and vital infrastructure can be maintained.

Bio-mediated soil improvement methods can be used to stiffen sandy subgrade and slopes and reduce the soil's susceptibility to erosion. Natural biological processes have been shown to improve the behavior of sand deposits by increasing the sand's strength, stiffness, and erosion resistance (Montoya and DeJong 2015, Lin et al. 2015, Shanahan and Montoya 2016). Microbial induced carbonate precipitation (MICP) treatment methods utilize natural soil bacteria to hydrolyze urea as a nutrient source and produce calcite cementation within the soil matrix. This bio-cementation process can be used to mitigate damage to highway subgrades and slopes by implementing the process in situ. The bio-cemented reinforced sand deposits would ultimately improve the resiliency of the coastal infrastructure by reducing the susceptibility to erosion in an innocuous, natural, and cost-effective manner.

## **Purpose and Scope**

An improved method to reduce erosion of sandy subgrades and slopes is needed to prevent erosion due to either precipitation or storm surge. Erosion of sandy slopes can lead to weaken slope stability and material flows into sensitive areas, such as estuaries, and erosion of sandy subgrades can lead to undermining pavement and potential pavement collapse. Sandy slopes are designed at a shallow, 3:1 slope to reduce issues associated with erosion and slope stability. Conventional methods to prevent erosion include a combination of biotic soil media (BSM) and compost blanket, geo-fabrics, rip-rap, and sandbags. These methods have limited success in preventing erosion; therefore, a soil improvement method that can reduce erosion susceptibility and increase the shear strength of the soil will have an improved performance of the sandy slopes and subgrades. Bio-

mediated soil improvement methods can provide improved performance of sandy materials by increasing their shear strength and erosion resistance in a natural way.

The overarching goal of this project is to implement a bio-mediated soil improvement method in situ and monitor its performance when exposed to natural conditions (e.g., weather fluctuations, precipitation, surface water, etc.). In order to implement field trials, a laboratory program was performed to develop the appropriate treatment method (e.g., level of cementation) to reduce erosion and increase shear strength. Furthermore, the ability of vegetation to take root post-treatment was evaluated, and a general cost comparison made between the developed bio-mediate method and biotic soil media (BSM) was conducted.

## **Research Approach**

The research scope discussed above was developed to establish a bio-cementation (i.e., MICP) method to improve the performance of the sandy subgrades and slopes that can be implemented by the Department. The recommended field implementation method (e.g., recipe, application method, etc.) for the Department was established through the laboratory and field experiments and feedback from the Steering Committee. The resulting bio-cementation treatment approach is compatible with vegetation re-establishing post treatment. The bio-cemented sand will provide significant increased strength and reduced erodibility of sandy slopes and subgrades, including when exposed to variable precipitation and weather, as well as improved performance under wave action.

## **Organization of the Report**

This report will present the results of the research study to develop the field implementation of MICP. A brief overview of the literature review is presented, with a focus on unsaturated soil MICP-treatment literature. The results of the laboratory and field research are then included within the report body, followed by recommendations and implementation and technology transfer plan.

## **Result of Literature Review**

Bio-mediated soil improvement is an emerging research field that has made substantial contributions in recent years (Mitchell and Santamarina 2005, Ivanov and Chu 2008, DeJong et al 2010, DeJong et al 2011, DeJong et al 2013). In general, bio-mediated soil improvement is a biologically-mediated chemical reaction that takes place within the soil matrix and improves the mechanical properties of the soil (e.g. strength and stiffness). Of the more studied methods to modify the mechanical properties of the soil with bio-geochemical reactions is microbial induced calcite precipitation (MICP) using ureolysis. MICP utilizes urea hydrolysis with calcium chloride as the chemical reaction to increase the alkalinity of the pore fluid and induce calcite precipitation. *Sporosarcina pasteurii*, a common alkalophilic soil bacterium, has a high urease activity and is used to facilitate the chemical reaction. The urease enzymes hydrolyze urea and produce ammonium and bicarbonate which induce calcium and carbonate to precipitate as calcite (Fujita et al 2008, Stocks-Fischer et al. 1999). The MICP process occurs naturally in situ cementing sand into sandstone; however, it can be harnessed and accelerated to be used as a natural soil improvement process.



Bio-mediated soil improvement research has addressed several societal needs. Cementation from MICP has been shown by the PI and others to increase the strength, stiffness, and dilative tendencies of loose, saturated soil susceptible to liquefaction (Zamani and Montoya 2019, Feng and Montoya 2015, Montoya and DeJong 2015, Lin et al. 2015, Montoya et al. 2013, Burbank et al. 2013, Chu et al. 2012, Chou et al. 2011, van Paassen et al. 2010, DeJong et al. 2006). Bio-mediated surficial soil treatments have also been shown to provide a stiff surficial crust by binding soil particles together and increasing the soil's resistance against wave action and wind erosion (Montoya et al. 2021, Shanahan and Montoya 2016, Gomez et al. 2014, Bang et al. 2011, Kavazanjian et al. 2009). The PI has evaluated the application of MICP in a wide range of soil mineralogy and saltwater pore fluid conditions (Mortensen et al. 2011). MICP research has also shown to be able to use the indigenous bacteria to induce the calcite cementation (Gomez et al. 2014, Burbank et al. 2011, Fujita et al. 2010). In all of these environments, bio-mediated soil improvement has successfully created bonds between soil grains and improved the mechanical properties of the soil.

Unsaturated soil environments, such as partially saturated sandy subgrades and slopes, have great potential for MICP treatments. The microbial induced calcite cement has a preference to precipitate at the particle contacts (DeJong et al. 2010), which has a much more dramatic impact on increasing the strength and stiffness of the soil compared to cementation coating the entire soil grain. In unsaturated environments, all of the treatment fluid will be retained within the menisci at the particle contacts. This will create an environment for calcite to precipitate at only the particle contacts, allowing the cementation to have an optimal effect on soil behavior. The proposed treatment of the unsaturated sand dunes is somewhat similar to the surficial methods used to reduce erosion due to wind (Bang et al. 2011, Kavazanjian et al. 2009); however, a deeper treatment zone is required to improve the performance of the sandy subgrades and slopes.

An unsaturated MICP treatment process has been developed in the PI's laboratory, that has resulted in similar or larger shear strengths compared to saturated MICP treatment methods (Shanahan and Montoya 2014). The results of this study indicates that in regards to the mass of calcite precipitated, unsaturated environments are more efficient than saturated environments in improving shear strength of sand. The unsaturated treatment process has also demonstrated an increase in shear stiffness, assessed using shear wave velocity and mass of carbonate, to depths of about a meter (Montoya et al. 2021).

Several independent studies have indicated that MICP improves the shear strength of sand by increasing both the friction angle (e.g.,  $\phi'$ ) and cohesion (e.g.,  $c'$ ) strength parameters. Feng and Montoya (2015) and Lin et al. (2015) both demonstrate that the friction angle of the MICP-treated sands increase from about 32 degrees to about 35 – 41 degrees, depending on the cementation level, and a cohesion up to about 40 – 60 kPa. These strength parameters were evaluated at confinements between 25 to 400 kPa. Several studies have also demonstrated that MICP is an effective treatment method to reduce erosion susceptibility (Shanahan and Montoya 2016, Gomez et al. 2014, Bang et al. 2011, Kavazanjian et al. 2009). Shanahan and Montoya (2016) evaluated MICP-treated sands subjected to wave action within the wave tank at the UNC Coastal Studies Institute, and demonstrated that: 1) MICP reduced erosion of the sand beach subjected to wave action at all levels of MICP-cementation tested (e.g., lightly to heavily cemented sands), 2) higher levels of MICP-cementation reduced erosion more than lighter levels of MICP-cementation, 3) the

most efficient reduction of erosion, in terms of mass of calcite precipitation, occurs at light to moderate levels of cementation. The results from this study are significant, indicating that even light to moderate levels of cementation may be enough to increase shear strength and reduce erodibility. Light to moderate levels of cementation is also more likely to have a reduced impact of the ecology of the treated soil, allowing vegetation to take root more easily and animals to still burrow in the deposit.

## Report Body

The following sections detail the results of the laboratory program, field implementation, field monitoring observations, vegetation compatibility experiments, and cost comparison.

### Laboratory investigation to development the treatment processes and quantify the improvement in erosion resistance

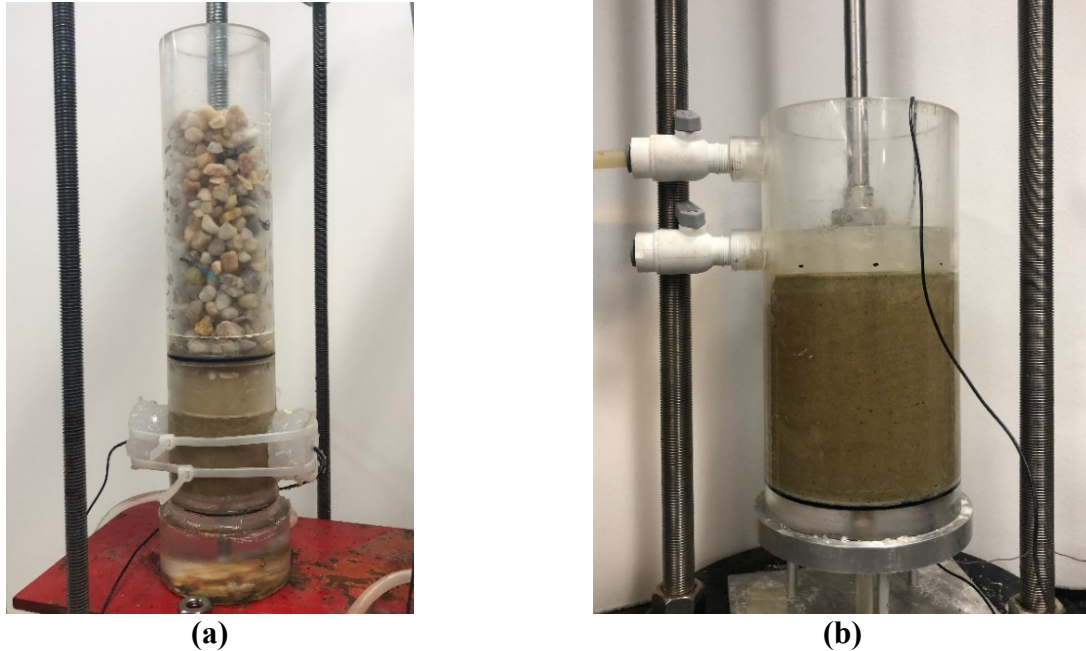
A laboratory program was developed to assess the ability of microbially induced carbonate precipitation (MICP) to treat coastal soil from Ahoskie, NC as an erosion mitigation technique. Chemicals with a lower grade than lab grade (e.g., agricultural grade) were investigated for use in the treatment solution at two different ratios of urea to calcium chloride in preparation for field application. During the treatment process shear wave velocity and the number of treatments were monitored continuously until a target shear wave velocity of 1100-1300 m/s was reached. The unconfined compressive strength and the erodibility of the treated sand were evaluated. The sand from the Ahoskie, NC field site was compared to standard Ottawa 20-30 sand, which was used as a benchmark since its MICP-cemented behavior is well studied.

#### *Soil Properties and Sample Preparation*

The physical properties of the two soils evaluated, Ottawa sand (OS) and Natural soil (NS) from Ahoskie, NC, are presented in Table 1. Air pluviation was used to prepare the specimens in cylindrical acrylic columns with diameters of 50.8 mm and 101.6 mm for the unconfined compression strength test (UCS) and erosion tests, respectively (Figure 1). The specimens were kept under a low effective stress during the treatment process (about 5 kPa). Bender elements were used for continuous monitoring of shear wave velocity and mounted on the bottom and top caps of the erosion test specimens and in the sides of the UCS test columns.

**Table 1. Physical Properties of the tested materials**

Soil Properties	OS	NS
USCS classification	SP	SP
D <sub>50</sub> (mm)	0.72	0.2
C <sub>u</sub>	1.19	2.8
C <sub>c</sub>	0.92	2.07
e <sub>min</sub>	0.502	0.550
e <sub>max</sub>	0.742	0.928
G <sub>s</sub>	2.65	2.65
Fines content (%)	0	11



**Figure 1. a) column used for performing UCS tests, b) Column of the erosion testing**

### ***Biological Treatment Process***

Bio-augmentation, the act of inoculated the soil with bacteria, is employed in the laboratory and field study presented herein. *Sporosarcina pasteurii* [American type culture collection (ATCC) 11859], a common alkalophilic soil bacterium was used as the catalyst for microbial induced calcium carbonate precipitation through urea hydrolysis reaction. The bacteria were cultured in an ammonium-yeast medium. The ingredients of the culture media were autoclaved and sterilized separately then the solutions combined and inoculated with *S. pasteurii* stock culture. The solution was incubated at 30°C in an incubator at a speed of 200 rpm for about 40 hours to reach an optical density (OD<sub>600</sub>) of 0.8 to 1.2. The cultures were centrifuged at 4,000 g for 20 min in 15 mL volume vials and the supernatant was replaced with fresh growth medium and centrifuged a second time. Vials containing the harvested bacteria were kept at 4°C for a maximum of 14 days.

Table 2 represents the ratio and concentrations of the components of the treatment solutions used for treating soil specimens. Industrial grade chemicals were used for solution preparation to reduce the treatment costs and making this method more practical for field-scale application. Surface percolation was used to treat the specimens. The bacteria were first introduced to the soil specimen with a solution containing urea portion of the cementation media given in Table 2 and kept for 3 to 6 hours to ensure attachment of bacteria to the particles. Afterwards, two pore volumes of the cementation media (Table 2), about 100 ml for the UCS specimens and 800 ml for erosion test specimens, was percolated every 12 hours to induce ureolytic-driven calcium carbonate precipitation (Mortensen et al. 2011). Since percolation was used to apply the cementation solution, all the specimens were unsaturated. Treatment continued until shear wave velocity of 1100-1300 m/sec was measured using bender element sensors.

**Table 2. Chemical recipe for cementation solution**

Solution	Urea Concentration (mM)	CaCl <sub>2</sub> Concentration (mM)	Urea to CaCl <sub>2</sub>
1	200	100	2:1
2	300	100	3:1

### ***Shear Wave Velocity Measurements***

Shear wave velocity measurements were performed as a proxy of soil improvement during the treatment process and progress of calcium carbonate precipitation since it increases as a function of the MICP treatment (Nafisi and Montoya, 2018). Bender elements were prepared and used for shear wave velocity measurements following the same procedure used by Montoya et al. (2012). Bender elements were mounted in the top and bottom cap of the erosion test columns and in the mid-height of UCS test columns. A signal generator was used to produce a 5-V, 100 Hz square wave and transmit it to the bender element and through the soil; an oscilloscope recorded the received wave by which the travel time and shear wave velocity were determined (Zamani and Montoya, 2018).

### ***Calcium Carbonate Measurements***

After performing the UCS and erosion tests, calcium carbonate content was determined by gravimetric acid washing. A small amount of soil (about 10 g) was oven dried and then soaked in 30 ml of 1 M HCL overnight. The supernatant was carefully removed with syringe and was replaced again with acid and repeated up to the point where no more bubbles were observed. Then the soil was washed with water and oven dried. The calcium carbonate percentage expressed as the reduced mass after acid washing divided by the mass of soil particles (Mortenson et al. 2011).

### ***Unconfined Compressive Strength***

After reaching the target shear wave velocity of 1100-1300, treatment processes were terminated and soil specimens were extruded and prepared for UCS tests. The specimens were extruded using a Shelby tube extruder modified for 2-inch (50.8 mm) inner diameter specimens. The UCS compressive tests (ASTM D2166) were performed on the specimens with different soil types and treatment recipes. The vertical strain rate of 1% per min was used for all tests and shearing continued until reaching failure. By end of shearing, samples from the top and bottom of the tested specimens were collected to determine the mass of calcium carbonate.

### ***Erosion Test***

A submerged impinging jet system (JET) is an apparatus that is used to assess soil erodibility. This system generates a surface shear force using a water jet which is a function of the diameter and distance of the nozzle from the soil surface (Hanson et al. 1990). The apparatus used in this study is the mini-JET system first introduced by Simon et al. (2010). This system is a modified and laboratory scaled version of the previous JET systems (Hanson and Cook 1997; Hanson et al. 2002). In this apparatus, a submerged impinging jet flow applies shear stresses on the soil surface. The shear stress on the soil surface increases by increasing the velocity or hydraulic head of water. Once the shear stress exceeds the critical shear stress  $\tau_c$ , soil particles start to detach, and soil surface deformation happens. The eroded depth of the soil increases with continued flow of water until it reaches a plateau which shows completion of the erosion process. Erodibility parameters

can be measured using this method are critical shear stress ( $\tau_c$ ) and erodibility coefficient ( $k_d$ ); this can be calculated using Eq.1:

$$\varepsilon_r = k_d(\tau - \tau_c)^\alpha \quad (\text{Eq. 1})$$

The exponent “ $\alpha$ ” is usually considered as unity for sands. The parameter  $\tau$ , is the induced shear stress which is calculated using Eq. 2 (Al-Madhhachi et al. 2013):

$$\tau = C_f \rho (C \sqrt{2gh})^2 \left(\frac{J_p}{J}\right)^2 \quad (\text{Eq. 2})$$

Where  $C_f = 0.00416$  is the coefficient of friction,  $\rho$  is the density of water,  $C \sqrt{2gh}$  is the velocity of the water through the orifice where  $g$  is the gravitational acceleration and  $h$  is the water head of the orifice,  $J_p$  is the product of the multiplication of the diffusion constant and diameter of the nozzle and  $J$  is the distance between the nozzle and the soil surface. The velocity of water is controlled by hydraulic head gradient and should be kept constant during the test.

### ***Laboratory Results and Implications for Field Application***

The testing program and characteristics of the specimens used for UCS and erosion tests are presented in Table 3 and 4, respectively. Each soil specimen is designated as indicated in these tables. The first letter is indicating the test type meaning “U” refers to the UCS test and “E” to erosion test. The second and third letters are referring to the soil type; “OS” is the Ottawa sand and “NS” is the natural soil from Ahoskie, NC and the numbers indicate the ratio of the urea to calcium chloride in the treatment solution.

The number of treatments required for reaching the target shear wave velocity of 1100-1300 m/sec varies for specimens prepared from the same type of soil and treated with different concentration ratios of urea and calcium chloride (Table 3 and 4). The number of treatments required to reach the same shear wave velocity increased with decreasing the concentration of urea to calcium chloride in the treatment solution. In higher ratios of the urea to calcium chloride, the concentration of the urea is higher and more urea is available to bond with the available calcium ions in pore fluid; therefore, the likelihood of precipitation of calcium carbonate is higher and smaller numbers of treatment is needed.

The calcium carbonate content of NS specimens is higher than OS specimens. The reason may lie in the difference between distribution of the pores throughout the soil matrix due to the shape of grain size distribution and the size of soil particles. The more well-graded nature of the NS in comparison to the OS results in the higher water retention capacity of the soil in unsaturated condition (Lu and Likos, 2004). As it was mentioned earlier, specimens were treated using surface percolation method, so during the treatment they are in an unsaturated condition. In the case of NS specimens, since more water occupies the pores between the soil grains, treatment solution can more easily move and precipitate in different locations between the particles (Cheng et al. 2013).

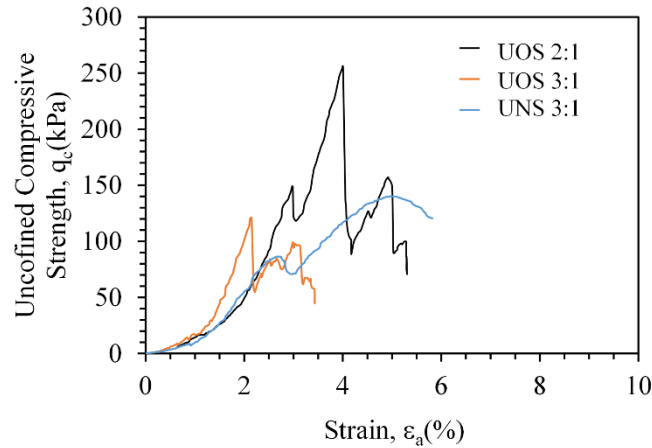
**Table 3. Testing program and specimen characteristics for UCS test**

Specimen	Diameter (cm)	Height (cm)	Initial void ratio	Number of treatments	Calcium carbonate content (%)	
					Top	Bottom
UOS2-1	5.08	4.56	0.55	33	3.98	4.56
UOS3-1	5.08	4.67	0.61	15	3.52	2.65
UNS3-1	5.08	3.71	0.56	19	10.22	11.92

**Table 4. Testing program and specimen characteristics for erosion test**

Specimen	Diameter (cm)	Height (cm)	Initial void ratio	Number of treatments	Calcium carbonate content (%)	
					Top	Bottom
EOS2-1	10.16	11.51	0.65	29	0.82	0.68
EOS3-1	10.16	11.72	0.66	15	0.33	0.44
EOS-untreated	10.16	11.53	0.67	-	-	-
ENS3-1	10.16	11.40	0.68	14	1.79	1.96
ENS-untreated	10.16	11.43	0.63	-	-	-

Stress-strain responses of the UOS2-1, UOS3-1 and UNS3-1 specimens are presented in the Figure 2. The UOS specimens demonstrated sudden drops of the shear strength with increasing the axial strain while the UNS specimen exhibited a more stress-strain path. The reason of such behavior of the UNS specimen may be attributed to the presence of about 11% fine particles that can provide lateral support for sand particles within the force chain against buckling. Presence of fines in addition to the more even distribution of the pores as a result of a relatively expanded particle size curve in UNS specimens in comparison to the UOS specimens leads to a more uniform cementation and more smooth stress-strain behavior. On the other hand, in UOS specimens, larger pore size and concentration of the cementation in the contact points results in local breakage of cementation and sudden drops in stress-strain path. The maximum unconfined compressive strength value was measured as 256 kPa and corresponds to the UOS2-1 while the UOS3-1 demonstrated strength of about 127 kPa. The reason for this difference can be attributed to the higher mass of calcium carbonate in UOS2-1 because of higher numbers of treatment required to reach the target shear wave velocity. Please note, the size correction for the UCS tests was performed to eliminate the effect of variable length to diameter on the level of shear strength.



**Figure 2. Results of the USC test performed on UOS and UNS specimens**

Summary of results obtained from the erodibility tests performed on the untreated EOS and ENS specimens and those treated with the urea to calcium chloride ratios of 3:1 to 2:1 are shown in Table 5.

**Table 5. Summary of the results of the erosion test**

Specimen	$\tau_c$ (cm <sup>3</sup> /Ns)	$k_d$ (cm <sup>3</sup> /Ns)
EOS2-1	0.22	2034
EOS3-1	0.61	1117
EOS-untreated	0.14	25725
ENS3-1	0.74	2729
ENS-untreated	0.09	33109

Erosion test results shown in the Table 5 indicate that  $\tau_c$  values increased and  $k_d$  values decreased compared to their untreated condition. This shows that erosion resistance of all specimens had improved. The critical shear strength of EOS2-1 and EOS3-1 increased about 1.5 and 4 times of the untreated specimen. This difference can be attributed to the strength of carbonate calcium precipitated with slower rate due to the use of varying concentration of treatment solutions (Al Qabany et al. 2013). The ENS3-1 specimen indicated 8 times improvement in  $\tau_c$  parameter. Comparison of the  $\tau_c$  parameter for the EOS3-1 and ENS3-1 exhibited close values which is compatible with UCS results in Figure 2.

As the main objective for the field application of MICP is erosion reduction, The 3:1 treatment solution (e.g., Table 2) was chosen for implementation in the field. Furthermore, since the 3:1 solution achieved the desired level of cementation quicker, it further reinforced the decision to use the 3:1 solution in at the field site (discussed below).



### Implementation of MICP treatments through field test sections

The field scale application of MICP was completed on a 3.33 to 1 (H:V) sandy slope with a 2.3 m height located in the Atlantic coastal plain in Ahoskie, NC. The slope was a part of North Carolina Department of Transportation's (NCDOT) maintenance facility and was located adjacent to a pond which was used as a water source for solution preparation during the MICP treatment. Prior to the field application, samples were collected from various locations of the slope for soil classification and index tests. Sieve analysis indicated a poorly graded sand (SP) with a similar grain size distribution along the slope surface. Physical properties of tested soil are summarized in Table 1. Preliminary in situ percolation tests performed on different locations on the slope indicated a lower hydraulic conductivity in the downhill of slope compared to the top of slope. Such observations may be attributed to the higher density or level of compaction in lower elevations of the slope.

Table 6. Properties of the tested soils

Soil type	USCS classification	D <sub>50</sub> (mm)	C <sub>u</sub>	C <sub>c</sub>	e <sub>min</sub>	e <sub>max</sub>	G <sub>s</sub>	Fines content (%)
Ahoskie sand	SP	0.2	2.8	2.07	0.55	0.93	2.65	4

Prior to setup installation, slope surface was cleared of any vegetation remaining. Three 1 m × 8 m testing plots with 0.5 m spacings were marked on the slope surface. Created plots were treated with three methods known as surface spray, PVDs, and surface trenches as shown in Figure 3.



Figure 3. Overall view of the field and test setups



### ***Water Intake System***

A battery-powered rotary pump (Wayne Inc.) with a maximum discharge rate of 22.08 l/min was used to extract water from the pond and discharge it into a 4164 l tank. A 140-micron sediment filter was connected to the pump's suction to trap the sediments and the suspended organic particles (e.g. algae, leaves, etc.) in pond water. The filter was attached to a floating plywood sheet to minimize its exposure to the sediments at the bottom of the pond. The 4164 l tank was used as a temporary container to store water and to allow more suspended solids to settle before use. A second similar pump was used to transfer water from the tank to three 1041 l tanks to prepare solutions during the treatment process. A coarse (50-micron) filter and a fine (25-micron) filter were connected to the pump inlet to avoid any clogging in treatment setups caused by any floating particles.

### ***Spray Method***

Surface spray method was used as one of the MICP-treatment implementation techniques in testing plot shown by green flags in right hand side of the Fig. 3. The spray setup was an irrigation system consisting of 25 spray nozzles with 32 cm spacing connected to a main hose. During treatment, the hose and sprayers were supplied with solution by a pump connected to one of the 1041 l tanks. Treatment solution was transferred from top to bottom of slope and recirculated back into the tank. The direction of the flow was reversed at treatment C<sub>7</sub> shown in Table 4. Immediately after the pump a control valve recirculated the excess water back into the tank. The valve was used to relief the excess water pressure and prevent pump damage and provided a continuous solution mixing in the tank. Prior to the installation, calibration tests performed on a single sprayer connected indicated a maximum discharge rate of 32.55 l/hr when connected to 138 kPa inlet pressure. Calibration tests with colored water demonstrated that the majority of the water was received in locations within 26 to 34 cm of the center of sprayer. Lower water volumes were received inside and beyond this ring-shaped wetting zone. Accordingly, 32 cm spacing between the two nozzles was chosen to ensure an overlap between the wetting zones of sprayers. Two regulating valves one on the midpoint of the hose and the other one at the end of the main hose were used to adjust the pressure distribution along the slope surface and to achieve a more uniform solution distribution.

### ***PVD Method***

PVDs, commonly known as wick drains were used as a solution delivery method for MICP-treatment of the middle test plot in Fig.3. PVD has been widely used as an efficient and cost effective method to facilitate consolidation and depth specific contamination removal from low permeability soils (Gabr et al. 1996, 1999; Schaefer et al. 2017; Warren et al. 2006). The PVD used in this study is a band-shaped element with 10 cm width and 1 cm thickness consisting of an inner core wrapped in an outer fabric jacket. The core is a corrugated polypropylene with drainage channels on both sides to accelerate the in-plane flow. Solution flows into the channels and enters the soil by passing through the nonwoven geotextile fabric which is in contact with the surrounding soil. PVDs were cut in 33 cm lengths and were inserted into a plastic adaptor from the top. The bottom section was sealed with a 1 cm impermeable sleeve to distribute the solution along the 30 cm exposed PVD length. The 30 cm length was chosen to ensure that treated zone does not exceed the study's purpose of surficial treatment. A metal plate with the dimensions similar to the PVD's was used to install the vertical drains into the soil along the slope surface. The plate was pushed into the soil and pulled out carefully. Each PVD was slid to the opening that preserved its shape temporarily due to strength increase cause by matric suction generation. The PVDs were installed

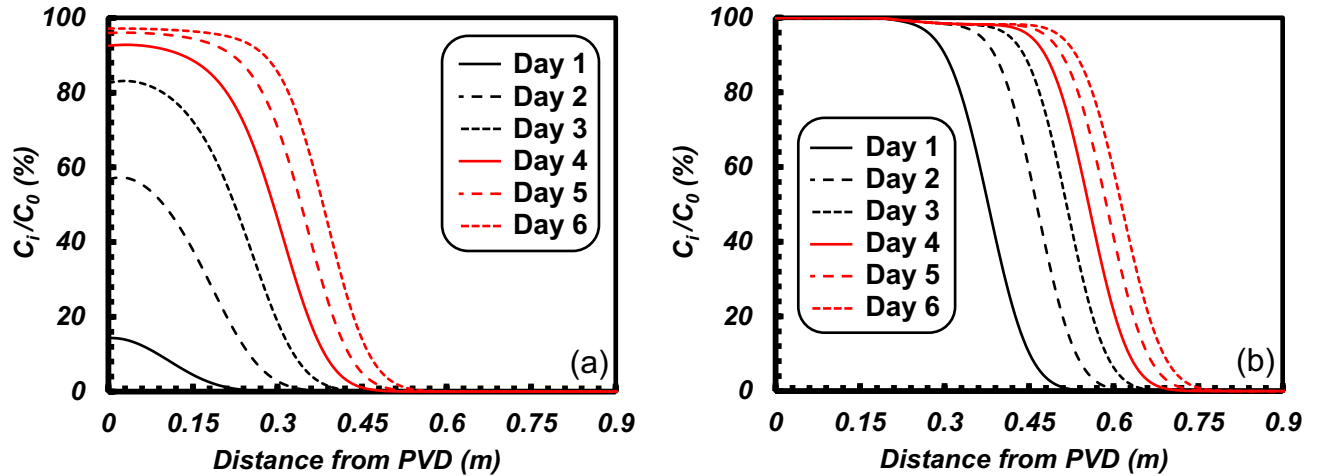
in two lines as shown in the middle section of the Fig. 3. Decision on the spacing between the PVDs was made by performing both numerical analysis and calibration tests.

Previous studies have indicated that cementation wedge follows the solution flow pattern and no cementation formation was observed beyond that (van Paassen et al. 2010). Seepage and reactive transport analysis were performed using SEEP/W and CTRAN/W (GeoStudio 2012, Alberta, Canada) software packages. A single PVD was modeled as a cylinder with an equivalent diameter ( $d_w$ ) of 0.04 m and 0.3 length (Hansbo 1979). Domain was modeled as a 4 m diameter and 2 m length to eliminate the effects of boundary condition. Soil was assumed to be in unsaturated condition and Soil Water Characteristic Curve (SWCC) and Hydraulic Conductivity Function (HFC) of a similar grain size distribution sand was used for the analysis (Elzeftawy and Cartwright 1981). Similar to the field plan two treatments per day with chemical recipes and concentrations shown in Table 2 was considered for the analysis. Table.5 presents a summary of input parameters used for the analysis.

**Table 7. Input parameters for the analysis**

Parameter	Value	Note
Geometry of domain	2 m height $\times$ 4 diameter	None
Density ( $\rho$ )	1528 kg/m <sup>3</sup>	Nuclear gage measurement
Hydraulic conductivity	$4.2 \times 10^{-5}$ (m/sec)	Lab measurements
Longitudinal dispersivity ( $\alpha_L$ )	0.3 m	Typically, $0.1 < \alpha_L < 10$ for distance 1 to 100 m (Anderson 1984)
Transversal dispersivity ( $\alpha_T$ )	0.3 m	(Do et al. 2019b)
Initial concentration ( $C_i$ )	36 kg/m <sup>3</sup>	Urea 0.3 M / CaCl <sub>2</sub> 0.1 M
Diffusion coefficient ( $D^*$ )	0.0001 cm <sup>2</sup> /sec	Typically, $10^{-4} < D^* < 10^{-5}$ in cm <sup>2</sup> /sec (Hall et al. 1953)
Adsorption ( $K_D$ )	None	No organic content
Decay half-life	None	No radioactive source

Analysis results for soil surface and depth of 30 cm (Figs. 4(a) and(b)) indicates that PVD tends to treat soil more in an axial direction rather than a radial direction. At 30 cm depth (Fig. 4(b)), all points within the 20 cm distance from the PVD receive solution with a 100% of the initial applied concentration. However, on the soil surface (Fig. 4(a)) by the end of the day 1 only a small percentage of initial concentration is received even within the 20 cm distance and beyond that no significant chemical concentration was received. Results of the calibration tests performed on a single PVD prior to the field application also indicated a wetting zone of about 10 cm radius in front of PVD and about 3 cm close to edges in the soil surface. The influence zone was extended to 15 cm in front and 10 cm in edge in the depth of 30 cm. Based on numerical results and calibration tests, to achieve a surficial treatment, a center-to-center and edge-to-edge spacing of 15 cm was chosen between PVDs along the slope surface and in the perpendicular direction.



**Figure 4. Normalized concentration received at different distances from the PVD at the end of each day (a) On soil surface and (b) At 30 cm depth.**

As shown in this Fig. 3, the number of PVDs in the two sets are not identical and one line consists of 25 PVDs, and the other one has 19. Such configuration was chosen to assess the precipitation pattern around a single PVD by reducing the effect of overlapping PVDs. During treatment, solution was pumped to the top of slope with a pump connected to a 1041 l tank. Solution then was divided into two streams and flowed downhill into the PVDs and excess amounts recirculated back to the tank. Each PVD was fed with solution by a 0.43 cm inner diameter tube connected to the adaptor and a main tube. A control valve installed immediately after the pump to avoid excess pressure build-up in the pump and to adjust the flow pressure within the system.

### ***Trenches Method***

The third test plot was treated with sixteen 60 cm long shallow trenches that were 20 cm wide and 15 cm deep with a center-to-center spacing of 50 cm as shown with blue flags on the left-hand side of the Fig. 3. Each trench was covered with approximately 3 cm of pea gravel to avoid local erosion of trench surface during treatment and to provide a uniform solution distribution within the trench. A layer of geotextile was placed between the pea gravel layer and the trench surface for separation purpose and to avoid the aggregates from being glued into the soil surface as a result of MICP-treatment. A set of narrow drainage channels was formed between the trenches to connect the trenches to each other. During the treatment, solution was pumped to the top of the slope to fill the first trench and then flowed through the channels to the downhill. A regulating valve was installed after the pump to keep a balance between the discharge rate and hydraulic conductivity of the soil and avoid solution runoff.

### ***Solution Preparation and Treatment Processes***

As it was mentioned earlier use of lower grade chemicals can reduce costs of the field application of MICP. Therefore, industrial grade urea and calcium chloride were used for treatment solution preparation. During treatment, separate 1041 l tanks and application pumps were used to apply solutions in each method. Treatment was started with application of biological solution and followed by cementation cycles. Solutions were prepared with chemical concentrations shown in

Table 2. Bacteria were grown in the lab and transported to the field and were stored in a 100 l tank until the next bioozing. A bacteria to solution volume ratio of 0.066 was maintained for all bioozings. Green food coloring was also added to solutions to keep a track of solution path within each test plot. Assuming an influence depth of about 0.5 m, treatment volume was calculated to occupy 30% of pore space. For spray and trenches method volume was determined as 500 l and was modified to 170 l for PVD method due to the covered area percentage. Treatment schedule for all three delivery methods is presented in Table 3. In this table, B<sub>i</sub> and C<sub>i</sub> denote biological and cementation treatment, respectively. All test plots received 3 biological and 14 cementation treatments in total. Solutions were applied two times a day and at least 3 hours of retention time maintained between treatments. For the ease of bacteria arrival scheduling the first biological treatment followed by four cementation treatments and the second and third biological treatments were followed by five cementation treatments. The PVD setup was installed in day 4 and treated from day 5 until the end of day 13 to the same cementation level as the others. The second treatment in day 3 and the first treatment for PVD method in day 9 were not completed due to inclement weather condition (As shown in Table 4). Daily precipitation data collected in Peanut Belt Research Station, located 27.4 km to the southwest of the field provided by North Carolina State Climate Office indicated that 7.4 mm, 22.9 mm, and 35.3 mm rainfall in third day, ninth day, and in total was received during the 13 days of treatment.

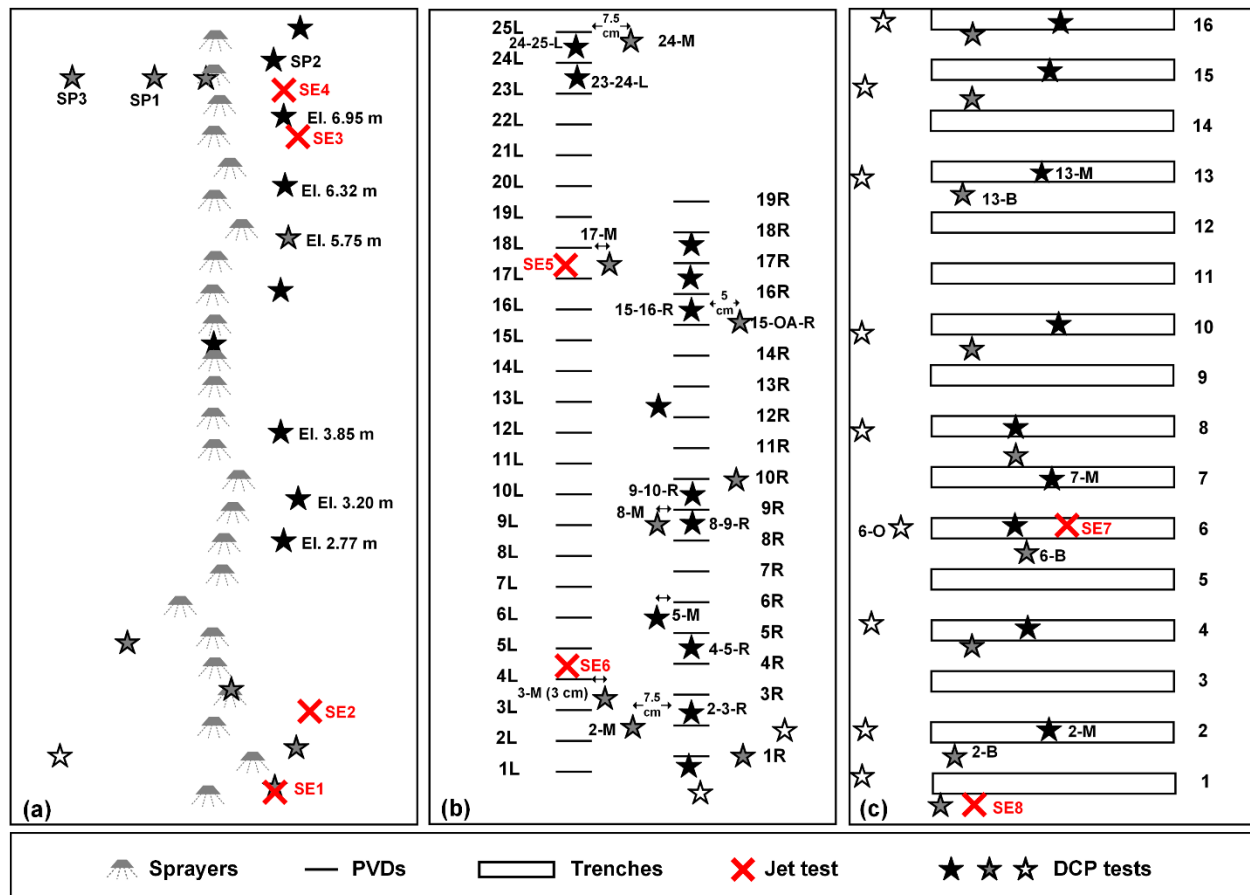
**Table 8. Treatment schedule for all three methods**

Day	Spray method		Trenches method		PVD method	
	Treatment type	Treatment volume (l)	Treatment type	Treatment volume (l)	Treatment type	Treatment volume (l)
1	- B <sub>1</sub>	- 500	- B <sub>1</sub>	- 500		
2	C <sub>1</sub> C <sub>2</sub>	500 500	C <sub>1</sub> C <sub>2</sub>	500 500		
3	C <sub>3</sub> -	500 -	C <sub>3</sub> -	500 -		
4	C <sub>4</sub> B <sub>2</sub>	500 500	C <sub>4</sub> B <sub>2</sub>	500 500		
5	C <sub>5</sub> C <sub>6</sub>	500 150	C <sub>5</sub> C <sub>6</sub>	500 300	B <sub>1</sub> C <sub>1</sub>	170 170
6	C <sub>7</sub> * C <sub>8</sub>	350 50	C <sub>7</sub> C <sub>8</sub>	200 150	C <sub>2</sub> C <sub>3</sub>	170 170
7	C <sub>9</sub> B <sub>3</sub>	450 200	C <sub>9</sub> B <sub>3</sub>	350 200	C <sub>4</sub> B <sub>2</sub>	170 170
8	C <sub>10</sub> C <sub>11</sub>	200 200	C <sub>10</sub> C <sub>11</sub>	200 200	C <sub>5</sub> C <sub>6</sub>	170 170
9	C <sub>12</sub> C <sub>13</sub>	200 200	C <sub>12</sub> C <sub>13</sub>	200 200	- C <sub>7</sub>	- 170
10	C <sub>14</sub>	200	C <sub>14</sub>	200	C <sub>8</sub> C <sub>9</sub>	170 170
11					B <sub>3</sub> C <sub>10</sub>	170 170
12					C <sub>11</sub> C <sub>12</sub>	170 170
13					C <sub>13</sub> C <sub>14</sub>	170 170

(\*) Direction of flow was reversed to top to bottom beyond this point in spray section

### ***Field Assessment***

At the end of the treatment processes, in day 14 several tests were performed in locations shown in Fig. 5 to evaluate the improvement of the MICP treated soil. Dynamic Cone Penetration (DCP) a commonly known device to assess the in-situ soil strength was used in accordance with ASTM D6951 (ASTM 2009). The setup consists of two connected 111 cm and 57.5 cm vertical shafts and a 60-degree cone attached to the tip of lower shaft (111 cm). A sliding donut hammer with 8 kg weight was dropped repeatedly from 57.5 cm height on an anvil attached to the lower shaft and drove the shaft tip into the soil. Penetration index (PI) was calculated by recording the numbers of drops and penetration depth and expressed as cm/blow. Jet test was used to quantify improvements of the surficial erodibility resistance soil. Tests were performed on untreated soil and 8 locations after the treatment as indicated in Fig. 5. Pond water and one of the pumps were used to provide pressurized water to perform jet tests. The erodibility parameters then were determined following the same procedure as stated in lab section. It is noteworthy to mention that the setup was placed on the soil surface and contrary to the lab tests where soil was inside the cylinder, the water jet was not completely in submerged condition. Therefore, the lower jet energy dissipation led to a more conservative measurement of erodibility parameters. Pocket penetrometer measurements were performed in random locations in all three test plots to estimate the surficial strength of soil. According to ASTM D 6169 (ASTM 2005), the measurements can yield a close approximation to UCS values. The setup consists of a piston that is pushed into the soil surface up to 6.4 mm to a marked groove. A calibrated spring converts the required stress to overcome soil's resistance to an indicator ring on pocket penetrometer's body. Measured values are in  $\text{kg/cm}^2$  and can directly be converted to kPa. Discrete calcium carbonate measurements were completed following the procedure mentioned in the lab section on samples from different locations and depths to have a measure of cementation levels and spatial distribution of precipitation.



**Figure 5. Map of the locations of performed DCP and jet tests in (a) Sprayers, (b) PVDs and (c) Trenches plot**

## ***Field Results and Discussion***

### ***Visual Observations***

At the end of the treatment process, cementation crusts with varying degrees were detected in all test plots. In spray test plot, crust thickness measurements indicated a minimum thickness of about 2.5 cm at the top and maximum of 14.5 cm at the downhill of the slope. In PVDs section, the cemented crust was only formed close to the downhill PVDs and created a stiffer surface compared to the soft soil around the top PVDs. PVDs removed from the soil indicated no signs of clogging and precipitation of the fabric Jacks. In trenches method, crusts only were generated inside the trenches and in walls of the channels connecting the trenches to each other.

### ***DCP Results***

DCP tests were performed on random locations prior to the field application and on all test plots after the treatment completion. Figs. 6(a-d) show the variation of PI values with depth for untreated soil and for three test plots treated with different solution delivery systems. PI is a measure of penetration resistivity of soil and a lower PI value indicates the higher soil resistance. As shown in Fig. 6(a), PI values of the untreated soil varied from 6 to 13 cm/blow for the surficial depths and decreased to 4 to 6 cm/blow for the depth of 30 cm. These values correspond to loose/very loose sand and soft/ very soft clay (Look 2014). The decrease in PI values and increased resistivity is a result of the confinement increase with depth. As shown in Fig. 6(a), PI measurements for

untreated soil do not start exactly from 0 cm, the result of insufficient soil surface strength to resist the weight of DCP setup.

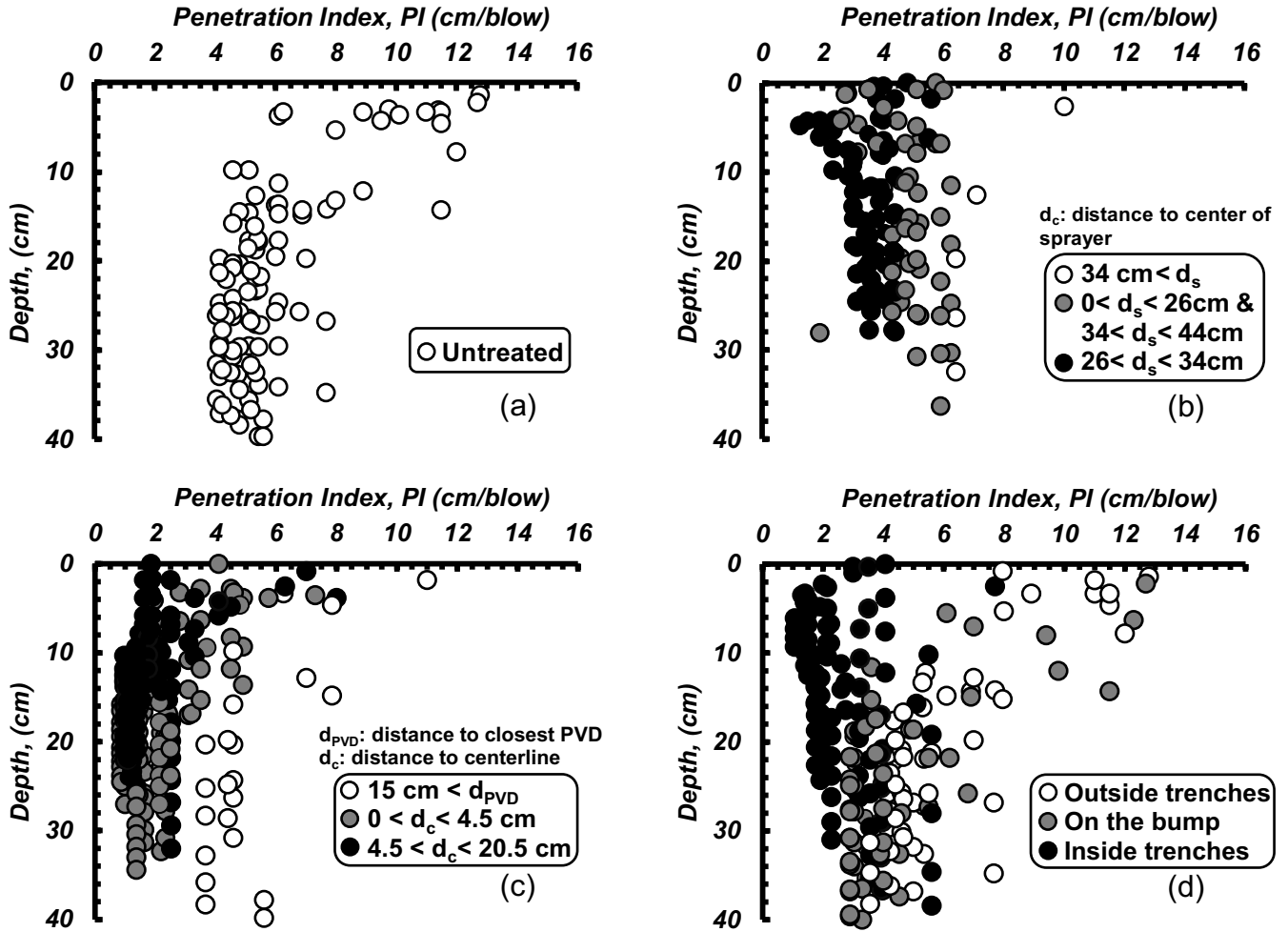
DCP test results for the spray method were divided into three groups according to the results of the calibration tests performed on a single sprayer described earlier. Points 26-34 cm from the closest spray nozzle received the maximum biological and cementation solution during the treatment (shown in black); points located within 26 cm or 34-44 cm from the center of spray shown in grey and points further than 44 cm represented by white [Fig. 6(b) and 8(b)]. The black data points are mostly located on the left side of Fig. 6(b) and demonstrate the lowest PI values and maximum improvement. Conversely, the white points, represent locations receiving minimal treatment, indicate a similar trend and PI values as untreated soil placed in the right-side of the figure. Locations shown in grey received less solution during treatment compared to the locations represented by black; therefore, demonstrate slightly higher PI values. However, both black and grey data sets follow a similar PI trend with depth. Contrary to the untreated soil, with the cementation crust formation and a surficial strength increase, PI values measurement started from the depth 0 cm similar to the observations reported by (Gomez et al. 2015). The measured PI values for treated soil with surface spray method ranged between 1.25 to 6 cm/blow for the upper 10 cm and 3.1 to 6 cm/blow for deeper depths. Indicating surficial soil's PI has enhanced up to that of medium dense sand or stiff clay by densification and particles bonding resulted from MICP-treatment (DeJong et al. 2010; Look 2014). The average PIs demonstrated 62% and 24% reduction in surficial and deeper depth values compared to the untreated soil. The larger decrease in PI values and the higher concentration of the smaller PIs in the shallow depths implies this solution delivery method is more suited for surficial applications.

Similar to the spray method and based on the calibration tests performed on a single PVD, points around the PVDs were categorized into three zones. Measured PIs for each zone are shown in Fig. 6(c). Points about 4.5-20.5 cm from the centerline of the test plot received treatment through the entire depth of the soil (shown in black). Points from 0-4.5 cm or 20.5-27.5 cm from plot's centerline that were located close to edges of the hypothesized influence zone are shown as grey data points. Results of the tests performed on locations outside the hypothesized treated zone (farther than 15 cm from the center of closest PVD) are also shown as white. The lowest PI values and maximum improvement was obtained in the locations close to PVDs (black data points). The white points indicate a similar pattern and PI values as the untreated soil. Grey points follow the same trend as the blacks and are located between the two data sets. In grey data set, the larger PI values were associated with the points affected only by the left or right side PVDs. However, in the locations close to the centerline of the plot, in depths deeper than around 15 cm, PI values became smaller and approached values of the black data set. This observation could be resulted from overlapping treated zones of PVDs and further cementation growth in deeper depths. PIs for the PVD method ranged between 1.85 to 8 cm/blow in the upper 10 cm and between 0.87 to 2.52 cm/blow in 30 cm depth (where PVDs end) of the soil profile. The values in depth reached the PI values of very stiff clay and rock (Look 2014). The average PI values decreased 48% and 72% on surface and in 30 cm depth compared to the untreated soil. This general trend implies a greater improvement in deeper depths resulted from cementation formation and growth. Moreover, in this test plot, the cemented crust was only detected around the PVDs in the downhill of the slope and no cemented crust was generated between the top PVDs. Therefore, unlike the spray method, most PI measurements start from depths below 0 cm as shown in Fig. 8(c). The greater improvement

and smaller PI values in deeper depths suggest this method is better suited for deep soil treatment applications.

PIs of the trenches plot were divided into three zones due to the location of the tested points relative to the closest trench (Fig 6. (d)). Points inside the trenches indicated the smallest PIs and maximum improvement (shown in black). Points located between two trenches and in solution flow direction are shown in grey. These points indicate a similar trend as the untreated soil with lower PI values in deeper depths. The lower PI values in depths deeper than 20 cm could be the results of the solution seepage and deeper depth treatment. Remaining points located outside the trenches exhibit a similar trend and PI values as the untreated soil (shown in white). PI values measurements appeared from the 0 cm depth only for the tests performed inside the trenches as cementation crust formation increased surficial soil strength. As shown in Fig. 6(d), PIs in trenches plot vary from 1 to 4.06 cm/blow for surface and 2.28 to 5.60 cm/blow in the deeper depths. The average PI values in surface and depth experienced 73% and 34% reduction compared to the untreated soil. These results demonstrated that the level of surficial improvement was greater than the spray method but in a more localized area, while less improvement was observed in depth compared to PVD method. A greater soil improvement at near-surface depths in plots treated with spray and trenches method suggests that the effect of cementation on soil strength is more pronounced in lower confinements, whereas at deeper depths (higher confinements) the effect of friction angle becomes more significant and cohesion component plays a marginal role in soil strength (Nafisi et al. 2019)





**Figure 6. DCP results for (a) untreated soil, treated with (b) sprayer, (c) PVDs and (d) trenches methods**

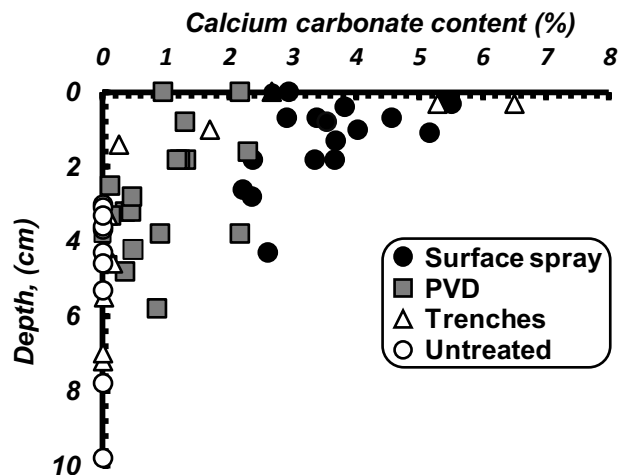
### Initial Penetration

Fig. 7 illustrates the initial penetration depths of DCP setup with the measured surficial mass of precipitation for all treatment methods. Generally, penetration depths decreased with an increase in calcium carbonate content. The initial penetration depths for untreated soil ranged from 3.1 to 9.8 cm. In PVDs method, the initial penetration depths decreased to the range of 0 to 5.8 cm with a limited progress of precipitation on soil surface. Penetration depths reach the minimum range of 0 to 4.3 cm with further progress of cementation and formation of a cemented crust in spray method. For spray method, points with the lower mass of calcium carbonate (about 2.2%) demonstrated the highest initial penetration depths (Fig. 8(a)). With further cementation progress and surficial strength increasing beyond the 3% mass of precipitation, the measured values reduced to maximum of 2 cm for most grey and black points. Although black data points were expected to show the lowest initial penetration depths, no clear distinction between black and grey points is observed in mass of precipitation of 2.4 to 3.3%. These black points were mostly attributed to locations in the upper half of the slope where developed precipitations were distributed in depth and generated crust was thinner compared to the lower half of the slope. Therefore, slightly higher initial penetration depths were obtained. In surface spray method, soil surface irregularities can

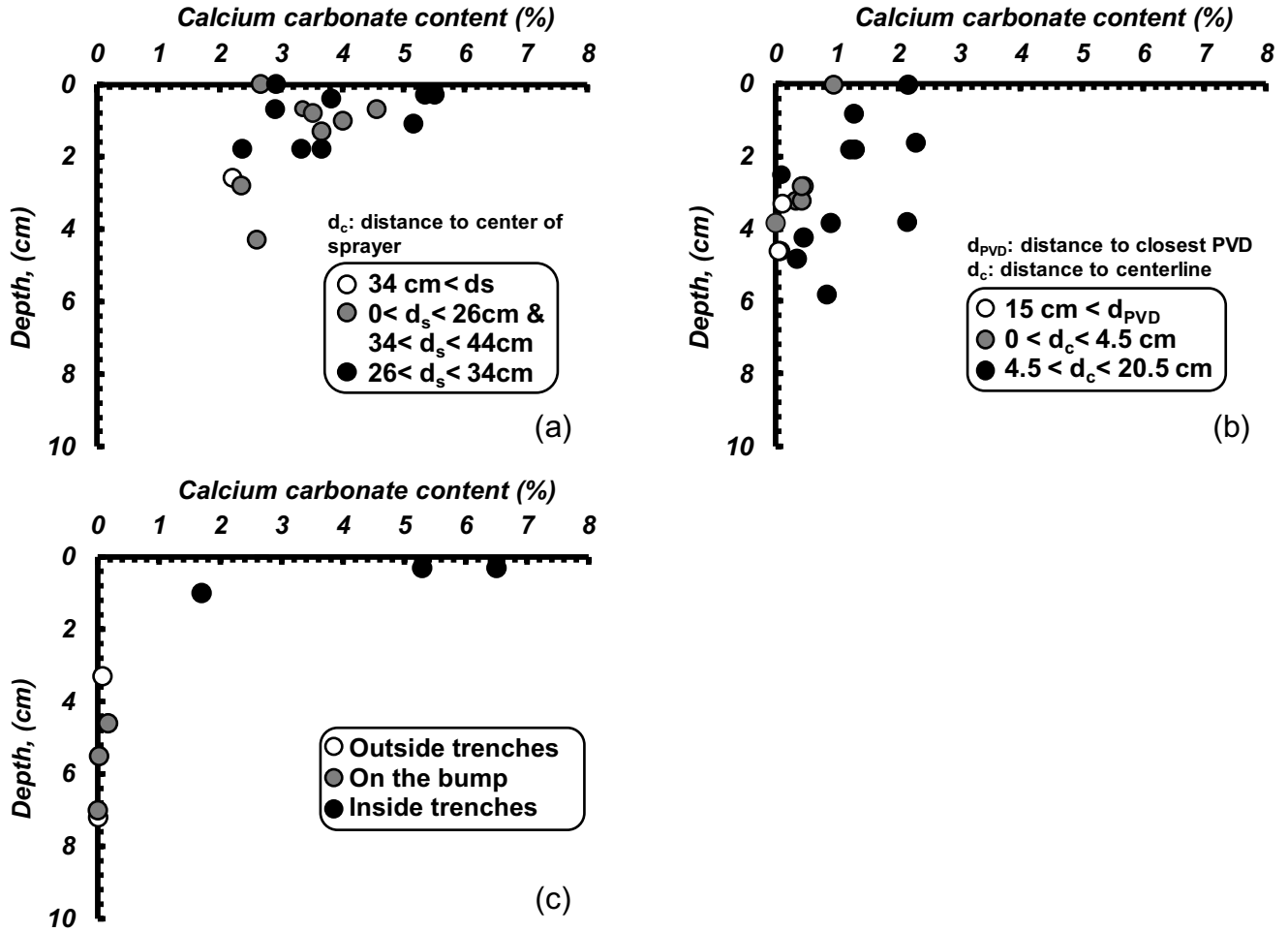
also contribute to localized uneven distribution of reagents and precipitated calcium carbonate on the soil surface. Such observations could also be the results of non-homogeneity of MICP-treated soil. Heterogeneity induced by the MICP process can be caused by an uneven distribution of bacteria and hydrolyzed urea on soil grains and contact points, spatial nonuniformity of supplied solutions, and development/presence of preferential flow paths within the soil (Mujah et al. 2016; Van Paassen et al. 2009).

The initial penetration depths for the PVD plot ranged between 0.0 to 5.8 cm for the mass of precipitations of 0 to 2%. As shown in Fig. 8(b), points are mostly concentrated around the 4 cm depth. The two points with zero free fall depth represent the 3-M and 2-3-R sampling locations in Fig. 5. In these two locations, PVDs received larger solution volumes due to the hydraulic head difference between the top and bottom of the slope. As it was also noticed during the treatments, the excess amounts of solution found a way to the shallow depths and cementation progressed up to the soil surface and formed a crust.

In the trenches method, the cementation crust was only developed inside the trenches where surficial treatments were received. Initial penetration depths for these locations ranged from 0.3 to 1 cm for mass of precipitation of 1.7 to 6.5% (Fig. 8(c)). Outside the trenches, the determined initial penetration depths observed to be similar to the untreated soil. In these locations, precipitation was initiated from the deeper depths and did not progress up to the soil surface.



**Figure 7. Initial penetration depths with mass of precipitation for untreated and treated soil**

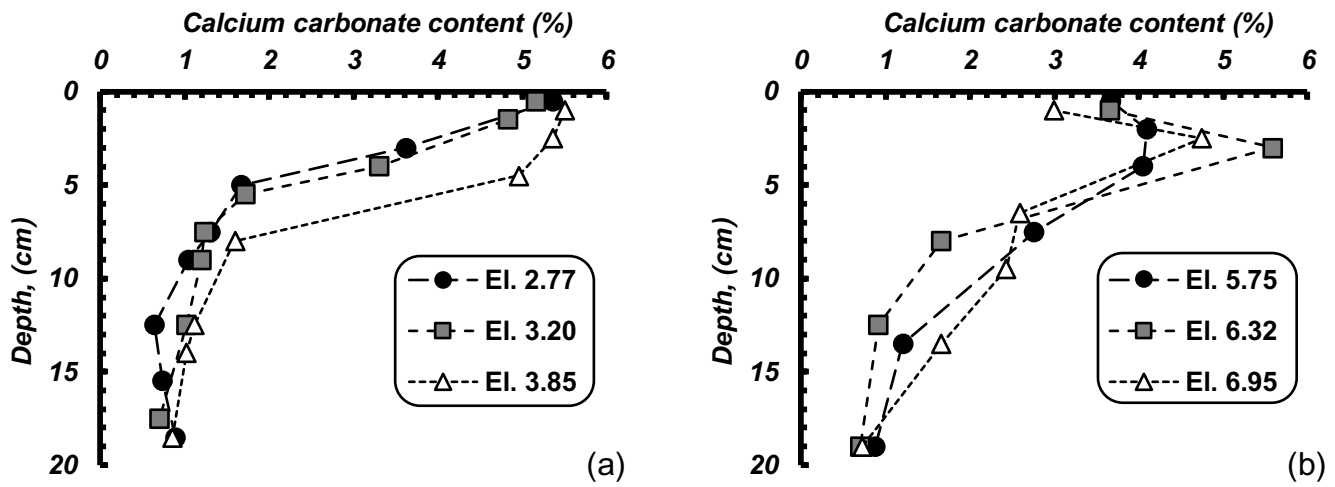


**Figure 8. Initial penetration depth with surficial mass of precipitation for different locations treated with a) spray method, b) PVD method and c) trenches method.**

### Precipitation Pattern

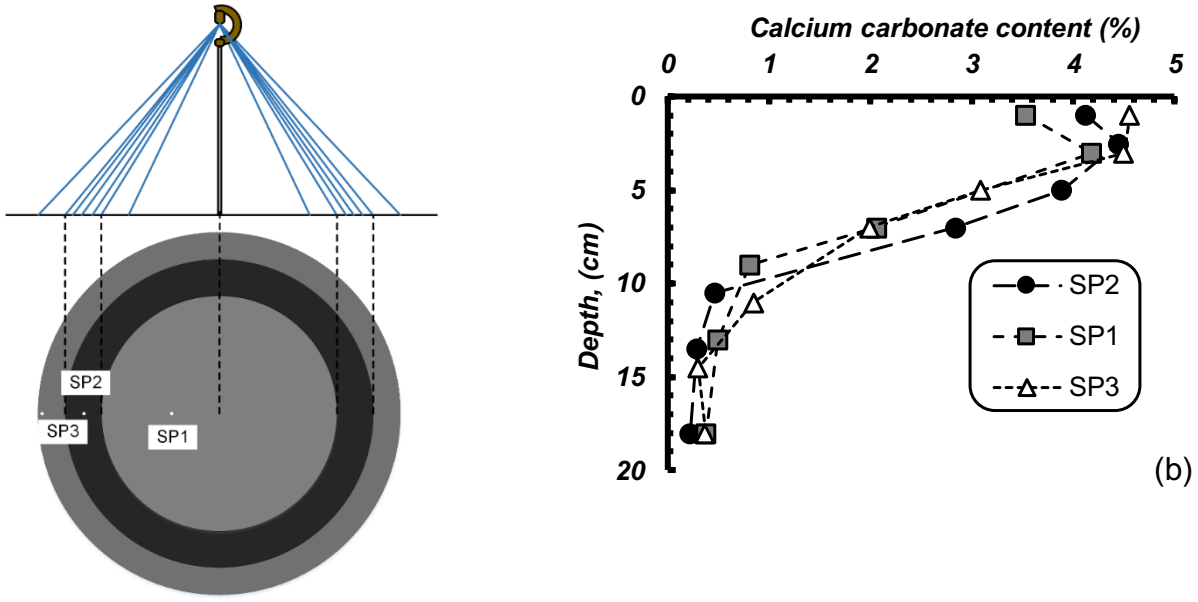
Mass of precipitation measurements with depth were completed on all test plots in different locations to evaluate cementation pattern along the slope surface and around treatment source. Fig. 9 presents results for six points that were located in approximately equal distances from the center of sprayers. For points on the lower half of the slope surface (Fig. 9(a)), the maximum precipitation values were achieved on the surface and were followed by a sudden decrease in values with depth increase [Fig. 9(a)]. Conversely, at higher elevations, precipitation became more distributed along the depth and the location of maximum precipitation shifted towards the deeper depths [Fig. 9(b)]. Such observations corroborate with the results of percolation tests performed prior to the MICP-treatment on the untreated slope that indicated downhill of slope had lower hydraulic conductivity compared to the top of the slope (Ghasemi and Montoya 2020). A lower hydraulic conductivity and smaller pore size may have resulted in higher concentration of cementation on the in point of treatment application (Mahawish et al. 2018; Rowshanbakht et al. 2016). A reduction in pore size and formation of cementation on the surface tends to hinder further development of precipitation in deeper depths by consuming the majority of required nutrients and chemicals for crystal formation (Cheng and Cord-Ruwisch 2014; Van Paassen et al. 2009). A slightly smaller precipitation contents with depth observed in bottom half of the slope where the hydraulic

conductivity is lower is in line with the results of previous studies on varying relative densities having different pore sizes (Mahawish et al. 2018; Rowshanbakht et al. 2016).



**Figure 9. Precipitation with depth for spray method plot. A) lower half and b) top half of the slope**

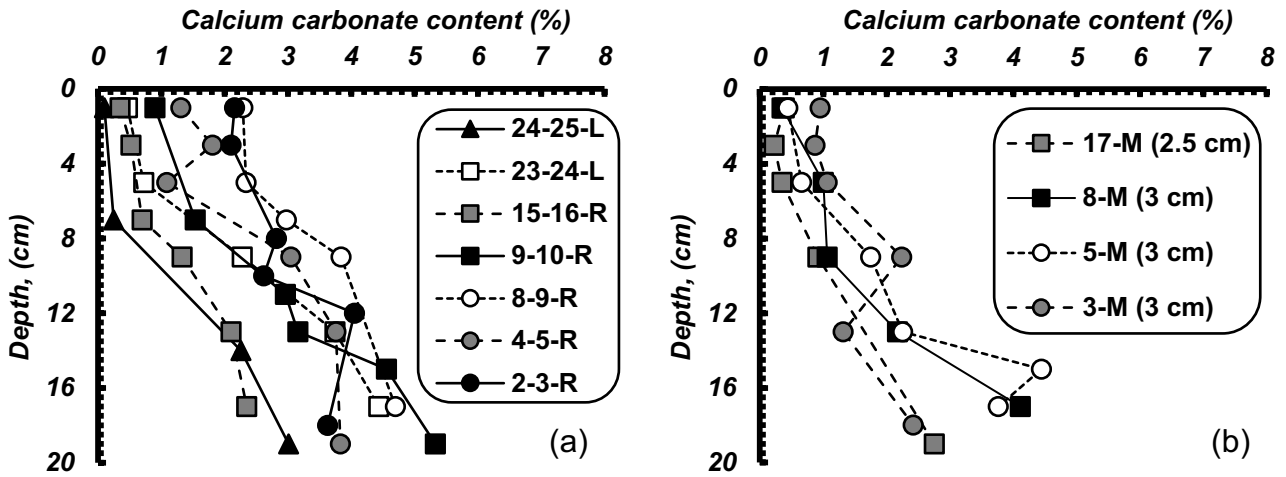
Precipitation pattern around a single sprayer was assessed by selecting the third sprayer from the top that was less effected by the runoff. Discrete mass of precipitation measurements with depth were performed on three locations (SP1, SP2 and SP3) with varying distances from center of sprayer. These points are in zones suggested by the results of calibration tests as shown in Figs. 10(a and b). Results indicated an approximately 1% higher precipitation for point SP2 located in the black area compared to the points in the grey area for the depth 4-10 cm. This observation is in line with DCP test results that indicated a generally higher improvement for the tests performed in the black area. The higher penetration resistance and mass of precipitation can be attributed to the greater biological and cementation solution volumes received in this region.



**Figure 10. a) Location of the points for mass of precipitation test and b) measured values with depth**

Fig. 11 presents calcium carbonate content with depth for twelve points along PVD test plot. Results for the points located in midpoint of the two successive PVD rows and farther than 4.5 cm distance from the centerline of the PVD test plot (within 3 cm horizontal distance from the edge of PVD) are shown in Fig. 11(a) and 8(b) respectively. In these figures, numbers indicate the closest PVDs to the tested point and “L” or “R” and “M” denote whether the point is in the left/right side PVD sets or is in the middle section. Numbers in parentheses are the horizontal distances from the PVD edges. For example, 2-3-R is a point located between the second and third PVDs belonging to the right set also shown in PVD plot map (Fig. 5(b)). In both Fig 11(a) and 11(b), precipitation pattern demonstrates an opposing trend towards sprayer method results. Calcium carbonate content started with a minimum value on the surface and increased with depth. In this treatment method, solution moves gravitationally through the PVD channels to deeper depths as fluid tends to choose the easiest flow path. Therefore, precipitation formation initiated from the deeper depths and with further treatments cementation progressed up to the soil surface. The lower surficial cementation contents in Fig. 11(b), compared to that of Fig. 11(a) implies that the progress of cementation on the surface is more in front direction of PVDs than in the edge direction. However, with a further progress of cementation treatment radius of successive PVDs grew and merged in deeper depths. Therefore, a minor difference between the cementation contents in deeper depths for different directions was observed.

Comparing the mass of calcium carbonate results for different locations along the slope indicated a generally greater mass of calcium carbonate with depth for downhill compared to the top of the slope. Downhill PVDs received higher solution volumes due to the hydraulic gradient between top and bottom of the slope and tendency of solution to move through the main tube towards the lower heads. Irregularity in this trend in some cases might be attributed to the nonhomogeneous distribution of chemicals/bacteria or local heterogeneity of the slope soil. These two factors may have caused solution to follow preferential flow paths and result in locally higher cementation concentration (Mujah et al. 2017; Van Paassen et al. 2009).



**Figure 11. Precipitation with depth for PVD method. a) points in midpoint of the two successive PVDs and b) Points within 3 cm horizontal distance from the edge of PVDs**

Precipitation pattern with depth around the four groups of PVDs are shown in Fig. 12 (a-d). Calcium carbonate contents follow a relatively similar shape and pattern with depth in each group. Generally, points in the midpoint of the successive PVDs that are located in overlapped areas of the two PVDs demonstrate a higher mass of calcium carbonate. The maximum values are associated with points located between the lower PVDs on the surface (points 2-3-R, 8-9-R and 23-24-L in Figs. 12(a), (b) and (d)). With distance increase in the edge direction, precipitation contents decreased specially in the surficial depths as in PVD method precipitation tends to be initiated from deeper depths and progress up to the soil surface. The minimum calcium carbonate contents are related to the points located close to the PVD test plot centerline (points 2-M and 24-M). However, even in these locations, calcium carbonate contents started to slightly grow in deeper depths.

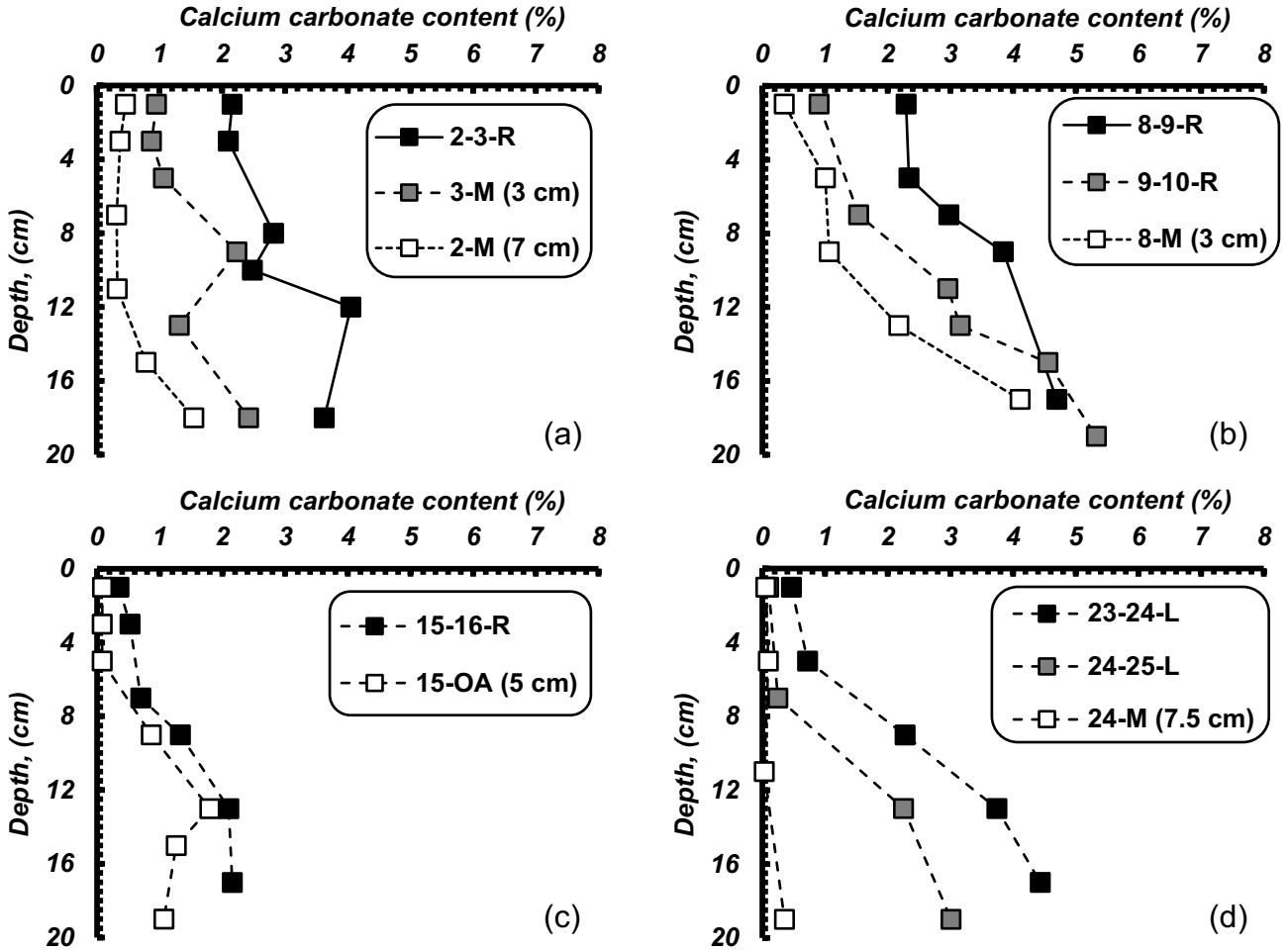
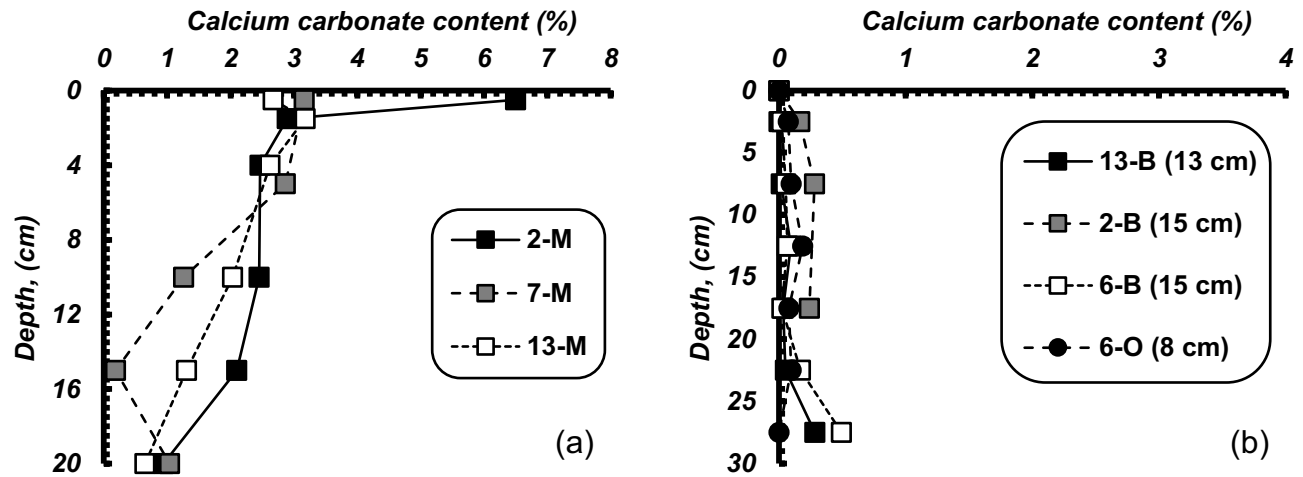


Figure 12. Precipitation pattern around PVDs a) 2 and 3 left, b) 8 and 9, c) 15 and 16 right, and d) 23 and 24 left.

### Trench

Fig. 13(a) and (b) present calcium carbonate contents with depths for points located inside and outside the trenches within a 15 cm distance from the trenches' wall. In Fig. 13(a), numbers indicate the trenches' number and the "M" denote the middle of the trench as shown in Fig. 5(c). In all three points, similar to the spray method and contrary to the PVD results the maximum calcium carbonate is in the surface and decreases with depth. The downhill trench (2-M), demonstrated the maximum surficial calcium carbonate content. Although the downhill soil has a smaller pore size, the greater calcium carbonate content with depth in point 2-M could be the results of a higher bacteria and nutrient volumes received gravitationally. The higher calcium carbonate with depth in point 13-M compared to the point 7-M, could be attributed to the larger pore size and being closer to the solution application location (Trench 16). In Fig. 13(b), number  $i$  represents the closest trench number and the letter 'B' denotes points located on the bump and midpoint of trenches  $i$  and  $i-1$ . The letter 'O' represents a point outside the trench and not in the flow direction. Numbers within the parentheses are indicating the distances from the trenches' wall. A minimal mass of calcium carbonate was detected in all cases (less than 1%). However, in solution flow direction calcium carbonate contents started to slightly grow in depths deeper than 20 cm.



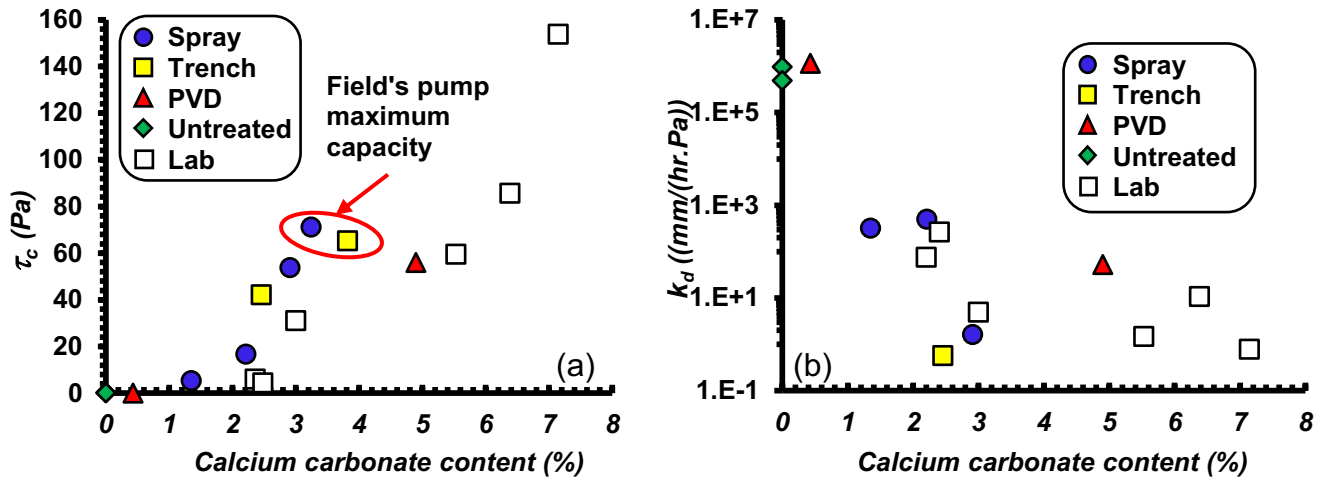
**Figure 13. Precipitation pattern a) In the middle of trenches and b) outside trenches**

#### Erodibility Parameters

Impinging jet tests were performed on untreated soil and on eight locations along the treated slope (shown in Fig. 5) to assess the erosion resistance of the MICP-treated soil. Eq.1 was used to determine the applied shear stress on the soil surface for a given jet velocity. The applied velocity was increased until the scour on the surface was initiated. The jet application time was increased until no more erosion on the surface was observed. The critical shear stress ( $\tau_s$ ) corresponds to the applied stress at which the maximum scour depth occurred. The erodibility coefficient ( $k_d$ ) and the exponent ( $\alpha$ ) were determined using least square curve fitting approach. The erodibility coefficient is a measure of how fast the erosion process takes place. Erosion processes for untreated soil was completed rapidly and within a 30 second. The measured critical shear stress was about maximum of 0.22 Pa for untreated soil and increased up to three orders of magnitude after the MICP-application (Fig. 14(a)). As shown in Fig. 14(b), erodibility coefficient of sand is on the order of  $10^5$  mm/(hr.Pa) and decreased exponentially down to 0.57 mm/(hr.Pa) with increasing cementation levels. These values are in the similar range of erodibility parameters as gravel and rip rap material (Briaud 2013). The exponent ranged from 0.72 to 2.68 for the tested points with no clear correlation between the mass of precipitation with the number of tested points. At lightly cemented levels, a slight improvement of the erodibility parameters is a result of increased surface roughness reported by several researchers (DeJong et al. 2006; Montoya and DeJong 2015). With further progress of cementation and formation of stronger bonds, erodibility parameters significantly improved (Do et al. 2019a; Shafii et al. 2019). Comparing results with the previous studies also exhibit a slightly lower mass of calcium carbonate compared to the tests treated under submerged condition (Amin et al. 2017; Do et al. 2019a; Jiang et al. 2017). A higher soil improvement with similar mass of calcium carbonate in unsaturated treatment compared to saturated soil condition also has been observed by other researchers (Cheng et al. 2013; Shanahan and Montoya 2016). As soil drains, pore solution tends to move towards the smaller pore throats until only exists in the form of water menisci and thin films coating the particles (Lu and Likos



2004). Therefore, concentration of generated cementation in particles contact points results in a more efficient cementation bond between soil grains compared to the saturated treatment where cementation could also be formed in unnecessary and inefficient locations (Cheng et al. 2013).



**Figure 14. Erodibility parameters with mass of precipitation. a) Critical shear stress and b) erodibility coefficient**

#### Pocket Penetrometer Measurements

Surficial soil strength measurements were completed by pocket penetrometer tests on 55 random locations along the test plots. Results then were compared to the UCS measurements from columns prepared in the lab (Fig. 15). No significant difference was observed between the columns treated with tap and pond water and therefore all data points are shown together. For both field and lab tests, shear strength increased with an increase in calcium carbonate content. The maximum field value was about 441.30 kPa and equal to the upper limit of the pocket penetrometer setup measurement. A general agreement between UCS and field pocket penetrometer measurements implies that this setup can be used as a quick measurement tool for unconfined compression strength of MICP-cemented soil. Similar to the initial penetration depth results from DCP tests, points located in PVD plot demonstrated the lowest mass of calcium carbonate precipitation and surficial strength as this method tends to treat soil from the deeper depths. As expected, surface spray and trenches methods exhibited higher mass of precipitation and surficial strength.

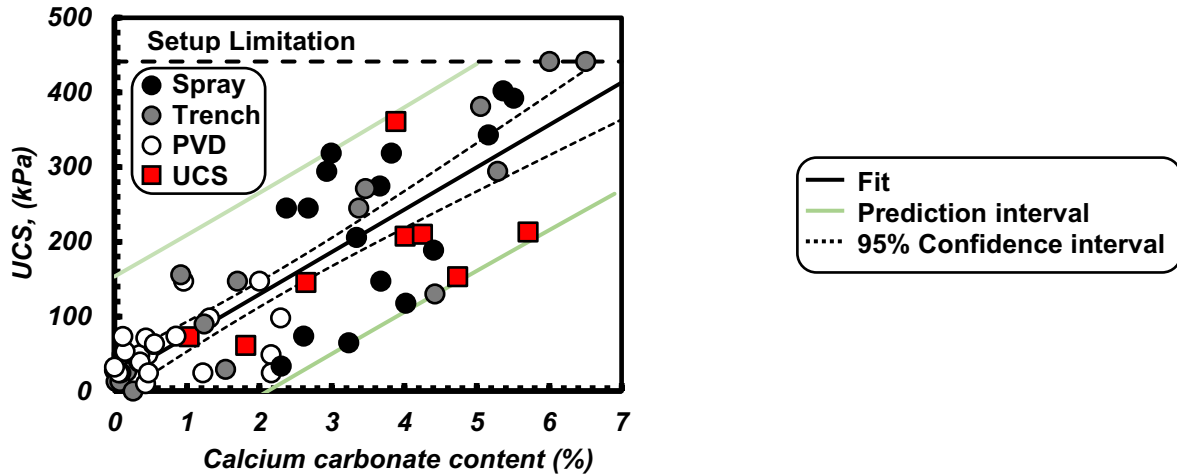


Figure 15. Comparison of UCS values from experimental and field measurements.

### Monitor permanence of the treatment

MICP-treated field plots were monitored overtime to assess the permanence of MICP-improvement or any potential degradations caused by seasonal weather phenomena. DCP tests were performed on all plots at the end of treatments on day 14 and 70, 158 and 331 days after. Tests performed inside the trenches for trenches plot, midpoint of the successive PVDs in PVD plot and in random locations long the slope surface for surface spray plot. During monitoring window, the area received a total precipitation of 738 mm according to North Carolina Climate Office. Field experienced a maximum and minimum temperature of approximately 35 to -8°C. The field was also subjected to the maximum average wind velocity of 6.57 m.s<sup>-1</sup> which is higher than the 5.3 m.s<sup>-1</sup> required velocity to initiate wind erosion of sand dunes (Maleki et al. 2016). The third measurement (158 days after) was performed after hurricane season and when Hurricane Dorian passed the field with a 189 km distance as a category 1 hurricane. The fourth measurement (331 days after) was conducted after the winter season to assess freeze and cold weather effect on cementation durability. During third and fourth measurements, trenches were completely covered with air blown soil. Soils were excavated from the trenches until the crust was exposed and then tests were performed. Measured PIs are located close to the maximum improvement range in left-hand side of the Fig. 16(a-c) and no significant reduction in penetration resistance are observed in any of the test plots. Results indicated that no significant degradation occurred in MICP-treated soil with time and change in environmental conditions such as extreme wind, temperature flocculation, heavy rainfall.

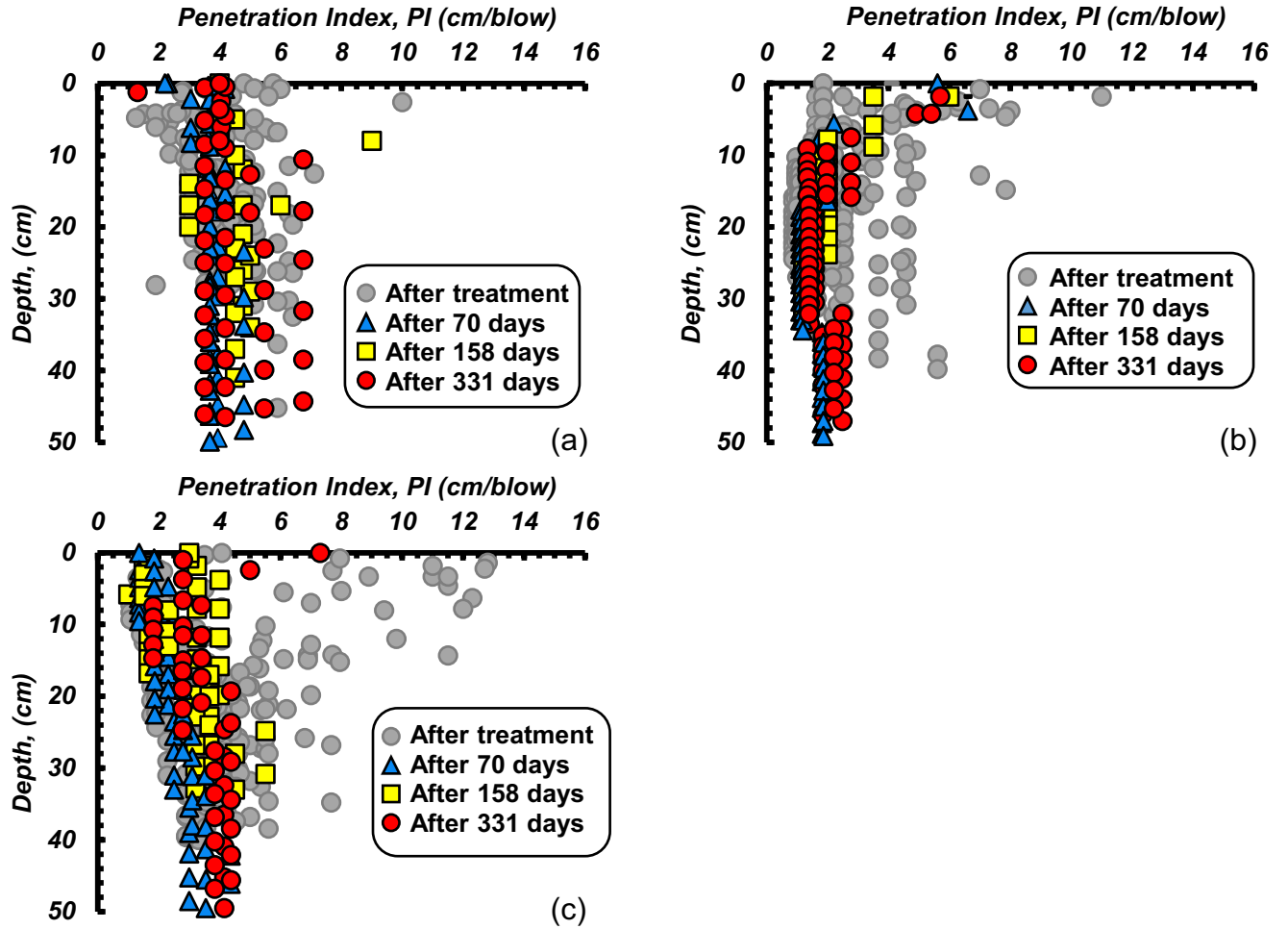


Figure 16. Field monitoring results for a) Surface spray, b) PVDs and c) Trenches method.

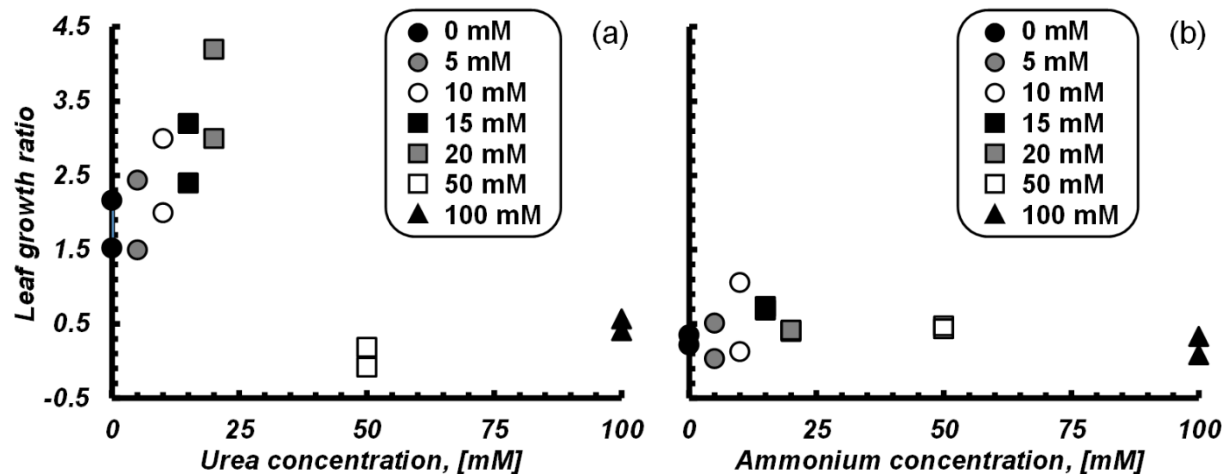
### Assess ability of vegetation to rebound after treatment

During the field work described above, Bermuda grass was observed to grow at the site. To assess the ability of vegetation to grow after the MICP treatments, sand from the field site was taken back to the laboratory and a suite of MICP treatments were conducted on the sand with established, healthy Bermuda grass.

Summary of the results of the plant batches treated with different chemicals and concentrations are shown in Table 3. Compared to ammonium, lower urea concentrations resulted in dryness of plants. In addition, adverse effects of excessive urea and  $\text{CaCl}_2$  were perceived by plants more rapidly compared to the ammonium solution. Maximum above ground leaf growth rate for the batches treated with ammonium and urea are shown in Fig. 17. In both batches with an increase in chemical concentration, growth rate followed an up and down trend. This means despite higher concentrations, treatment with lower concentration solutions (less than 25 mM urea and less than 20 mM ammonium) promoted plants growth. Such observation is more pronounced in urea treated specimens.

**Table 9. Summary of the effect of solution chemistry**

Batch	Chemicals	Tested Concentrations [mM]	Observations
1	Urea	5, 10, 15, 20, 50, 100	<ul style="list-style-type: none"> <li>5 to 20 mM: no visual changes in plants was observed. New seedlings were germinated. pH started from 5 and reached 7 at the end of 14<sup>th</sup> treatment.</li> <li>50 and 100 mM: after 5<sup>th</sup> treatment, grass leaves exhibited signs of stress. By the end of 14<sup>th</sup> treatment, all smaller and weaker seedlings were dead. Stronger leaves turned yellow and showed tip dryness. Effluent pH started from 5 and increased to 7 after 2<sup>nd</sup> treatment and reached about 9 at the end of 14<sup>th</sup> treatments.</li> </ul>
2	NH <sub>4</sub> Cl	5, 10, 15, 20, 50, 100	<ul style="list-style-type: none"> <li>5 to 20 mM: No visual changes was observed in specimens. pH ranged from 5 to 6.</li> <li>New seedlings grew in plants treated with 5 to 50 mM solutions.</li> <li>50 and 100 mM: Effluent pH ranged between 5 to 6.5 with no significant changes. After 12<sup>th</sup> treatment, plants that were treated with 100 Mm exhibited tip dryness and the ones that were treated with 50 mM solution turned slightly yellow with no signs of dryness.</li> </ul>
3	CaCl <sub>2</sub>	100	<ul style="list-style-type: none"> <li>Effluent pH was about 5 after all treatments. Plants started to dry after 5<sup>th</sup> treatment. At the end of 14<sup>th</sup> treatment, only strong and healthy seedlings survived. New seedlings started to grow in one of the cups</li> </ul>
4	Na <sub>2</sub> HPO <sub>4</sub>	0.295, 0.59	<ul style="list-style-type: none"> <li>After all treatments, effluent pH was about 5. No stress signs were observed in plants at the end of treatments.</li> </ul>
5	urea, CaCl <sub>2</sub> Na <sub>2</sub> HPO <sub>4</sub>	300 100 0.59	<ul style="list-style-type: none"> <li>Plants started to dry after the 4<sup>th</sup> treatment and completely died after the 10<sup>th</sup> treatment.</li> <li>Rinsing with water three hours after the treatment application, slightly delayed and reduced the dryness of plants. Plants turned yellow at the end of 6<sup>th</sup> treatment. By the end of treatment 14<sup>th</sup>, stronger plants survived.</li> </ul>



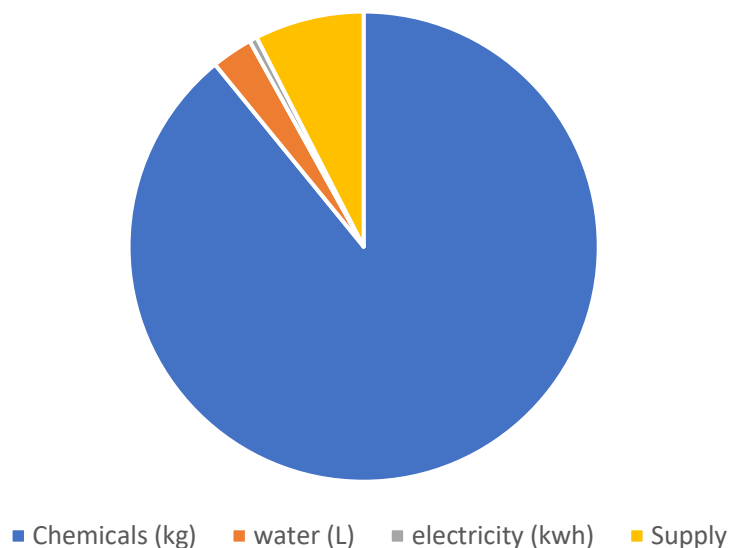
**Fig. 17. Above ground leaf growth rate for plants treated with varying concentrations of a) urea and b) ammonium.**

In addition to evaluating the effect of MICP on established Bermuda grass, the effect of MICP cementation on the ability for seeds to germinate and grow was also evaluated. Seeds in untreated and lightly cemented specimens began to germinate after two days. In moderately and heavily cemented soils, germination started later in days 5 and 8, respectively. By the end of day 19, a full surface coverage of healthy plants was observed in untreated, lightly, and moderately cemented specimens. On the contrary, only few seedlings grew in heavily cemented specimens. Untreated and lightly cemented specimens exhibited the longest root length. In moderately cemented soil, roots penetrated slightly into the cemented soil. However, in heavily cemented specimens, roots only grow in the surficial 4 mm untreated soil and did not penetrate into the underlying stiffer soil. These observations are in agreement with the results of studies on soils with different penetration resistances (Whitmore and Whalley 2009). Soil strength significantly effects the stress applied by the roots to penetrate into the soil (Bengough et al. 2011). Increase in soil strength mainly constrain the ability of plant root growth and results in shorter root length (Tracy et al. 2011). If the pores and fractures in the soil are not large enough higher pressure is needed for the root to rearrange and push the particles aside (Bengough et al. 2011). With the progress of cementation, particle bonds becomes stronger and more calcium carbonate precipitates on the soil particles (DeJong et al. 2010). Resulted increase in strength and density of soil in heavily cemented levels makes it is harder for roots to penetrate further into the soil.

### **Cost assessment and comparison to traditional methods**

A preliminary cost assessment was made based on the treatment methods deployed in the field site in Ahoskie, NC. Based on the costs from the project field deployment, and extrapolated to an acre, preliminary cost are presented herein. As demonstrated in Fig. 18, the vast majority of the cost with the field application of MICP is associated with the chemicals needed to grow the bacteria and induce cementation. The cost associated with bio-augmentation (i.e., growing bacteria to inject into the soil and then induce cementation), when extrapolated to an acre and to achieve a heavy level of cementation, are predicted to range from \$62,000 - \$118,000, depending on price/quality of the yeast extract used to grow the bacteria. Outside the scope of the current study, but relevant

for field application is the use of bio-stimulation (e.g., enriching the indigenous bacteria to induce cementation). By removing the cost associated with growing the bacteria in the laboratory the cost reduce to approximately \$29,000 - \$32,000 per acre. Once again, these prices are predicted based off from extrapolating small-scale purchases of urea and calcium chloride to induce the cementation; it is likely that addition savings from the manufacturer could be made with larger purchases.



**Fig. 18. Example breakdown of costs associated with MICP field application. Example shown above associated with the surface spraying method.**

The Department currently uses biotic soil media (BSM) and compost blanket seeding as a treatment to encourage vegetation and in turn reduce surface erosion. It is important to note that while these treatments are used to reduce surficial erosion they do not modify the soil in a similar way that MICP does (e.g., do not increase shear strength or stiffness). The costs for BSM and compost blanket seeding are approximately \$6,150 and \$8,000 per acre, respectively (personal communication with Mr. Jeremy Goodwin, NCDOT Steering Committee). These costs are about 4 – 5 times lower than the approximate costs for bio-stimulated MICP. However, there are a few additional benefits that MICP treatments provide, namely that there is a substantial increase in shear strength and stiffness of the soil, which may be necessary for slope stability concerns, and that the field monitoring of the application indicated the treatment has a long life (e.g., reapplication not necessary, as reseeding may be with the other methods). Additionally, ongoing work indicates that MICP is quite resilient as an erosion mitigation method for sand experiencing wave action (Fig. 19) (Montoya et al. 2021), which means that MICP may be more suitable within coastal rights-of-ways where other erosion mitigation methods are not sufficient.





**Figure 19. Bio-cemented dune during wave testing in the Large Wave Flume (right) adjacent to the untreated dune experiencing significant erosion (left) (Montoya et al. 2021)**

## Findings and Conclusions

An experimental program was performed to investigate the effect of MICP treatment solutions with varying ratios of urea to calcium chloride on unconfined compressive strength (UCS) and erodibility parameters of two types of soil. All specimens were treated up to the target shear wave velocity of about 1100-1300 m/sec. Different numbers of treatments were required to reach the target shear wave velocity using varying treatment concentrations, and the results of the UCS indicated that different types of soil treated with the same treatment solution can show different stress-strain behavior depending on the grain size distribution of the particles. In addition, higher calcium carbonate can lead to higher shear strength of the specimen. All specimens displayed significant improvement in erodibility parameters. Improvement of the erodibility parameters and strength of the specimens revealed that in addition to the mass of calcium carbonate, the chemical concentration used for MICP treatment can be effective in the level of improvement.

MICP was successfully implemented in the field as a soil improvement method for shallow depths. Treatment was applied to a coastal sandy slope through three solution delivery systems known as surface spray method, use of PVDs, and shallow trenches. Mechanical soil improvement achieved with the use of lower grade chemicals and performing treatment under inclement weather condition. Pond water was used as a source of water for solution preparation during the treatment and its compatibility with MICP process was verified using UCS tests prior to the field experiment.

Dynamic cone penetration (DCP) tests were performed to have an assessment of soil improvement along the soil profile. All test plots exhibited a significant penetration resistance improvement either in depth or surface. The level of improvement followed the overall trend of the precipitation pattern. Impinging jet tests, pocket penetrometer, and initial penetration depth measurements were completed to evaluate the surficial soil improvements and erodibility resistance. Surficial strength and erodibility parameters significantly improved with increase in mass of calcium carbonate. A higher erosion resistance compared to the values reported in literature for saturated soil treatment is the results of the unsaturated MICP-treatment and a more efficient cementation bond. Strength values measured with pocket penetrometer was also shown to be consistent with laboratory unconfined compression tests with varying cementation levels.

The surface spray method created a wider treated zone with the maximum soil improvement on the surface. Implying that the method can be used as an easy and effective method for surficial improvement applications such as sand dune protection, dust control, erosion and scour mitigation, etc. The PVD method is capable of providing a deeper treated zone from surface to the depths of interest. The maximum improvements in the deeper depths suggested that this method is better suited for deep soil applications such as slope stability. The application of MICP with PVDs method can be a cost-effective technique in large-scale projects to create a large number of cemented columns in depth. Trenches method improved both surficial and deeper soil properties, however, in a more localized manner.

The permanence of the stabilized soil was confirmed with monitoring the treated soil with time and after extreme environmental conditions. Monitoring the field indicated that severe weather conditions such as freeze and thaw, heavy rainfall, and a hurricane had no significant adverse effect on the strength of MICP-treated soil.

Bermuda grass was evaluated to assess its ability to rebound after MICP treatments. The grass was treated separately with ingredients and byproducts of MICP-solution to assess the compatibility of the chemicals with plants. Compared to ammonium, urea and  $\text{CaCl}_2$  effected plant health in earlier stages of treatment. Lower urea and ammonium concentrations promoted plants health and growth, however in 50 mM concentrations or higher, younger seedlings did not survive. Results indicated that regular MICP-treatment concentrations are higher than tolerance range of plants. It is recommended to apply treatment solutions with concentrations lower than 50 mM and on fully grown plants. Addition of phosphate to cementation solution and also rinsing specimens three hours after the treatment slightly alleviated the adverse effects of chemicals on plants. In addition, applied concentrations of phosphate exerted no changes in formed morphology of precipitated calcite. Seed germination and growth of Bermuda grass was assessed through specimens treated to different levels of cementation. After 19 days, seeds planted in untreated, lightly cemented and moderately cemented soils indicated similar seedling growth and coverage. Conversely, sparse seedlings grew in heavily cemented sand. This indicates that up to a certain level of cementation, both MICP soil improvement and plant growth can coexist.

## **Recommendations**

Bio-cementation is recommended for use with roadways in sandy material with a shallow slope (i.e., 3:1 horizontal:vertical) due to the erodibility and stability of the material. The MICP



treatment process increases the strength (e.g., strength parameters  $\phi'$  and  $c'$ ) and reduces erodibility (e.g.,  $\tau_c$ ) of sandy soil, which can provide a more competent material that may support a 2:1 slope, thus reducing the right-of-way extent. The recommended treatment recipe is the 3:1 recipe described in Table 2, which provides a quicker cementation process and larger reduction in erosion compared to other recipes tested in the project. The recommended treatment implementation approach is the surface spraying method, based on the field implementation results and conversations with the Steering Committee.

## **Implementation and Technology Transfer Plan**

The research product developed in this project is the recipe and implementation methods to induce MICP on a coastal sandy deposit to reduce erosion and increase shear strength. The research product will improve the resiliency of sandy slopes and subgrades by preventing erosion-induced damage. Sandy slopes may be designed at a steeper slope, thus reducing the extent of required right-of-way by the Department. In addition, coastal highways susceptible to erosion during storm events may experience less damage after a storm event, increasing the ability of the communities to recover quickly. The repair and maintenance costs will also decrease due to improved performance of these highways.

The research product is anticipated to be used in two different manners: 1) implemented by the State Maintenance Operations, in conjunction with Division Engineers (namely Divisions 1, 2, and 3 for coastal deposits), during repair and reconstruction of coastal slopes and roads; and 2) integrated into the design of new construction by the State Geotechnical Engineer. The MICP-treatment process can be demonstrated to the Steering Committee, along with the necessary resources to purchase the required supplies and chemicals. Guidance on evaluating the resulting bio-cementation levels using tools such as the DCP will also be provided based on the results presented herein.

Training on field implementation of MICP can be conducted by the NCSU research team to the appropriate groups within NCDOT. The cultivating and mixing of ingredients, and demonstration of the spraying process can be presented in a workshop for groups interested in implementing the treatment process in the field. Utilizing the improved MICP properties in a design process can also be covered in a workshop and/or manual for groups within NCDOT interested in the design process.

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