

Bio-mediated soil improvement utilized to strengthen coastal deposits

Amélioration du sol biologiquement négociée utilisée pour renforcer les dépôts côtiers

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ABSTRACT - Vital coastal lifelines can be vulnerable during large storm events. Large wave action and high sea levels erode the sandy soil that supports coastal infrastructure, including highways, structures, pipelines, and other utilities. Damage from these events can result in severe property damage, loss of revenue, and large repair costs. Natural bio-geochemical methods can be used to reinforce the erodible sandy soil to help prevent damage to the infrastructure. Utilizing naturally-occurring biological metabolic activity, calcium carbonate cementation can be induced *in situ* to bind the sand grains together, thereby improving the strength and stiffness of the soil and in turn preventing erosion of the coastal deposits. Microbial induced carbonate precipitation (MICP) has been shown to be an effective method to improve the soil behavior in saturated conditions subjected to undrained monotonic and seismic loading in both laboratory and centrifuge tests. Applying this proven natural treatment technique to unsaturated coastal soils can improve the soil's resiliency during large storm events. Results indicate that the strength of the unsaturated soils increase from intermittent surficial treatments. Rigid-walled soil column tests were conducted to evaluate the effectiveness of treating sandy soils by flooding the surface of the soil with the appropriate microbes and nutrients and allowing free drainage. Clean fine sand, typical of coastal dune deposits, was used in the soil column tests. The strength of the cemented sand was evaluated using unconfined compression tests. A discussion of upscaling the results from the laboratory tests to application *in situ* to improve the resiliency of coastal infrastructure is also presented herein.

1. INTRODUCTION

Vital coastal lifelines can be vulnerable during large storm events. Large wave action and high sea levels erode the sandy soil that supports coastal infrastructure, including highways, structures, pipelines, and other utilities. Damage from these events can result in severe property damage, loss of revenue, and large repair costs. The outer banks of North Carolina have seen several hurricanes in recent years (Irene in 2011, and Sandy in 2012) which have inflicted damage to vital coastal lifelines as illustrated in Figures 1 and 2.

Natural bio-geochemical methods can be used to reinforce the erodible sandy soil to help prevent damage to the infrastructure. Utilizing naturally-occurring biological metabolic activity, calcium carbonate cementation can be induced *in situ* to bind the sand grains together, thereby improving the strength and stiffness of the soil and in turn preventing erosion of the coastal deposits. Microbial induced carbonate precipitation (MICP) has been shown to be an effective method to improve the soil behavior in saturated conditions subjected to undrained monotonic and seismic loading in both laboratory and centrifuge tests (Montoya et al., 2013, Mortensen and DeJong, 2011, DeJong et al., 2006). Applying this proven natural treatment technique to unsaturated coastal soils can improve the soil's resiliency during large storm events. Results indicate that the strength of the unsaturated soils significantly increase from intermittent surficial treatments. Rigid-walled soil column tests were conducted to evaluate the effectiveness of treating sandy soils by flooding the surface of the soil with the appropriate microbes and nutrients and allowing free drainage. Clean fine sand, typical of coastal dune deposits, was used in the soil column tests. Changes in the strength of the sand from the unsaturated cementation treatments was evaluated using unconfined compression tests. A discussion of upscaling the results from the laboratory tests to application *in situ* to improve the resiliency of coastal infrastructure is also presented herein.



Figure 1. A section of Highway 12 at the edge of Rodanthe, N.C. undermined by erosion due to the storm surge and wave action during Hurricane Irene. (Photo: News & Observer, Aug. 31, 2011)



Figure 2. High ocean waves from Hurricane Sandy lap against Highway 12 and erode the underlying sand. (Photo: News & Observer, Nov. 14, 2012)

2. MATERIALS AND METHODS

2.1. Sand and Specimen Preparation

Four soil column specimens were prepared by dry pluviation to a target relative density of 40%. The soil column specimens had a 50.8 mm (2 in) diameter and an aspect ratio of 2:1. Ottawa 50-70 sand was used for the initial cementation trials, because of the published results with the sand (DeJong et al., 2006, Mortensen and DeJong, 2011, Montoya et al., 2013, Martinez et al., 2013). A summary of the sand characteristics is listed in Table I.

Table I. Ottawa 50-70 Sand characteristics

	Ottawa 50-70 Sand Characteristics
D ₅₀ (mm)	0.22
C _u	1.4
C _c	0.9
G _{max}	2.65
e _{min}	0.55
e _{max}	0.87
Mineralogy	Quartz
Shape	Round

2.2. Biological Treatment Process

Sporosarcina pasteurii (ATCC 11859), a urea hydrolyzing bacterium, was grown at 30 °C in an Ammonium-Yeast Extract medium (ATCC 1376: 0.13 mol l⁻¹ Tris buffer (pH=9.0), 10 g l⁻¹ (NH₄)₂SO₄, and 20 g l⁻¹ yeast extract). Individual ingredients were autoclaved separately and mixed together post-sterilization. The growth medium was inoculated with the *S. pasteurii* stock culture and incubated aerobically at 30 °C in a shaking water bath (200 rpm) for approximately 40 hrs before harvesting at a final optical density (OD₆₀₀) of 0.8-1.0. Cultures were centrifuged at 4000 g for 10 min in 15 mL volumes and washed in fresh growth medium. Harvested bacteria were stored in the centrifuge vials at 4 °C for a maximum of 2 days.

Urea-calcium cementation media was used to induce ureolytic-driven calcite precipitation. A summary of the components and concentrations are presented in Table II.

Table II. Chemical recipe for cementation media

Chemical	Chemical Concentration (M)
Urea	1.0
CaCl ₂	0.25

Cementation treatments were performed by flooding the top surface of the soil column, and allowing the cementation media to freely drain through the sand (Figure 3). Bacteria were introduced into the soil during the initial cementation flush. Calcium chloride was not included in the initial treatment with the bacteria to prevent precipitation during inoculation. Cementation treatments were repeated every 3 to 6 hours. Two pore volumes of nutrients were used in each treatment flush (concentrations of nutrients presented in Table II). The cementation treatments were repeated for a total of 40 times.

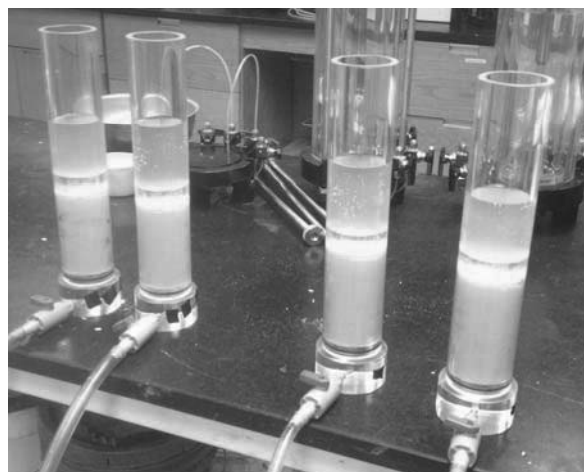


Figure 3. Initial biological flush through soil columns. Cementation flushes allowed to free drain through pluviated soil.

2.3. Specimen Shearing

After cementation was completed, the specimen was flushed with water to remove residual chemicals from the cementation treatments. The cemented sand was removed from the soil columns. The cemented soil columns were then subjected to unconfined compression tests until failure. A GeoJac automated load actuator was used to perform the unconfined compression test.

2.4 Mass of Calcium Carbonate Measurements

The mass of calcium carbonate was determined post-test using methods outlined in ASTM D4373, *Standard Test Method for Rapid Determination of Carbonate Content in Soils*. At the end of the cementation treatments, oven dried cemented sands are dissolved in hydrochloric acid and the resulting pressure generated from the dissolution of calcium carbonate is measured. The generated pressure is equated to an equivalent mass of calcium carbonate. The percentage of mass of calcium carbonate is expressed as the mass of calcium carbonate divided by the mass of soil (not including calcium carbonate).

3. RESULTS

3.1 Calcium Carbonate Content in Soil Columns

Mass of calcium carbonate was taken in the top and bottom of the cemented soil column, which are reported in Table III. As indicated in Table III, the mass of calcite in the four soil columns is relatively small compared to published results from other MICP treatment studies (Weil et al., 2011). However, the cementation within the soil column was extremely uniform, as indicated by the mass of calcium carbonate of the top and bottom samples (Table III).

Table III. Summary of Mass of Calcium Carbonate

Soil Column	Mass of CaCO ₃ (%)
1 (top)	0.082
1 (bottom)	0.081
2 (top)	0.102
2 (bottom)	0.103
3 (top)	0.070
3 (bottom)	0.068
4 (top)	0.070
4 (bottom)	0.068

3.2 Cemented Sand Compressive Strength

Unconfined compression tests were performed on the cemented soil columns (Figure 4 and Figure 5). As mentioned, the mass of precipitated calcium carbonate is relatively small compared to published results from other MICP treatment studies; however even at low mass of calcium carbonate levels, unconfined compression tests were able to be performed on the cemented sand columns. A summary of the compression test results are listed in Table IV.

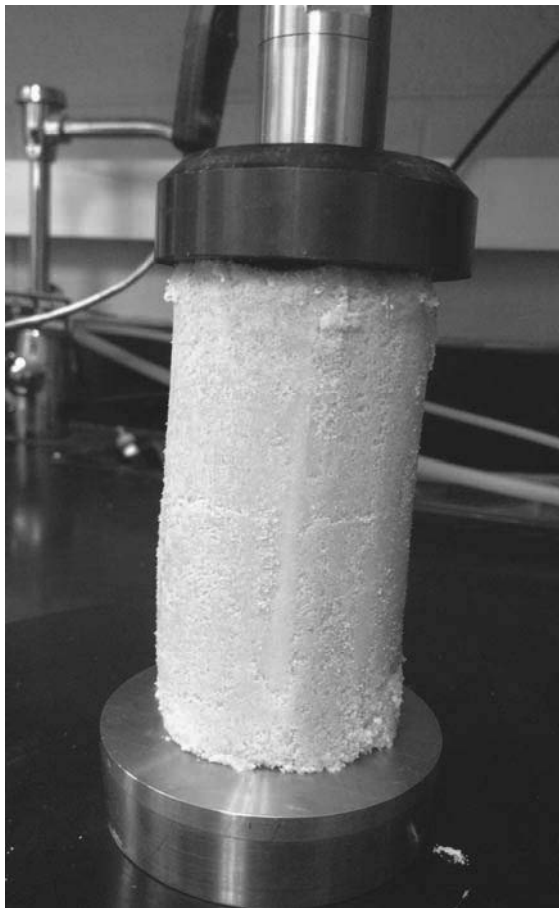


Figure 4. Cemented soil column mid-test during the unconfined compression test.



Figure 5. Failed cemented soil column at the end of the unconfined compression test.

Table IV. Summary of Compressive Strength

Soil Column	Unconfined Compressive Strength (kPa)
1	5.2
4	5.4

As indicated in Table IV, unconfined compression tests were performed on only two of the four columns. Two of the soil columns were not able to be tested because they were disturbed during extraction from the soil column walls. The cemented soils were especially vulnerable because of the low levels of cementation. To rectify the tendency for disturbance, the soil in the remaining columns was extracted from the soil column walls by creating vertical slices through the acrylic walls and allowing the soil to be removed through the sliced opening.

The unconfined compressive strength of the cemented sand columns was about 5 kPa. Other studies found that MICP treated Ottawa 50-70 sand could get compressive strengths of about 170 to 350 kPa at higher levels of cementation (Faison and Mahin, 2012).

The angle of the failure plane in soil columns 1 and 4 was about 63 degrees from the horizontal. This failure plane angle is representative of soil with a friction angle of 36 degrees. Untreated Ottawa 50-70 sand has a friction angle of about 33 degrees (Montoya, 2012). Based on previous work, MICP treated sand with a friction angle of 36 degrees is typical of sand treated to a shear wave velocity of 400 m/s (Montoya, 2012). An approximate shear wave velocity of 400 m/s corresponds to the strength data, indicating the cemented soil columns represent lightly cemented sand.

For use as a treatment process for coastal sand deposits, an appropriate level of MICP cementation should be used. A high enough level of cementation should be used to resist induced shear loads from waves and storm surges, and a low enough level of cementation so that native wildlife, such as birds, burrowing animals, and dune grass, can still interact with the coastal deposits. Further work will include upscaling the

treatment process using a wave tank to identify optimum ranges of cementation for treatment of coastal deposits.

4. CONCLUSIONS

MICP can be used to reinforce sandy coastal deposits to improve the resiliency of vital lifelines during large storm events. Soil columns of clean fine sand were treated with MICP, and resulted in lightly cemented sand. The lightly cemented sand had an increase in strength, as demonstrated with the unconfined compression tests, and increase in friction angle. The free-draining treatment process was designed to be similar to likely treatment processes of unsaturated surficial sands in situ. This treatment process provided uniform levels of cementation throughout the height of the soil column. The light levels of cementation achieved in the soil columns provide an increase in shear strength while still allowing for birds, burrowing animals, and dune grass to interact with the coastal deposits. Future work involves investigating the optimal range of MICP cementation to provide enough strength to resist the loads from large storm events while continuing to support the coastal ecology.

5. REFERENCES

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