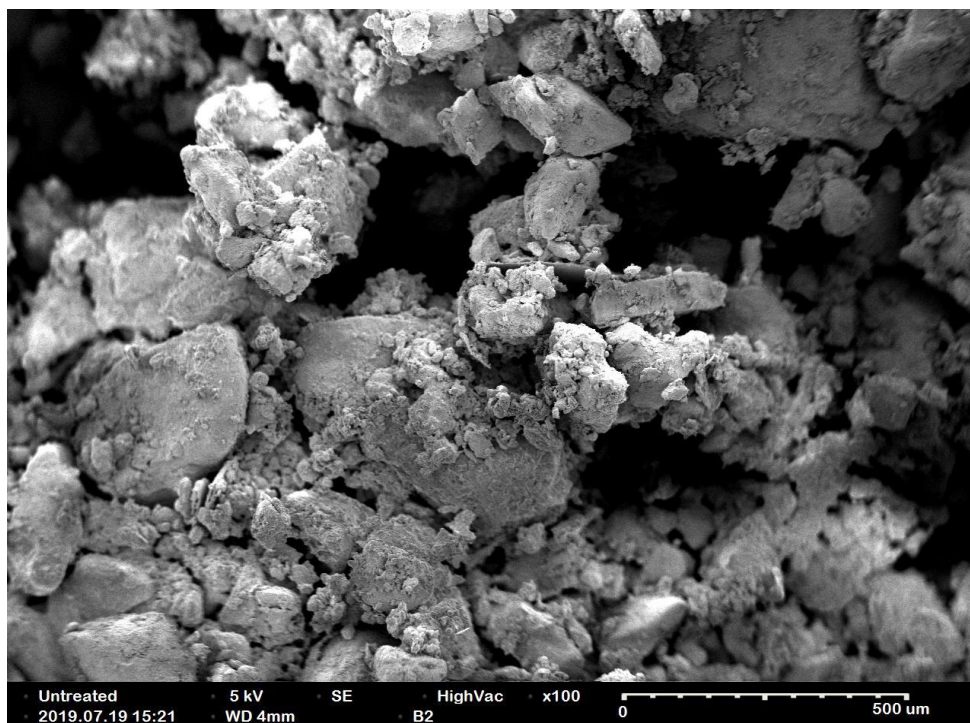


# RECLAMATION

*Managing Water in the West*

## **Application of Enzyme Induced Carbonate Precipitation (EICP) for Channel Lining and Repair, Low Volume Road Stabilization, Embankment Construction, and Erosion Control**

**Research and Development Office  
Science and Technology Program  
(Final Report) ST-2019-1840-01**



**U.S. Department of the Interior  
Bureau of Reclamation  
Research and Development Office**

**October 2019**



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carbonate may bind the soil particles together, fill pore spaces, and increase the roughness of the soil particles, resulting in an increase in the shear strength, stiffness, and dilatancy characteristics of the soil. In this study, laboratory tests were conducted to evaluate the feasibility of EICP for: (i) bulk stabilization of the soil; and (ii) surficial stabilization for fugitive dust control. Results demonstrated a potential for use of EICP as a mitigation method for fugitive dust. The use of EICP for bulk stabilization will require further investigation as soil samples exhibited carbonate precipitation, but no significant cementation.

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## **Research and Development Office Science and Technology Program**

**Facilities Engineering Group, Yuma Area Office, YAO-2110**

**(Final Report) ST-2019-1840-01**

## **Application of Enzyme Induced Carbonate Precipitation (EICP) for Channel Lining and Repair, Low Volume Road Stabilization, Embankment Construction, and Erosion Control**

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Prepared by: Angel Gutierrez, Ph.D., P.E.  
Civil Engineer, Facilities Engineering Group, Yuma Area Office

---

Checked by: John Fleming, Ph.D.  
Hydrologist, Water Systems Engineering Group, Yuma Area Office

---

Technical Approval: Samuel Garcia, P.E.  
Supervisory Civil Engineer, Facilities Engineering Group, Yuma Area Office

---

Peer Review: Carrie Scott, P.E., P.M.P.  
Chief, Technical Support Office, Yuma Area Office

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# Acronyms and Abbreviations

ASU	Arizona State University
BOR	Bureau of Reclamation
CBBG	Center for Bio-Mediated and Bio-Inspired Geotechnics
EICP	Enzyme-Induced Carbonate Precipitation
IC	Ion Chromatography
NASA	National Aeronautics and Space Administration
ppm	parts per million
RO	Reverse Osmosis
SEM	Scanning Electron Microscope
TDV	Threshold Detachment Velocity
USCS	Unified Soil Classification System

# Executive Summary

Erosion, caused by either water or wind, continues to be a concern in the engineering community. An increase in water demand throughout the Southwest United States has seen higher flows travel through embankment canals that were originally built in the early 1900's. These higher flows increase erosion potential along canal banks that cannot be easily repaired or would require complete concrete lining of the system. Fluvial erosion is not the only cause for concern within arid and semi-arid regions. Aeolian processes tend to be a larger concern due to the dry, cohesionless soils found in these areas. These already dry areas are further deteriorating due to the ongoing drought in the Southwest United States which has caused receding water bodies to expose dry playas that are easily eroded by wind. In addition to soil loss, the airborne soil particles are a source of health concerns for people living in these areas. The purpose of this project was to evaluate the use of Enzyme Induced Carbonate Precipitation (EICP) to stabilize soils to reduce water and wind erosion potential. Two methods were studied (i) mass stabilization for canal lining and other engineering applications and (ii) surficial stabilization for mitigating wind erosion. The tests were conducted on soils obtained in the vicinity of Yuma, Arizona. The EICP-treated samples for mass stabilization all exhibited calcium carbonate precipitation but did not exhibit significant cementation. Further investigation is required to identify the mechanisms that inhibit the efficacy of the EICP treatment in these soils. For surficial stabilization of the soils, wind tunnel and penetration tests showed that the specimens treated with a carbonate spray had a crust strength and wind erosion resistance greater than that of dry soil. Comparison between the wind erosion resistance of EICP-treated soils and the soils treated by application of water was not possible due to the limitations of the wind tunnel: in both cases, the maximum wind tunnel velocity was attained without significant erosion. However, even if the wind resistance of the soil treated with water is equal to that of the EICP-treated soil, the enhanced wind resistance of the carbonate crust in the EICP-treated soil is expected to be more durable than enhanced wind resistance due to application of water.



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# Introduction

EICP is an exciting new method for soil improvement that has seen significant development in the industry recently. It can be used for a variety of civil engineering applications, as stated in Hamdan (2015). Two different applications were studied as part of this project: mass stabilization and surficial stabilization. Each method will be further introduced in subsequent sections of the report.

## Mass Stabilization

A series of laboratory tests were conducted by the Center for Bio-mediated and Bio-inspired Geotechnics (CBBG) at Arizona State University (ASU) for an initial feasibility assessment of biogeotechnical stabilization via EICP of soils. The soils were provided by the U.S. Bureau of Reclamation (BOR) from sites in the vicinity of Yuma, Arizona. EICP is a soil stabilization method in which an aqueous solution comprised of urea, calcium chloride, and urease enzyme is applied to the soil. The urease catalyzes hydrolysis of the urea, creating carbonate ions ( $\text{CO}_3^{2-}$ ) in solution and increases the pH and alkalinity of the solution. At supersaturation, the  $\text{Ca}^{2+}$  ions (from the calcium chloride) and  $\text{CO}_3^{2-}$  ions combine to precipitate as calcium carbonate. The precipitated calcium carbonate may bind the soil particles together, fill pore spaces, and increase the roughness of the soil particles, resulting in an increase in the shear strength, stiffness, and dilatancy characteristics of the soil. In this study, laboratory tests were conducted to evaluate the feasibility of EICP for bulk stabilization of the soil. Bulk stabilization column tests to assess the ability of EICP to enhance the shear strength of the test soils were completed.

## Materials and Methods

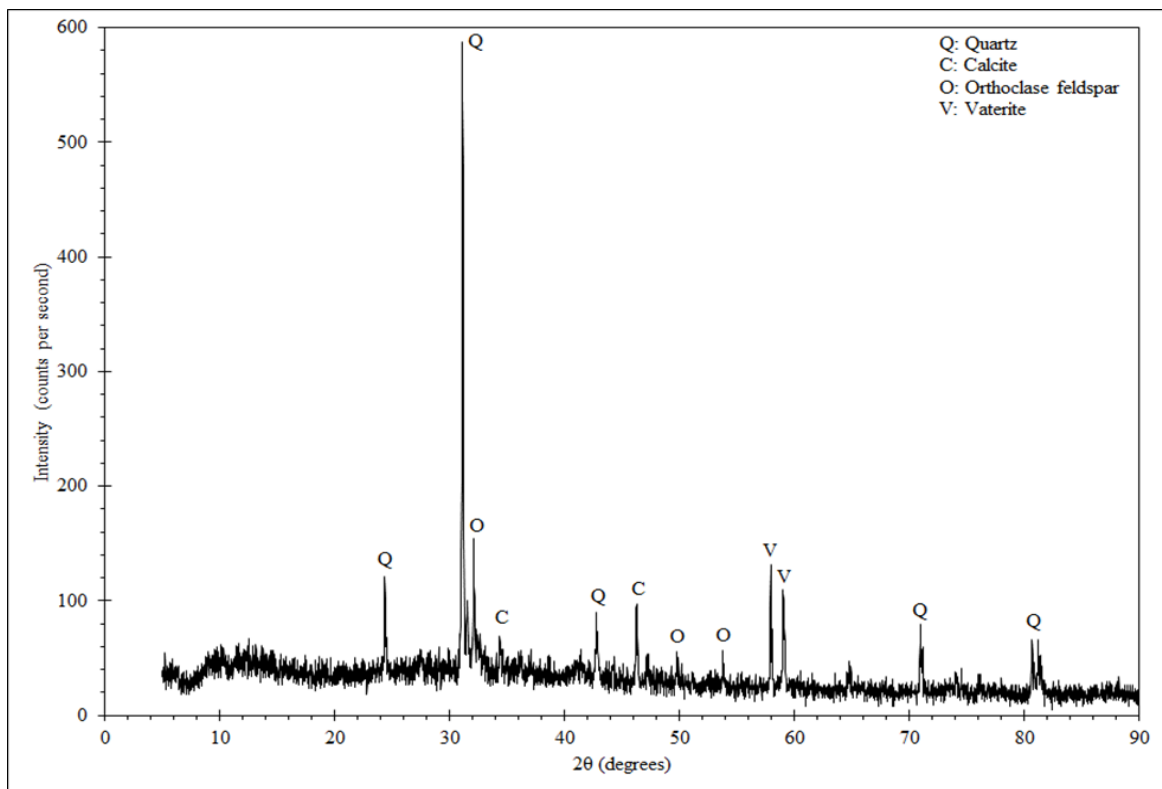
### Soil Samples

EICP bulk stabilization tests were conducted on six samples, designated Sample No. 1, 4, 5, 7, 11, and 12, of sand and silty sand obtained from various locations in the Yuma area. Samples 2, 3, 6, 8, 9, and 10 were not tested for bulk stabilization because of excessive fines content. The sampling locations, fines content, and Atterberg limits of the samples are reported in Table 1. Fines content and Atterberg limit tests were conducted in general accordance with the relevant ASTM standards. Based upon the fines content and Atterberg limits of the samples, Sample No.7 was classified as a clean sand (poorly graded, or SP, based upon visual observation) in the Unified Soil Classification System (USCS). Samples 4, 5, and 11 were dual classified poorly graded silty sand, SP-SM in the USCS. Samples 1 and 12 are silty sands, classified as SM in the USCS. The fines in Samples 4,5, 7, and 11 were non-plastic while the fines in Samples 1 and 12 were classified as low plasticity silt in the USCS. The mineralogy of Samples 5 and 7 was characterized by X-ray diffractometry. The diffractograms, shown in Figures 1 and 2, indicated the presence of quartz, calcite, vaterite, and orthoclase feldspar in the specimens.

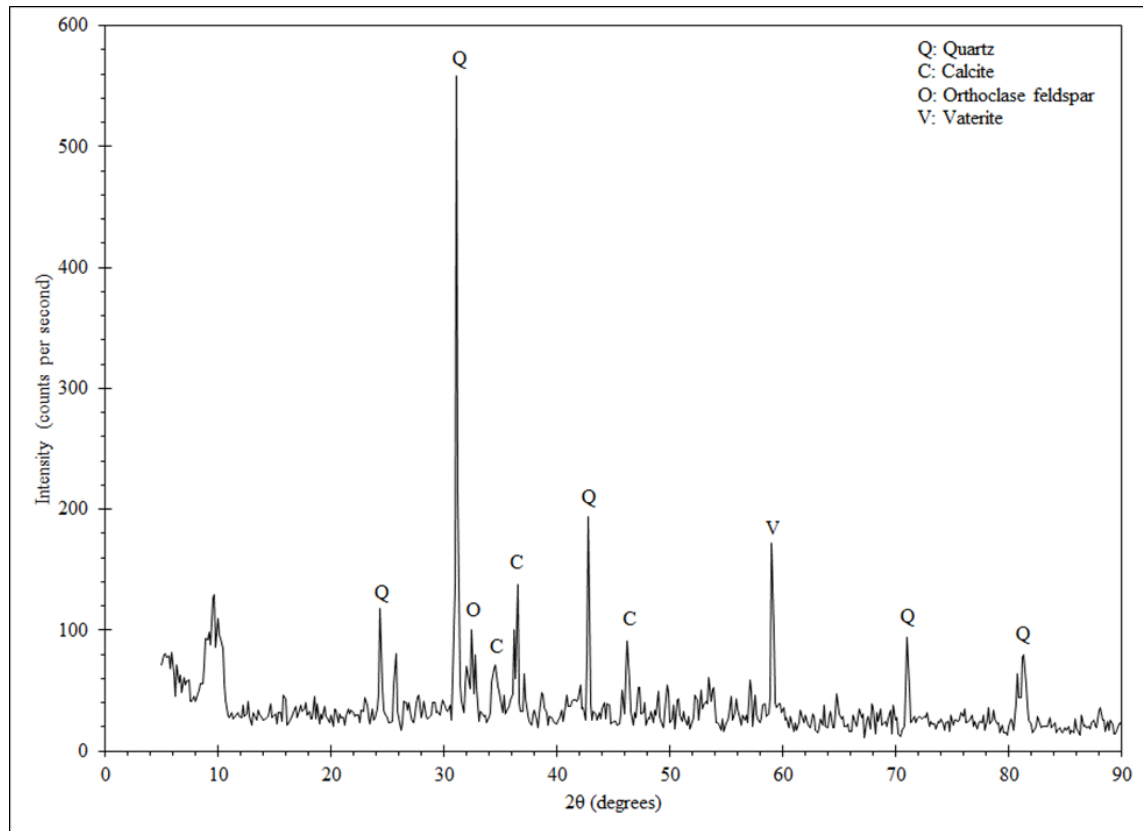
**Table 1. Sampling locations and fines content of soil used for EICP stabilization experiments.**

Sample No.	Location/Description	Percent passing No. 200 sieve	Atterberg limits
1	Yuma County Water User's – West Main Canal	42%	LL=23%, PI = 11%
4	Unit B – Dirt Road	10%	Nonplastic (NP)
5	Yuma Mesa – Dirt Road	8.4%	Nonplastic (NP)
7	All-American Canal	2.6%	Nonplastic (NP)
11	Seepage area near discharge point	5.4%	Nonplastic (NP)
12	Seepage area near beaver dam	15%	LL = 18%, PI = 7%

LL: liquid limit; PI: plasticity index



**Figure 1. X-ray diffractogram of fine fraction (passing No. 200 sieve) of Sample 5. The X-rays were generated from a cobalt (Co) source ( $K\alpha = 1.79026 \text{ \AA}$ ).**



**Figure 2. X-ray diffractogram of fine fraction (passing No. 200 sieve) of Sample 7. The X-rays were generated from a cobalt (Co) source ( $K\alpha = 1.79026 \text{ \AA}$ ).**

### Experimental Setup for Bulk Stabilization

In the EICP bulk stabilization tests, samples were treated in 50 mm ( $\approx 2$ -in.) diameter acrylic tubes to form columnar specimens. The bottom of the tube was closed with a plastic cap and sealed with an adhesive. A polypropylene liner was placed inside the acrylic tubes to facilitate the extraction and testing of the treated specimens. Approximately 150 g of soil was added to each acrylic tube to create a specimen of approximately 45 mm in height. Following placement of soil within the tube, the EICP treatment solution was prepared and mechanically mixed with the soil inside the tube. Approximately one pore volume of treatment solution was added during each treatment cycle. The first cycle of treatment was performed by mixing the treatment solution with the soil using a spatula followed by light tamping of the soil-treatment solution mixture.

When additional cycles of treatment were applied to the specimen, a small cut was made in the cap at the bottom of the acrylic tube and the treatment solution from the previous cycle was allowed to drain. After the free liquid in the column drained, the drainage orifice was sealed with an adhesive and approximately one pore volume of treatment solution was slowly added to the top of the specimen and allowed to gradually percolate into the soil. After adding the treatment

solution, the top of the acrylic tube was closed with a cap to minimize evaporation. Additional EICP tests were conducted on samples 5 and 7 after: (i) washing the sample with tap water through the No. 200 sieve (75  $\mu\text{m}$  openings) and over-drying the retained fraction; and (ii) washing the sample using deionized water through a “coffee- filter” sieve ( $\approx 20 \mu\text{m}$  openings) and air-drying the retained fraction. Additional EICP tests were also conducted on sample 4 after pretreating the soil with a base in order to modify the surface charge characteristics of the soil. One pore volume of a pretreatment solution comprising of 0.5 M calcium hydroxide was added to the soil and was allowed to cure for a period of 48 h. At the end of the curing period, the pretreatment solution was drained and the EICP treatment solution was added.

Figure 3 shows the typical setup of soil columns treated via EICP. Table 2 presents a summary of the EICP testing performed for this study, including the number of treatment cycles, any special treatment conditions, and the percentage of calcium carbonate in the soil before and after treatment.



**Figure 3. Typical setup of soil columns treated via EICP.**

**Table 2. Summary of EICP treatment of soil columns and measured calcium carbonate content.**

Sample No.	Specimen No.	Treatment Description	CaCO <sub>3</sub> % of Untreated Soil	CaCO <sub>3</sub> % of Treated Soil	Difference
1	1-1	2 treatment cycles	1.1%	4.5%	3.4%
4	4-1	2 treatment cycles	2.1%	3.3%	1.2%
4	4-2	Pretreated with 0.5 M Ca(OH) <sub>2</sub> , 1 treatment cycle	2.1%	4.7%	2.6%
4	4-3	Washed through No. 200 sieve followed by pretreatment with 0.5 M Ca(OH) <sub>2</sub> , 1 treatment cycle	2.1%	4.0%	1.9%
5	5-1	3 treatment cycles	1.1%	2.9%	1.8%
5	5-2	Washed through No. 200 sieve, 2 treatment cycles	1.1%	5.0%	3.9%
5	5-3	Washed through "coffee filter" sieve, 2 treatment cycles	1.1%	5.6%	4.5%
7	7-1	3 treatment cycles	0.9%	4.0%	3.1%
7	7-2	Washed through No. 200 sieve, 2 treatment cycles	0.9%	3.3%	2.4%
11	11-1	2 treatment cycles	1.9%	4.3%	2.4%
12	12-1	2 treatment cycles	2.7%	3.9%	1.2%

## **EICP Treatment**

The EICP treatment solution used for the bulk stabilization of soil columns was composed of

1.0 M urea, 0.67 M calcium chloride dihydrate, 3 g/L urease enzyme (manufactured by Fisher Scientific, urease activity  $\approx 4200$  U/g), and 4 g/L non-fat dry milk. The amount of urease enzyme added to the treatment solution is reported in enzyme units (U); the catalytic activity of 1 U can liberate 1.0  $\mu\text{mol}$  of ammonia (or ammonium ions) from urea per minute at pH of 7.0 and temperature of 25°C. Thus, the concentration of urease in the EICP treatment solution is  $\approx 12,600$  U/L. The treatment solution also includes non-fat dry milk, which is an organic additive that has been reported to act as an enzyme stabilizer (Nemati and Voordouw, 2003) and has been found to have a significant influence in soil strengthening using EICP treatment (Almajed et al., 2019). Between 1 and 3 cycles of this EICP treatment solution were applied to each soil specimen. The specimens were allowed to cure for 48 h at room temperature during each treatment cycle.

## Summary of Testing

The EICP-treated soil specimens were extruded from the columns and visually inspected for cementation. In addition, a sub-sample of the treated soil was retrieved from each specimen for measurement of calcium carbonate content. The carbonate content specimens were washed (to remove soluble salts), oven-dried, and then digested using hydrochloric acid. The digested specimens were washed and oven-dried again. The reduction in the mass of oven-dried specimens after acid digestion was used to calculate the percentage of calcium carbonate by weight of the test specimen. The calcium carbonate content of the untreated soil was also measured using the same procedure.

## Results and Discussion

None of the EICP-treated soil columns exhibited significant cementation, including the samples subjected to multiple cycles of treatment. However, a strong odor of ammonia was detected in all the treated soil columns, implying that urea was hydrolyzed by the urease (the first step in the biocementation process) and measurable amounts of calcium carbonate were precipitated in each treated sample. Table 2 presents the measured calcium carbonate content of the treated and untreated soil samples. The calcium carbonate content in the specimens taken from the treated soil columns ranged, on a dry weight basis, from 1.2% to 4.5% more than the calcium carbonate of specimens recovered from the corresponding untreated samples. These values are consistent with the theoretical maximum calcium carbonate content based on the volume of EICP solution added is estimated as  $\approx 1.3\%$  per cycle of treatment. Measured values greater than the theoretical maximum may be attributed to non-uniformity in the initial carbonate content in the recovered samples, non-uniform carbonate precipitation in the columnar specimens, and the small size of the carbonate content test specimens, which amplifies small errors in the soil mass measurements when evaluating carbonate content.

The absence of cementation in the treated specimens is contrary to previous experience of CBBG with bulk stabilization of soils, wherein even soils that did not cement in one cycle of treatment cemented after one or two additional cycles of treatment. However, Whiffin et al. (2007) found that a threshold value of 3.5% carbonate precipitation by weight was necessary to develop measurable cementation in soils when treated with microbial carbonate precipitation in which the hydrolysis of urea was catalyzed by ureolytic microbes. Therefore, it is possible that cementation could be achieved with additional cycles of treatment. It is also possible that trace elements in the soil, e.g., copper, which is known to be toxic to some enzymes, and small amounts of other



constituents, e.g., sulfate, are interfering with binding of the carbonate to the soil particles. Further testing would be required to determine the reason(s) for the absence of cementation in the test specimens.

## Conclusion

Laboratory tests were performed to evaluate the feasibility of using EICP for bulk stabilization of soil recovered from sites in the vicinity of Yuma, Arizona. The potential for EICP-based soil stabilization was evaluated by treating columnar soil specimens with 1 to 3 cycles of an EICP cementation solution. The EICP-treated samples all exhibited calcium carbonate precipitation but did not exhibit significant cementation. Further investigation is required to identify the mechanisms by which various soil properties influence the efficacy of the EICP treatment.

## Surficial Stabilization

A series of laboratory tests were conducted by the CBBG at ASU for an initial feasibility assessment of biogeotechnical stabilization via EICP of soils provided by BOR from sites in the vicinity of Yuma, Arizona. EICP is a soil stabilization method in which an aqueous solution comprised of urea, calcium chloride, and urease enzyme is applied to the soil. The urease catalyzes hydrolysis of the urea, creating carbonate ions ( $\text{CO}_3^{2-}$ ) in solution and increasing the pH and alkalinity of the solution. At sufficiently high supersaturation, the  $\text{Ca}^{2+}$  ions (from the calcium chloride) and  $\text{CO}_3^{2-}$  ions combine to precipitate as calcium carbonate. The precipitated calcium carbonate may bind the soil particles together, fill pore spaces, and increase the roughness of the soil particles, resulting in an increase in the shear strength, stiffness, and dilatancy characteristics of the soil. In this study, laboratory tests were conducted to evaluate the feasibility of EICP treatment soil for surficial stabilization to enhance wind erosion resistance of the soil (i.e., fugitive dust mitigation).

## Materials and Methods

### Soil Samples

Surficial stabilization tests were conducted on six samples, designated Sample Numbers 1, 4, 5, 7, 11, and 12, of poorly graded sand and silty sand obtained from various locations in the Yuma, AZ area. These samples are among the samples previously tested to evaluate the potential for bulk stabilization using EICP. The sampling locations, fines content, and Atterberg limits of the samples are reported in Table 1.

### EICP Treatment

The EICP treatment solution used for fugitive dust control was composed of 0.6M urea, 0.4M calcium chloride dihydrate, 1.0 g/L urease powder manufactured by Fisher Scientific, (urease activity  $\approx 4200$  U/g), and 4.0 g/L non-fat dry milk. Three of the treated specimens were treated with  $2.43 \text{ L/m}^2$  of solution while the fourth was treated with an additional 50% solution, i.e.,  $3.66 \text{ L/m}^2$ . The EICP treatment solution was prepared in two separate solutions: a  $\text{CaCl}_2$ -Urea

mixture and a urease-stabilizer mixture. These two mixtures were combined at a 50:50 ratio and mixed for 30 seconds before being sprayed onto the soil surface. The EICP treatment solution was applied in a single pass to each soil specimen. The specimens were cured for at least 48-hours at room temperature before testing.

## **Water Treatment**

The water control specimen was treated with a  $2.43 \text{ L/m}^2$  solution of water purified using reverse osmosis (RO) water. The RO water was sprayed onto the surface and allowed to cure for at least 48-hours at room temperature.

## **Experimental Setup for Erosion Control**

In the EICP fugitive dust wind tunnel erosion control tests, specimens for treatment and testing were prepared in 22.8 cm (9-in.) diameter by 3.81 cm (1.5-in) deep commercial baking cake pans. The interiors of the cake pans were coated with spray paint to inhibit rust from developing in the specimen container. A spacer was placed in the bottom of the pan to reduce the amount of soil needed for each specimen. Either a Styrofoam inset with thickness of 0.75" or a metal disk with thickness of 1.27 cm (0.5-in) was used for this purpose. The specimens were prepared as follows:

- the pan was filled halfway with soil;
- the edge of the pan was lightly tapped 15 times around the circumference;
- additional soil was added to overfill the pan;
- the pan was once again tapped around the edges 15 times;
- the excess soil in the pan was leveled off so the sample surface was flush with the top of the pan.

Soil, at its natural moisture content, was placed in the pans prior to treatment. Following placement within the pan, the treatment solution was prepared and sprayed onto the surface of the soil. For the specimens prepared using  $2.43 \text{ L/m}^2$  of treatment solution, the volume of treatment solution was enough to fill one pore volume over approximately the top 0.45 cm of the specimen. For the one specimen prepared using  $3.66 \text{ L/m}^2$  of treatment solution, the treatment solution volume was enough to fill approximately the top 0.68 cm of the specimen. The as-prepared total density of each specimen after treatment is reported in Table 3.

**Table 3. Specimen Preparation Details.**

<b>Sample No.</b>	<b>Specimen No.</b>	<b>Treatment Description</b>	<b>Moist Density (kN/m<sup>3</sup>)</b>
1	1-1	1 treatment (2.43 L/m <sup>2</sup> )	19.01
4, 5, 7, 11	2-1	1 treatment (2.43 L/m <sup>2</sup> )	11.95
4, 5, 7, 11	2-2	1 treatment (3.66 L/m <sup>2</sup> )	11.99
4, 5, 7, 11	2-3	Dry control	12.67
4, 5, 7, 11	2-4	Water control (2.43 L/m <sup>2</sup> RO water)	21.74
12	3-1	1 treatment (2.43 L/m <sup>2</sup> )	15.30

Each pan was treated by spraying the treatment solution as uniformly as possible onto the surface and allowing it to cure for at least 48 hours. Six specimens were prepared in this manner, including four treated pans and two control pans. One of the control specimens was treated with a water solution and allowed to cure before being tested and the other control specimen was untreated.

Four specimens, including the two control specimens, were composite specimens prepared by mixing together equal amounts of soil from samples numbered 4, 5, 7, and 11. The other two treated specimens were sourced from individual sample bags: one from bag number 1 and one from bag number 12.

After curing, the specimens were wind tunnel tested, penetration tested, the crust thickness was measured, and crust calcium carbonate contents were evaluated. Resistance to wind erosion was evaluated in the ASU NASA Planetary Wind Tunnel. This wind tunnel is designed to produce laminar flow for measurement of the threshold detachment velocity (TDV) of the specimen. TDV is defined as the wind speed at which the soil is continuously detached from the surface and entrained in air. The wind tunnel has a maximum safe operating velocity of 24 m/s (54 mph). Figure 4 shows the placement of the specimen into the wind tunnel with the surface flush with the bed of the wind tunnel and the pan secured with tape.



**Figure 4. Specimen 2-3 (dry control) set into the floor of the wind tunnel and taped to secure during testing.**

The wind tunnel testing procedure was as follows:

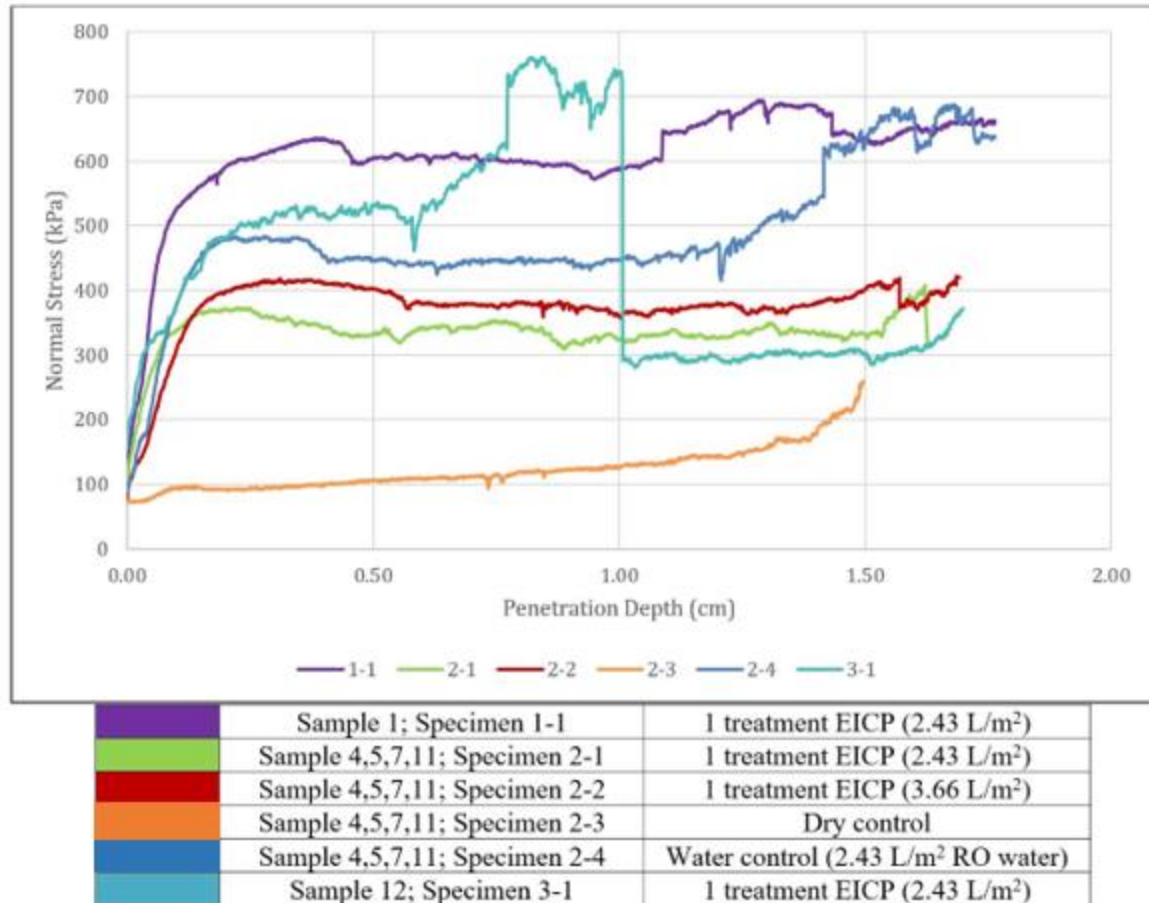
- record the mass of the specimen and secure it in the wind tunnel;
- starting from the initial wind velocity of approximately  $\sim 2.8$  m/s, steadily increase the wind velocity to 5 m/s over approximately 2 minutes and hold for 1 minute;
- steadily increase the wind velocity over approximately 2 minutes to 10 m/s and hold for 1 minute;
- progressively increase the wind velocity to 5, 20, and 24 m/s, taking approximately 2 minutes for each increment of increased velocity and holding the velocity for 1 minute at each step;
- based on visual monitoring through the backlit wind tunnel window; observe and take notes of particle detachment at each wind speed;
- remove the specimen from the wind tunnel and record its mass.

Each wind tunnel test took about 15 minutes to complete. This test procedure was kept consistent for each run even if TDV was attained before reaching the maximum safe wind tunnel speed of 24 m/s.

Following the completion of the wind tunnel testing, penetration testing was performed on intact portions of the crust. In the penetration tests, a 0.64 cm (0.25-in)-diameter flat-nose cylindrical probe affixed to an unconfined compression machine loading piston was pushed into the specimen at a constant rate of 0.10 cm/min (0.04 in/min) and the normal force exerted on the crust was recorded. This test was performed at three points spread out over the surface and the reported results are the average of the three trials. Figure 5 shows the penetration testing setup and location of the three penetration tests on one of the specimens. Figure 6 shows the averaged penetration versus depth curves for the six specimens that were tested.



**Figure 5. Specimen 2-2 (226 L/m<sup>2</sup> EICP treatment solution) undergoing penetration testing (left) with the spacing between tests (Right).**



**Figure 6. Comparison of EICP treated and untreated specimens crust strength from penetration testing.**

The thickness of the crust of the four EICP-treated specimens and one water-treated specimen were measured using calipers. Sections of the treated specimens were sampled using a spatula to separate the crust from the uncemented layers. Figure 7 shows sections of the crust from an EICP treated specimen.



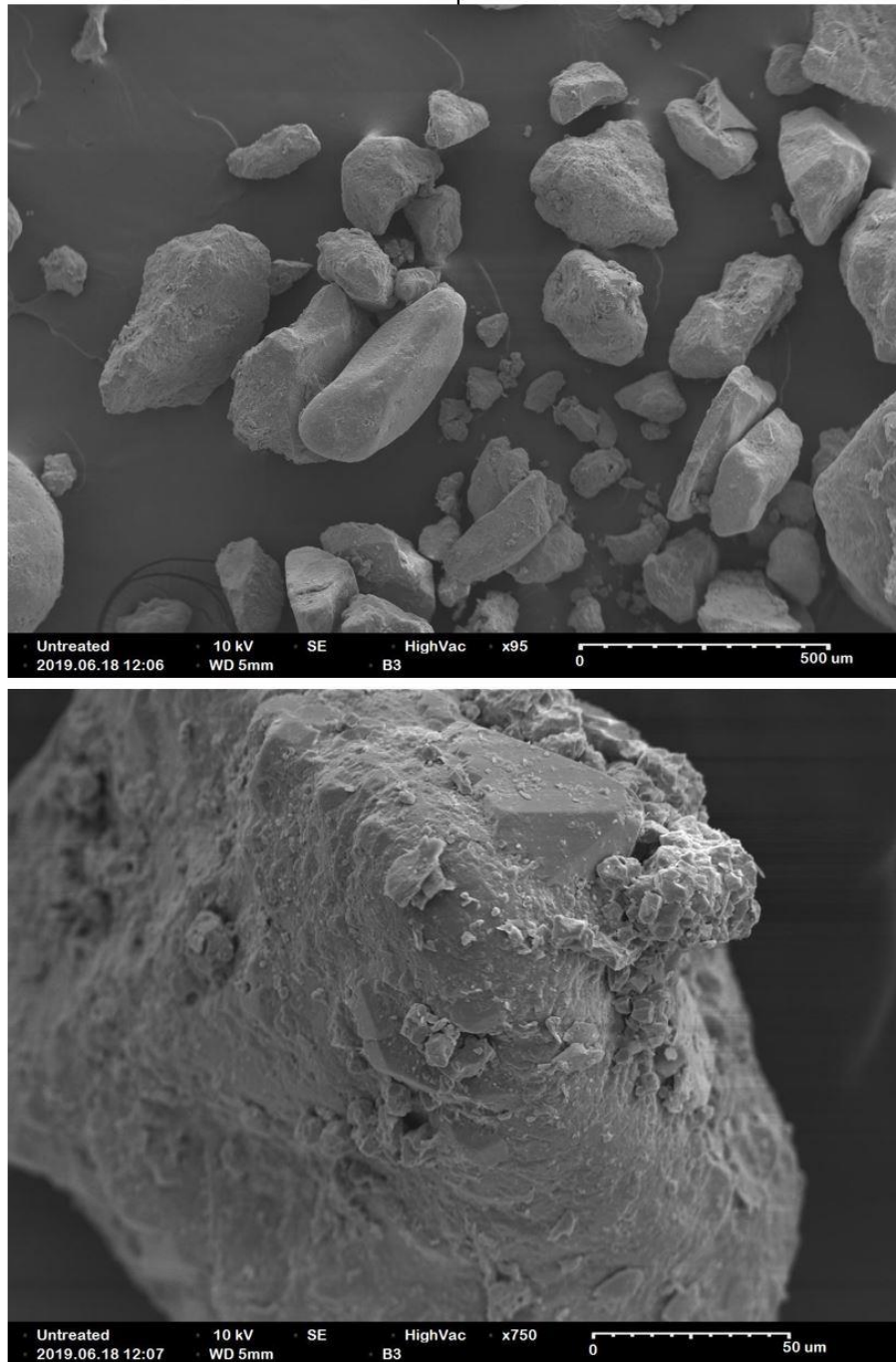
**Figure 7. Crust measurements of specimen 2-1 (Left) and 1-1 (Right).**

Carbonate content was measured with a calcimeter in general accordance with The Standard Test Method for Calcium Carbonate Content in Soils (ASTM D 4373 84). Carbonate content measurements were made on the soil before treatment and on crust specimens recovered after treatment. The carbonate content reported herein for the crust is the average of the values for specimens recovered from the upper and lower regions of crust.

### **Scanning Electron Microscope Imaging**

Scanning Electron Microscope (SEM) imaging was conducted to look for evidence of calcium carbonate precipitation and inter-particle cementation within the crust.

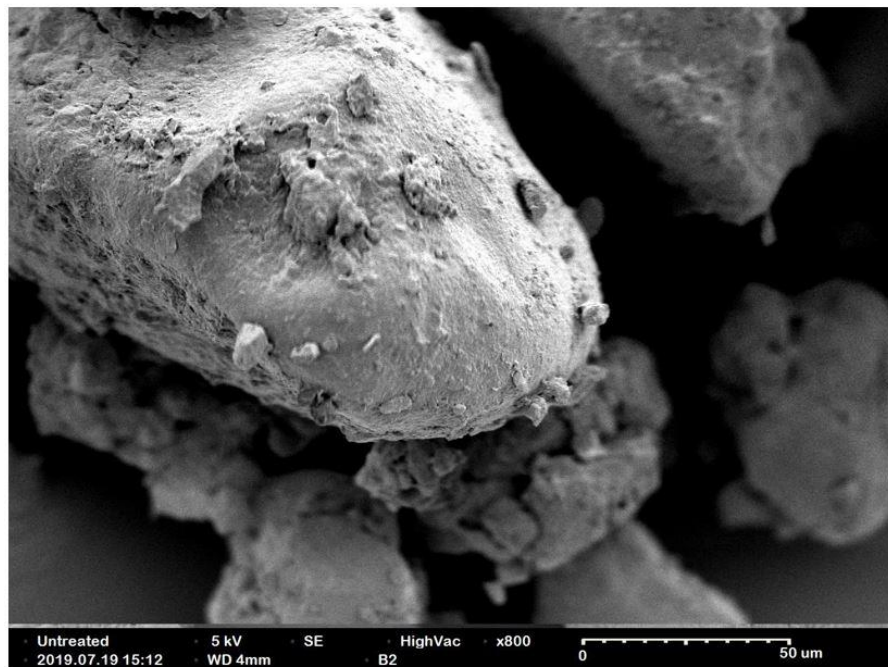
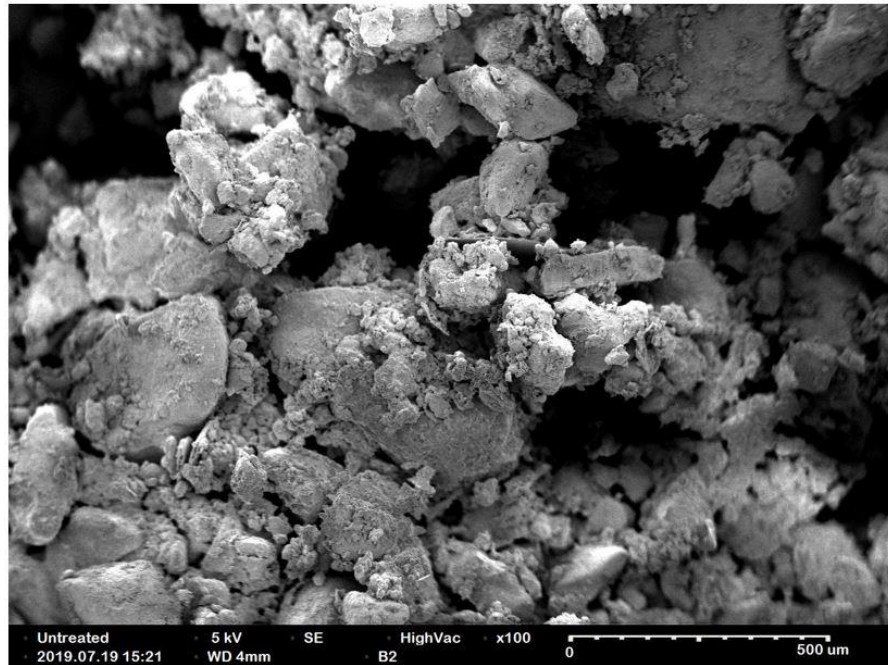




Specimen 2-3

Figure 8. SEM results of untreated soil from specimen 2-3.





Specimen 2-1

Figure 9. SEM results of treated soil from specimen 2-1.

## **Ion Chromatography (IC) Analysis**

An IC analysis was run on a specimen of native soil to establish the ionic composition of the soil. Ions the IC analysis was calibrated for included: lithium, ammonium, potassium, magnesium, calcium, fluorine, chlorine, nitrite, bromine, nitrate, sulfate, and phosphate.

The procedure for preparation of specimens for the IC analysis was as follows:

- 10 grams of the specimen were placed into a test vial with 13-mL of RO water;
- after 24 hours of soaking, 1 mL of fluid was extracted from the test vial through a filter and syringe;
- 499 mL of RO water was added to the fluid extracted from the test vial;
- the 500 mL diluted solution was sampled and run through the ion chromatographer.

## **Results and Discussion**

Carbonate content testing indicated that tested soils had a natural carbonate content of 2.6% to 4.8% on a dry weight basis. Visual observation indicated that the minerals and fines already present in the soil formed a weak crust after being treated with RO water and allowed to cure for 48 hours.

Wind tunnel test results are summarized in Table 4. Only the untreated dry specimen had a TDV within the limits of the system, (i.e., less than 24 m/s), and showed significant mass loss following wind tunnel testing. The untreated dry specimen had a TDV of ~12 m/s (4.5 mph) with a mass loss of approximately 20.0% over the test. The treated specimens, including the water-treated control specimen, showed no detachment up to the limit of the wind tunnel (24 m/s) and an insignificant average mass loss after testing, with measurements yielding between 0.02% and 0.10% and an average of approximately 0.05%.

The penetration results are summarized in Figure 6. Figure 6 shows the dry untreated specimen has a significantly lower penetration resistance than the other test specimens, consistent with the wind tunnel test results. The penetration resistance for the treated specimens was somewhat variable but, in all cases, significantly greater than that of the dry untreated specimen. The water-treated specimen, specimen 2-4, had a penetrative resistance in the middle of those for the four EICP-treated specimens.

Formation of a crust was observed on all pans including the control pan treated only with RO water. A strong odor of ammonia was detected when preparing all the other treated specimens, indicative of urea hydrolysis, the first step in the EICP process. Table 4 presents the measured calcium carbonate content of the soil measured before treatment and on the crust of the treated specimens. The value reported in Table 4 for the crust is the average of the carbonate content of specimens recovered from the top and bottom of the crust. There was very little variation in carbonate content between top and bottom of the crust. The average carbonate content of the crust was, on a dry weight basis, around 1.5% more than the calcium carbonate of the untreated portion of the specimen.

**Table 4. Summary of EICP treatment of soil samples and measured calcium carbonate content of the crust (~top 1.5 cm of specimen)**

Sample No.	Treatment Description	Specimen No.	Wind Erosion Mass Loss (g)	Crust Thickness (cm)	CaCO <sub>3</sub> Content of Untreated Soil (approx. avg.)	CaCO <sub>3</sub> Content of Treated Soil Crust (approx. avg.)	Diff.
1	2.43 L/m <sup>2</sup>	1-1	0.05%	1.38	5.65%	6.73%	1.08%
4, 5, 7, 11	2.43 L/m <sup>2</sup>	2-1	0.02%	1.61	2.63%	4.06%	1.43%
4, 5, 7, 11	3.64 L/m <sup>2</sup>	2-2	0.02%	1.09	2.63%	3.99%	1.36%
4, 5, 7, 11	Dry	2-3	18.89%	0.00	2.63%	-	-
4, 5, 7, 11	RO water	2-4	0.05%	1.16	2.63%	2.63%	0.00%
12	2.43 L/m <sup>2</sup>	3-1	0.10%	1.15	5.22%	6.01%	0.79%

SEM results on crust specimens are presented in Figure 8 and 9. Precipitation is noted on and in between sand particles. Though pre-existing precipitation and precipitation related to the native carbonate content of the soil cannot be distinguished from precipitation formed by EICP treatment, these images appear to show a difference in carbonate morphology and carbonate content, with an increase in carbonate crystal precipitation in the treated specimen compared to the untreated specimen. The increase in carbonate precipitation between the two specimens appears, at least visually, to be greater than the measured increase in overall carbonate content, perhaps because the SEM images are more localized in the very top of the crust (the specimen averaged carbonate content over the top 1.5 cm of the crust).

During mass stabilization testing covered in earlier sections, it was hypothesized that the native soil may contain substances that may inhibit the binding of the precipitated carbonate to the soil particles (e.g. sulfate). Table 5 shows the concentration in ppm for the ions analyzed by IC for the composite specimens formed from soil samples 4, 5, 7, and 11, including the untreated specimen (specimen 2-4) and samples from the crust of the specimens that were treated with 2.43 L/m<sup>2</sup> of treatment solution (specimen 2-1) and 3.64 L/m<sup>2</sup> of treatment solution (specimen 2-2). A “n.a.” in the table either means the ion concentration in the solution was too high or too low to be detected. The IC analysis found a sulfate concentration of 0.54 to 0.58 ppm in the three composite specimens that were tested. The presence of sulfate may suppress urease enzyme

activity, which could be a factor that contributed to absence of cementation in the treated specimens.

**Table 5. Summary of IC analysis of untreated and EICP treated specimens from composite specimens from samples 4,5,7, and 11 (All quantities in ppm)**

<b>Ion concentration (ppm)</b>	<b>Na</b>	<b>K</b>	<b>Mg</b>	<b>Ca</b>	<b>F</b>	<b>Cl</b>	<b>Br</b>	<b>NO<sub>3</sub></b>	<b>SO<sub>4</sub></b>
Treated (2.43 L/m <sup>2</sup> )	0.769	1.268	0.479	1.760	0.074	0.690	0.470	0.422	0.540
Treated (3.64 L/m <sup>2</sup> )	0.734	1.298	0.500	3.020	n.a.	3.432	n.a.	0.475	0.578
Untreated	0.657	1.254	0.463	1.544	n.a.	0.253	n.a.	0.407	0.557
	<b>Li</b>	<b>NH<sub>4</sub></b>	<b>PO<sub>4</sub></b>						
Treated (2.43L/m <sup>2</sup> )	n.a.	n.a.	n.a.						
Treated (3.64 L/m <sup>2</sup> )	n.a.	n.a.	n.a.						
Untreated	n.a.	n.a.	n.a.						

## Conclusion

The potential for EICP-based soil stabilization of soils from the Yuma, Arizona area for fugitive dust control was evaluated by treating soil specimens with an EICP treatment solution. Wind tunnel and penetration tests showed that the specimens treated with carbonate spray had a crust strength and wind erosion resistance greater than that of untreated dry soil. Soil that had been wetted with RO water and allowed to dry had a similar crust strength to the EICP-treated soil and also had an enhanced erosion resistance. Limitations of the wind tunnel used in wind erosion testing did not allow for evaluation of the actual wind resistance of the EICP or water treated specimens. The enhanced erosion resistance of the wetted soil may be attributed to dissolution and subsequent precipitation of minerals in the native soil. Even if the wind resistance of the soil treated with water is equal to that of the EICP-treated soil, the enhanced wind resistance of the carbonate crust in the EICP-treated soil is expected to be more durable than the crust formed by application of water. EICP treatment should also be a viable method for soils which do not form a crust following wetting and drying.

## Conclusion and Future Work

Tests were conducted at the ASU CBBG to evaluate the feasibility of using EICP as a method to mass stabilize and surficially stabilize soils to mitigate erosion. Mass stabilization tests consisted of treating soil from the Yuma area with an EICP solution in columns. The tests showed calcium carbonate precipitation, but no cementation of soil particles that would translate higher erosion

resistance. Surficial stabilization tests demonstrated that EICP treated soils have, at a minimum, the same strength as water wetted soils. However, the EICP-treated soils are expected to have a longer lasting crust than what was seen with wetted soils, as the wetted soil crust is likely to dissipate upon subsequent re-wetting.

Future tests should focus on understanding what mechanisms are inhibiting biocementation of soils from the Yuma area. CBBG has previously conducted mass stabilization testing on other soils with great success. The hypothesis is that sulfates in the selected soils are impeding cementation. Future work for surficial stabilization should begin with laboratory testing of soil from areas that have considerable fugitive dust issues, such as the Salton Sea Playa. Testing should include testing of wet soils, wet soils that are allowed to dry, and rewetted soils that were allowed to dry, and should employ a more powerful wind erosion testing device such that the threshold detachment velocity of EICP-treated and of wetted samples can be measured.

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