Use of Biocementation for Slope Stabilization of Levees

Final Report
November 2018

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Midwest Transportation Center

U.S. Department of Transportation
Office of the Assistant Secretary for
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Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.

4. Title and Subtitle	5. Report Date
Use of Biocementation for Slope Stabilization of Levees	November 2018
	6. Performing Organization Code

7. Author(s)	8. Performing Organization Report No.
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9. Performing Organization Name and Address	10. Work Unit No. (TRAIS)
Civil, Construction, and Environmental Engineering Iowa State University Town Engineering Building, 813 Bissell Rd Ames, IA 50010-8664	**11. Contract or Grant No.** Part of DTRT13-G-UTC37

12. Sponsoring Organization Name and Address		13. Type of Report and Period Covered
Midwest Transportation Center 2711 S. Loop Drive, Suite 4700 Ames, IA 50010-8664	U.S. Department of Transportation Office of the Assistant Secretary for Research and Technology 1200 New Jersey Avenue, SE Washington, DC 20590	Final Report **14. Sponsoring Agency Code**

15. Supplementary Notes

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16. Abstract

While levee embankments are the first line of defense for urban flooding, recent flooding events have revealed widespread slope instability of embankments around the country that can lead to levee failures. This work aimed to improve the slope stability of earthen levees by strengthening the soil through the use of a biologically-inspired technique called biocementation.

The major objective of this study was to determine the optimal and most practical biocementation method that results in the best performance of levee slopes under various flooding conditions.

A novel biocementation method called bacterial enzyme-induced calcite precipitation (BEICP) was tested. This method differs from the well-studied microbial-induced calcite precipitation (MICP) method mainly in the size of the biological agent (whole bacterial cell vs. enzyme), which influences the agent's mobility in soils of different grain sizes.

The BEICP methods for soil strengthening were optimized in laboratory-scale column experiments. The optimized methods were then used to construct levees in an experimental flume system.

The results indicated that the BEICP treatment resulted in significant strengthening of the surface of the soil specimens, which were measured as increases in unconfined compressive strength. The strengthened samples were able to resist erosion for a longer time period under overtopping scenarios of water challenges with high water velocity in a flume. Therefore, BEICP offers a sustainable and economical method for treatment of soil surfaces to improve erosion resistance.

The results of this study will help mitigate flooding events that could cause major issues in transportation infrastructure and traffic safety.

17. Key Words	18. Distribution Statement
biocementation—flood mitigation—levee slope stabilization—unstable embankments	No restrictions.

19. Security Classification (of this report)	20. Security Classification (of this page)	21. No. of Pages	22. Price
Unclassified.	Unclassified.	25	NA

Form DOT F 1700.7 (8-72) **Reproduction of completed page authorized**

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Sponsored by
Midwest Transportation Center and
U.S. Department of Transportation
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ACKNOWLEDGMENTS

The authors would like to thank the Midwest Transportation Center and the U.S. Department of Transportation Office of the Assistant Secretary for Research and Technology for sponsoring this research. The Iowa State University Department of Civil, Construction, and Environmental Engineering provided match funds for this project.

LITERATURE REVIEW

The slope stability of levees is one of the key factors for the prevention of catastrophic flooding, especially in urban riverine systems. In recent years, levee failures were observed in major flooding events such as during Hurricane Katrina in New Orleans, Louisiana, in 2005 (Sills et al. 2008) and the Mississippi River flood in 2011 (Davidson et al. 2013). In many of these cases, levee failures were due, at least in part, to slope instability and susceptibility to erosion (Li et al. 2013).

There is a strong need for levee stabilization to prevent such failures in areas that are prone to flooding, especially with the increasing effects of climate change (IPCC 2007).

Microbial-induced calcite precipitation (MICP) is a biocementation method used for soil stabilization that relies on bacterial activity to produce calcium carbonate ($CaCO_3$, calcite). The method utilizes the enzyme urease to produce ammonium (NH_4^+) and carbonate (CO_3^{2-}) during the urea hydrolysis process (Fauriel and Laloui 2012). This ureolysis reaction will also cause an elevation in pH. Bacterial ureolysis is utilized in biocementation to form calcium carbonate ($CaCO_3$) when Ca^{2+} ions are added, which will then connect soil particles together to result in soil strengthening. The chemical reactions for urea hydrolysis and the formation of calcium carbonate are shown below (Qabany and Soga 2013):

$$CO(NH_2)_2 + 2H_2O \rightarrow 2NH_4^+ + CO_3^{2-}\ pH\ \uparrow \quad (1)$$

$$Ca + CO_3^{2-} \rightarrow CaCO_3\ \ pH\ \downarrow \quad (2)$$

The main purpose of the MICP method is to increase the soil strength, preferably without sacrificing permeability. In the MICP method, the voids volume of the soil specimen is filled with precipitated calcium carbonate. The presence of the calcium carbonate bridging results in an increase of the stiffness in soil (DeJong 2006). The correlation of the calcium carbonate precipitation and the soil particles is the key factor that increases the soil strength. As tested by van Paassen (2009), the unconfined compressive strength test showed the soil strength increased, while the traxial compression test also showed a higher value of the compressive strength after MICP treatment of soil.

The use of a different biocementation technique called bacterial enzyme-induced calcite precipitation (BEICP) was tested in this study. Both MICP and enzyme-induced calcite precipitation (EICP) have been shown to lead to soil stabilization through the formation of calcium carbonate precipitates that bind soil particles together (DeJong et al. 2011).

In MICP, the urease enzymes that are critical for biocementation are located within bacterial cells (*Sporosarcina pasteurii*), whereas in BEICP, the enzymes are provided in an aqueous cell-free suspension (Hoang et al. 2018). One of the major differences between MICP and EICP is the mobility of the biological agent due to differences in size; bacterial cells used in MICP are ≥1 µm long and therefore, are less mobile compared to enzymes used in BEICP (~10 nm in

diameter). As such, BEICP is likely to be more effective in stabilizing fine-grain soils compared to MICP as has been shown in a recent study (Hoang et al. 2018).

In this project, BEICP-treated soil samples were tested for their resistance to erosion to determine whether BEICP is an effective method for levee stabilization. Soil specimens were surface-treated with the BEICP protocol, then tested for their erosion resistance in a flume.

MATERIALS AND METHODS

Controlled Soil Column Materials and Testing Methods

The controlled soil columns were tested in the flume with the goal of determining the erosion rate. Soil column specimens were prepared for the controlled tests. Two of the five soil specimens were untreated specimens; the other eight soil specimens were treated with the variation of the enzyme type and concentrations. All the soil column specimens were prepared with Ottawa sand and silt. The silt was collected from Iowa loess soil that was passed through a No. 200 sieve. The soil column specimens were prepared by adding 5 percent water of the total weight to obtain the optimum dry unit weight. The compaction method was used for the specimen preparation. The summary of the soil column specimens is shown in Table 1 along with their geotechnical properties.

Table 1. Soil column specimen preparation

	Materials					
Specimen	Weight of soil column (g)	Silt content (%)	Water content (%)	Specific gravity	Initial void ratio	Initial void volume (ml)
No. 1	296.19	10	5	2.649	0.435	48.74
No. 2	290.95	10	5	2.649	0.540	56.37
No. 3	292.65	10	5	2.649	0.530	55.67
No. 4	242.51	10	5	2.649	0.494	43.1
No. 5	256.46	10	5	2.649	0.412	38.03

The soil column specimens, 2 in. height and 2.5 in. diameter, were built using PVC pipes cut to 3.5 in. heights. The space under the soil specimen (~1 in. height) was filled with gravel to provide a drainage system for the soil column specimen. Scrub pads were used between the gravel and soil specimens to separate the soil specimen and the gravel layers. A piece of scrub pad was also attached on the bottom of the column to provide free drainage. A typical specimen is shown in Figure 1.

Figure 1. Typical soil column specimen

Enzymes to be used in the BEICP method were prepared by growing *S. pasteurii* cells in growth medium (containing 20 g/L tryptic soy broth, 10 g/L ammonium sulfate, 0.13 mol/L Tris base, and an overall solution pH of 9.0) for 48 hours with shaking at 160 rpm. Total proteins including urease enzymes were extracted from the harvested cells in two ways. Method 1 was performed through sonication of the cell suspension (in the spent growth media) for six 10-min cycles with a 2-min rest in between to lyse the cells. The rest periods were necessary to ensure that the samples did not overheat, which may cause protein denaturation. Following sonication, the suspension was centrifuged to remove cells and the supernatant was used as the enzyme solution. Method 2 was used to obtain purer and more controlled enzyme samples. Cells were harvested, washed, and suspended again in 50 mM phosphate buffer (pH 8.0), then sonicated for 15 2-min cycles with a 1-min rest in between. The suspension was centrifuged and the supernatant was filtered through 0.2 µm pore size membranes, after which the solution was dialyzed in 50 mM phosphate buffer using 3,500 Da cutoff dialysis membranes to remove impurities. The dialyzed sample was then used as the enzyme solution in subsequent procedures described as follows.

The spray method of applying enzyme and chemical solutions was tested first. The treated specimens were prepared with varying enzyme types and concentrations. Nos. 1, 2, and 3 were treated with enzyme solution prepared through Method 1; Nos. 4 and 5 were treated with enzyme solution prepared through Method 2; and Nos. 6 and 7 were untreated specimens. The Nos. 1–5 specimens were treated with five spray cycles that reached the optimum unconfined compressive strength. The total volume of enzyme solution used was based on the initial void volume; the volume of enzyme solution sprayed on the soil specimens should be at least equal to the void volume of each soil specimen. For each spray cycle, the appropriate volume of enzyme solution was first sprayed onto the top surface of the soil specimen followed by air-drying of the specimen, and then the appropriate volume of the chemical solution containing 0.3 M calcium chloride and urea was sprayed. The next spray cycle started after the specimens were air dried. Typical details of the spray cycle process are shown in Table 2.

Table 2. Typical spray process

	Spray Cycle No.				
	1	**2**	**3**	**4**	**5**
Enzyme volume	15g	15g	10g	6g	3g
Chemical solution volume	20g	15g	5g	4g	3g
Starting time	3:06 p.m.	7:23 p.m.	11:12 p.m.	1:10 a.m.	8:30 a.m.
Weight before spray enzyme	521.6g	553.83g	575.13g	578.90g	584.86g
Weight after spray enzyme	539.35g	566.59g	582.81g	583.44g	587.18g
Weight before chemical solution	538.81g	564.78g	582.61g	582.47g	584.17g
Weight after chemical solution	555.84g	576.07g	586.95g	585.97g	586.90g
Cycle waiting time	4 hr 17 min	3 hr 51 min	2 hr	7 hr 20 min	
Oven dry weight after spray	553.83g	575.13g	578.90g	584.86g	529.44g

All the treated specimens were treated with five spray cycles, allowed to air dry for 5–7 days, and placed in the oven at 55°C for two days before testing in the flume. The variations in the enzyme solution concentration and volume used for each specimen are shown in Table 3.

Table 3. Summary of controlled specimens enzyme preparation

	Enzyme Variation			
Specimen	**Method**	**Concentration**	**Void Volume (ml)**	**Amount Used (ml)**
No. 1	1	NA	48.74	54
No. 2	1	NA	56.37	56
No. 3	1	NA	55.67	56
No. 4	2	0.9 mg/ml	43.1	50
No. 5	2	0.2 mg/ml	38.03	50

Method 1 of enzyme solution preparation did not allow for enzyme concentration measurements

For flume testing of samples, the PVC tubes containing the treated soil specimens were placed in the flange attached on the plywood board to keep them stable. Figure 2 shows the flange attached on the plywood and how the soil column specimens were placed in the flume.

Figure 2. Flange attached on the plywood (left) and flume test set up (right)

During the flume test, the water height was set up to be slightly higher than the top of the soil column specimen to mimic an overtopping scenario. Figure 3 shows some of the specimens during the flume tests.

Figure 3. Testing No. 1 specimen (left) and Nos. 2, 3, and 4 specimens (right)

The velocity of the flume on top of the soil column specimens is around 19 cm/s. Detailed information on each flume test is shown in Table 4.

Table 4. Flume test

Flume Tests	Water height	Flume velocity	Testing specimens
Test 1	10.1 cm	19.5756 cm/s	No. 1
Test 2	11.2 cm	18.9087 cm/s	Nos. 2, 3, and 4
Test 3	12.0 cm		Nos. 6 and 7

Levee Specimen Material and Preparation

In the levee model testing, two models were tested. The first one was treated with the type 1 enzyme, and the other one was treated with the type 2 enzyme.

The levee model was prepared in a plastic frame with a 4:1 slope. In the levee model preparation, the Ottawa sand was mixed with 10 percent silt and 5 percent of water. Two layers of the soil were compacted to obtain the optimum dry unit weight. The spraying procedure for BEICP was applied on the surface of the levee model. Both types of enzyme were used for levee model preparation (concentration of 0.09 mg/ml used for type 2). The volumes of the enzyme solution

and urea and calcium chloride solution were calculated based on the best result from the controlled soil column specimens. The details of the prepared levee model are shown in Table 5.

Table 5. Compaction process of levee model

	Layer 1 Specification	**Layer 2 Specification**
Thickness	2 in. height	2 in. height
Weight of soil	9900	6710
Weight of water	495	335.5
Silt content	10%	10%
Moisture content	5%	5%
Specific gravity	2.649	2.649
Total weight	**17440.5 g**	

The spray process was based on the controlled specimen spray process, and the volumes of the enzyme solution and urea and calcium chloride solution used for each cycle were proportionally increased. In the spray process, the waiting time between each cycle was relatively longer than the time used to prepare the controlled soil column specimens, since the surface area was much larger and needed more time for drainage. The detailed spray cycle is shown in Table 6.

Table 6. Spray process of levee model with enzyme concentration of 0.09 mg/ml

	Spray Cycle No.				
Sample Preparation	**1**	**2**	**3**	**4**	**5**
Enzyme volume	830.5g	588g	427.02g	346.92g	206.48g
Chemical solution volume	840g	573g	410g	305g	200g
Starting time	5:30 p.m.	1:00 a.m.	8:30 a.m.	7:30 p.m.	8:30 a.m.
Cycle waiting time	7.5 hrs	7.5 hrs	11 hrs	13 hrs	

Figure 4 shows the levee model after the spray process and before testing.

Figure 4. Levee model before testing

Levee Testing Method

The first levee model was tested in the flume. This levee model was built only on one side, while another side was covered with Styrofoam to prevent erosion on the side of the levee model. The levee model was placed in the flume as shown in Figure 5.

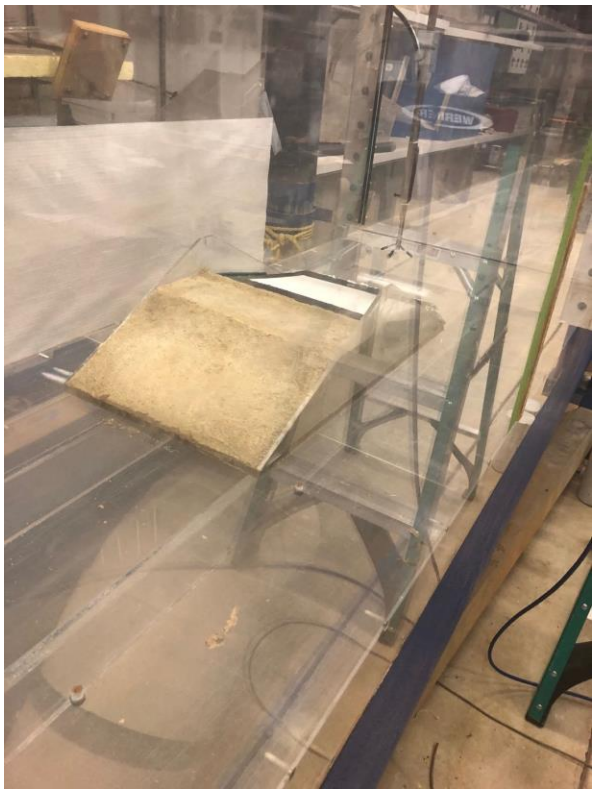

Figure 5. No. 1 levee model flume test set up

During the flume test of the first levee model, the water height was slightly higher than the levee model. The water velocity was changed from 13.506 cm/s during the first 6 minutes, while there was an 8.5-minute gap due to some movement of the levee model, the water velocity during the last 5 minutes was 23.1121 cm/s. This levee model was tested in the flume and the test is shown in Figure 6.

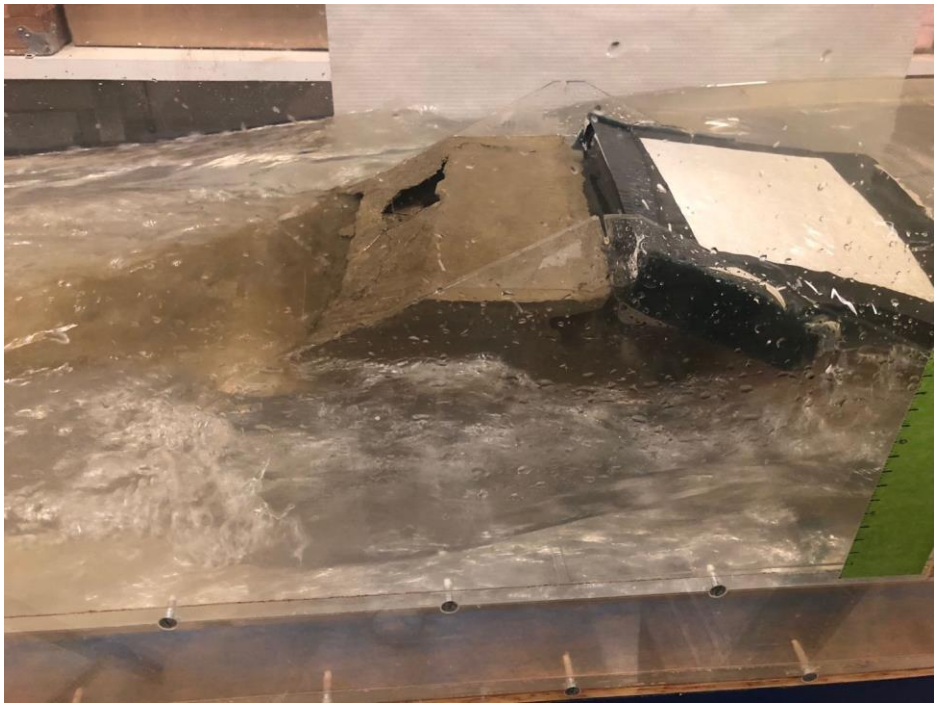

Figure 6. No. 1 levee model during flume test

RESULTS AND DISCUSSION

The No. 1–4 and 6–7 specimens were tested in the flume with the water and flume information described earlier. The specimens were placed in the water until erosion was observed on the surface. Typical pictures of the soil column surface of treated soil specimens and untreated soil specimens are shown in Figure 7.

Figure 7. MICP treated specimen after flume test (left) and untreated specimen after flume test (right)

Weight loss in each specimen following the flume test was recorded as a quantitative measure for the degree of erosion. The oven dry weight of the soil column specimen was measured before and after flume testing. The unconfined compressive strength was measured with a pocket penetrometer after the flume test and oven dry process. A summary of the results for comparison between treated and untreated specimens is shown in Table 7.

Table 7. Summary of controlled specimens

Specimen	Enzyme concentration (mg/ml)	Weight loss (g)	Testing time	Unconfined compressive strength (TSF)	psf
No. 1	NA	19.5	100 min	1.75	3500
No. 2	NA	12.34	60 min	4.0	8000
No. 3	NA	16.07	60 min	4.5	9000
No. 4	0.9	17.54	60 min	3.0	6000
No. 5	0.2	NA	NA	1.75	3500
No. 6	NA	22.5	6 min	1.0	2000
No. 7	NA	19.3	5 min	1.5	3000

The weight loss and the unconfined compressive strength of each specimen are shown in Figures 8 and 9.

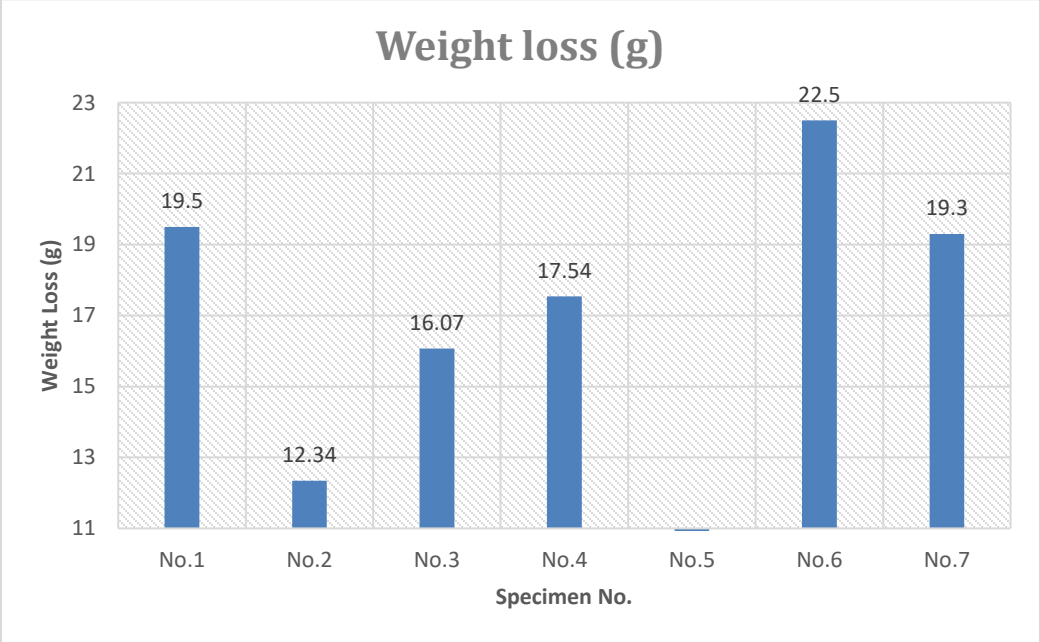

Figure 8. Weight loss of controlled specimens

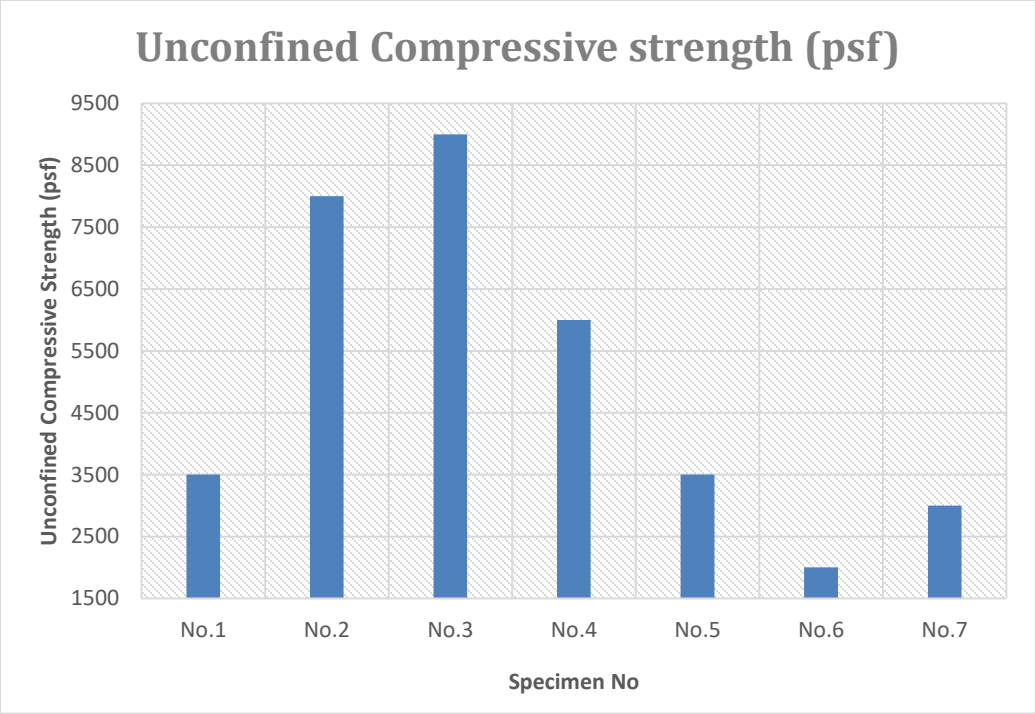

Figure 9. Unconfined compressive strength of controlled specimens

The Nos. 6 and 7 specimens were untreated specimens, and these two specimens had around 20 g of weight loss after only 5 minutes in the flume water, whereas all the BEICP-treated specimens exhibited observable erosion after approximately 60 minutes. Compared to all the other controlled specimens, Nos. 1, 2, and 3 were treated using the same method, same type of enzyme, and same spray cycle process. However, the No. 1 specimen was tested after one week of air drying and one day of oven drying, whereas Nos. 2 and 3 were tested following 12 days of air drying and 2 days of oven drying. Comparing the weight loss and unconfined compressive strength, the No.1 specimen had more weight loss than Nos. 2 and 3, and a lower unconfined compressive strength. The Nos. 2, 3, and 4 specimens were tested together. The Nos. 4 and 5 specimens were treated with the type 2 enzyme, which had a lower concentration than the type 1 enzyme. The Nos. 2, 3, and 4 specimens were tested together. The No. 4 specimen had greater weight loss and a lower unconfined compressive strength compared with the Nos. 2 and 3 specimens. The No. 5 specimen was not tested in the flume, only the unconfined compressive strength was tested. The unconfined compressive strength of the No. 5 specimen was the same as the No. 1 specimen, and both were 1.75 TSF, which is 3500 psf. Compared with the Nos. 6 and 7 specimens, all the bio-treated specimens tested in the flume had a lower weight loss and a higher unconfined compressive strength than the two untreated specimens.

While analysis of the levee test results was underway, the researchers noticed significant improvements in erosion resistance in levees that were treated with type 2 enzymes compared to type 1.

CONCLUSION

In conclusion, this project showed that a novel biocementation method, BEICP, was effective in treating the surface of soil column and levee samples to achieve improved erosion resistance. BEICP offered a sustainable, bio-inspired technology that allowed for surface treatment of soils with a range of soil particle sizes and porosities.

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