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Research Article

Influence of Rainfall-Induced Erosion on the Stability of Sandy Slopes Treated by MICP

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As an environmentally friendly technology, microbially induced calcite precipitation (MICP) is widely used to improve the engineering properties of soil. The goal of this study was to investigate the effect of rainfall-induced erosion on the stability of sandy slopes which were treated by MICP technology. The observation of the erosion pattern of low concentration (0.25 M Ca) and high concentration (0.5 M Ca) of MICP-treated slopes, the mechanical behaviors of MICP-treated and cement-treated samples, and the effects of rainfall-induced erosion on the roughness of 0.5 M Ca MICP-treated and 10% cement-treated slope were studied through visual observation, unconfined compressive tests, and roughness tests. For the 0.25 M Ca MICP-treated sample, surface erosion was found to occur soon after the start of the rainfall erosion test, while for the 0.5 M Ca MICP-treated sample, the slope surface remained intact after exposing to the rainfall for 24 hours. Through unconfined compressive tests, it can be concluded that the 0.5 M Ca MICP treatment achieved a high strength, which was similar to 10% cement-treated sand. The roughness test results showed that the surface of 0.5 M Ca MICP-treated slope looked smoother than the uneroded surface after 24-h rainfall-induced erosion. On the contrary, the surface of the 10% cement-treated slope became rougher after 24-h rainfall-induced erosion. These results indicated that the MICP-treated sandy slope had lower resistance against rainfall-induced erosion compared to the cement-treated sandy slope.

1. Introduction

Rainfall-induced slope failures are reported to occur during or immediately following periods of intense or prolonged heavy rainfall. These slope failures frequently happen on natural slopes in a variety of materials, including residual and colluvial soils, in tropical or subtropical climates [1]. Many disaster reports have shown that the instability of sandy slopes was triggered by heavy rain, which is the most common sandy slope failure type and has caused economic and life losses in recent years. So how to improve the properties of sandy soil against rainfall-induced erosion gained a lot of attention from researchers worldwide for decades. As traditional construction and building materials, cement could be used to improve sandy slopes. While the production process of cement will cause depletion of natural resources and environmental damage, which is energy-intensive, carbon dioxide and other pollutants can be released during the process, such as sulfur oxides, nitrogen oxides, and carbon monoxide into the atmosphere. Due to these environmental concerns, the research of alternate materials attracts researchers worldwide.

As an environmentally friendly technology, microbially induced calcite precipitation (MICP) has been developed rapidly as an innovative technique in the recent decade [2–7]. The MICP process happens under enzymatic hydrolysis of urea in the presence of calcium salts. Dissolved ammonium (NH_4^+) and inorganic carbonate (CO_3^{2-}) can be produced during the urea hydrolysis process. The produced carbonate ions react with calcium ions in the calcium-rich environment to precipitate as calcite crystals. The calcite crystals are precipitated to act as bridges between soil particles and bond them together to improve their engineering properties. MICP technique has been successfully applied at multiscale levels because it is environmentally friendly, such as improving the strength and stiffness of sandy soil [8, 9] and preventing soil from erosion [10, 11].

Rainfall simulators have been used as research tools widely for field or laboratory characterization of hydrogeomorphological studies, including runoff and erosion characteristics. The primary purpose of a rainfall simulator is to simulate natural rainfall accurately and precisely. In the meantime, rainfall simulators control the intensity and duration of the rainfall which is random otherwise [12]. Rainfall simulators are advantageous because rainfall can be produced on-demand quickly wherever necessary without having to wait for natural rainfall at the intensity and duration required. In this study, a rainfall simulator was designed to investigate the influence of rainfall-induced erosion on the MICP-treated sandy slopes.

Soil surface roughness is an important parameter in understanding the mechanisms of soil erosion by water and wind. Many erosion is related to surface processes, such as depressional water storage, raindrop, or wind shear detachment. Measurement techniques of soil surface roughness can be classified by measurement dimension and sensing type. The former includes two-dimensional (2D) profile measurements and three-dimensional (3D) measurements. 3D measurements give a more realistic surface representation and allow for the calculation of physical surface parameters. 3D measurement was used in this study to investigate the effects of rainfall-induced erosion on MICP-treated and cement-treated sandy slopes.

The goal of this study was to investigate the effect of rainfall-induced erosion on the stability of sandy slopes which were treated by MICP technology. In this study, the observation of the erosion pattern of low concentration (0.25 M Ca) and high concentration (0.5 M Ca) of MICP-treated slopes, the mechanical behaviors of MICP-treated and cement-treated samples, and the effects of rainfall-induced erosion on the roughness of 0.5 M Ca MICP-treated and 10% cement-treated slope were studied through visual observation, unconfined compressive tests, and roughness tests.

2. Materials and Methods

2.1. Sands. The Mississippi local sand shown in Figure 1 was used to construct the experimental slopes. This sand was obtained from Jackson, Hinds County, Mississippi. Its median particle size was 0.33 mm. It was classified as well-graded fine sand following the Unified Soil Classification System (USCS).

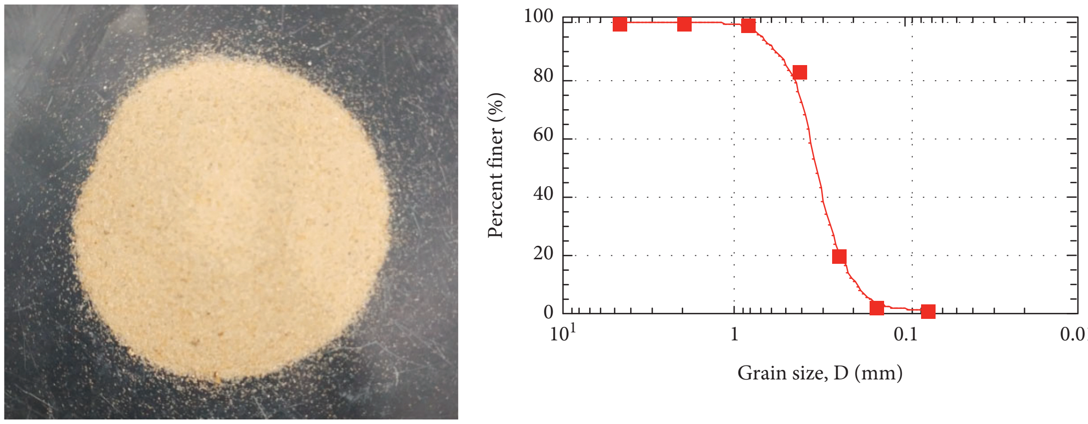
2.2. Portland Cement. Portland cement (TYPE I/II, ASTM C150 [13]) was used as the cementing agent in the cement-sand samples. The specific gravity of cement grains is 3.15. And its early strength gain allowed the various curing times ranged from 7 to 21 days.

2.3. Bacterial Suspension and Cementation Solution. The bacteria used in the experiments were *Sporosarcina pasteurii* (ATCC 11859). The bacterial concentration was controlled by measuring the absorbance (optical density) of the suspension using a spectrophotometer (Genesys 20, Thermo Scientific) at a 600-nm wavelength. A higher OD600 value means a higher bacterial growth rate, and more calcite precipitation and property improvement may be resulted. The OD600 of bacterial solution in this study was kept as 0.6, and the urease activity of bacterial solution was 3.31 mM hydrolyzed urea/min. The ammonium-yeast extract medium (growth medium; ATCC 1376) was used to grow the bacterial cultures. This medium is constituted by following per liter of deionized water: (1) 0.13 M tris buffer (pH = 9.0), (2) 10 g $(NH_4)_2SO_4$, and (3) 20 g yeast extract. Ingredients were mixed uniformly and autoclaved to prepare this growth medium. The bacterial and growth medium were centrifuged at 4,000 *g* for 20 min after incubating aerobically at 30°C in a shaker at 200 rpm overnight. Then the supernatant was removed and replaced by a fresh growth medium before the bacteria were resuspended every time. The bacterial and growth medium were stored in centrifuge tubes at 4°C until used.

A cementation medium was used to provide chemical compositions for ureolysis in the MICP process, including urea, $CaCl_2.2H_2O$, NH_4Cl, $NaHCO_3$, and nutrient broth [14]. The chemical concentration of cementation media in this article was 0.25 and 0.5 M Ca with a urea-Ca^{2+} molar ratio of 1 : 1. The chemical compositions are shown in Table 1.

2.4. Rigid Full Contact Mold. The rigid full contact mold (RFCM) shown in Figure 2 includes a rigid holder and a flexible layer. The rigid holder was made of polypropylene (PP) perforated sheet with a 6.35 mm thickness. The rigid holder was assembled with different pieces of PP sheet by long screw rods and nuts. The holder size can be varied to meet different needs. The RFCM was used to prepare samples for rainfall-induced erosion test with a dimension of 300 mm × 300 mm × 50 mm $(L \times W \times H)$.

2.5. MICP-Treated Sample Preparation. The MICP-treated samples were prepared in a batch tank reactor using the immersing method as shown in Figure 3(a). For rainfall-induced erosion samples, the uniform mixture of 8000 g sand and 2500 mL bacterial solution was mixed and compacted into the rigid full contact mold well-defined. Then covered the sample with a geotextile cover and submerged the whole mold into the 0.5 M Ca cementation media. For UCS test samples, 140 g sand was uniformly mixed with 45 mL bacterial solution, and then air pulvinated into the chamber of the full contact flexible mold. The size of the unconfined compression test mold was 38.1 mm in diameter and 76.2 mm in height. The molds consisted of an annular part, a bottom, and a cover. These samples were placed on the shelf of the batch reactor. Then, the entire shelf was slowly immersed into the batch reactor that was filled with 0.25 or 0.5 M Ca cementation media. MICP treatments were carried out at the ambient temperature of the laboratory for 7 days. Following removal from cementation media and lifting the geotextile covers, all samples were submerged in



(a) (b)

FIGURE 1: Mississippi local sand used in the experiments: (a) image of sand and (b) particle size distribution curve of the local sand.

fresh water to wash residual, loose particles, and unbonded precipitates. Finally, the samples were oven-dried until their weight reached constantly. The dry samples were used for the following testing.

2.6. Cement-Treated Sample Preparation. Cement-treated samples were prepared by mixing dry sand with cement and water. The proportion of added cement was 5% and 10% by mass of dry sand in this study. For the preparation of rainfall-induced erosion samples, 8000 g dry sand, 800 g (10%) cement, and 2200 mL water were mixed.

To achieve a uniform mixture, similar to the mixing ratio in [4], the mixture was added into a waterproof rigid mold with a dimension of 300 mm × 300 mm × 50 mm ($L \times W \times H$) in three layers and compacted, then cured in a relative humidity of 95 ± 5% and constant temperature of 25°C for 7 days. For UCS test samples, 140 g of dry sand was mixed with 7 g (5%) or 14 g (10%) of dry cement and 40 mL of water. Then the mixture was added to a rigid mold and cured for 7 days in a constant humidity of 95 ± 5% and a constant temperature of 25°C. The rigid mold was 76.2 mm in height and 38.1 mm in diameter. The samples were oven-dried at 105°C to dismiss the excess moisture after demolding. The following tests were conducted on the samples after oven drying.

2.7. Rainfall-Induced Erosion System. Rainfall simulators are basic equipment to duplicate the physical characteristics of natural rainfall as closely as possible. It can be separated into two main types based on the way in which the raindrops are produced: (1) non-pressurized nozzle simulators and (2) pressurized nozzle simulators. In the non-pressurized nozzle simulators, water drops fall under the effect of gravity. These simulators are unrealistic for field use that a huge height (10 m) is needed for water drops to achieve the terminal velocity. The water drops strike the ground at a velocity much lower than the terminal velocity and with lower kinetic energy, only if the simulator is hoisted very high. That is why the pressurized nozzle simulators are extensively preferred for studies at large area field. In these simulators, raindrops were produced through single or multiple nozzles, while the drop intensities and velocities are usually exaggerated as the water is released under pressure—since a pressurized nozzle rainfall simulator was designed in this study.

TABLE 1: Chemical compositions for cementation media.

Chemicals	Chemical concentration (g/L)	
	0.25 M Ca	0.5 M Ca
NH_4Cl	10.0	10.0
Nutrient broth	3.0	3.0
$NaHCO_3$	2.12	2.12
Urea	15.0	30.0
$CaCl_2.2H_2O$	36.8	73.5

2.7.1. Design of Rainfall Simulator and Erosion Flume. Experimental design to perform erosion experiments consists of a rainfall simulator and an erosion flume (Figure 3(b)). A rainfall simulator is made of a PVC frame attached with a raindrop plate. The raindrop plate with multiple nozzles is installed on the PVC frame at the height of 1.0 m from the flume bed to ensure the terminal velocity of raindrops. Water is supplied from the water supply system. Laying under the rainfall simulator at the height of 5 cm from the ground is the erosion flume, which was fixed as a slope angle of 35°. The slope angle was considered to present the inclination of natural soil slopes at which shallow slope failures are common [15].

2.7.2. Rainfall Uniformity. The coefficient of uniformity (CuC) defined by [16] is the most widely used measure of spatial uniformity, which is in percent as

$$\text{CuC} = \left(1 - \frac{\sum_1^N |X_i - \overline{X}|}{N\overline{X}}\right) 100, \quad (1)$$

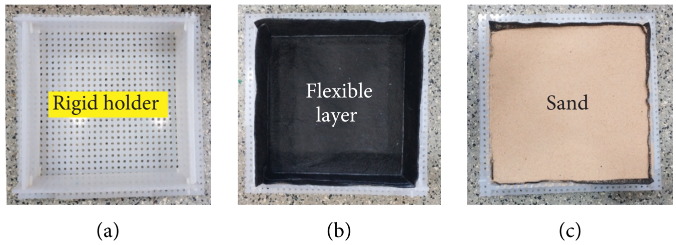


FIGURE 2: Rigid full contact mold: (a) empty mold, (b) covered with geotextile in the bottom, and (c) filled with sand.

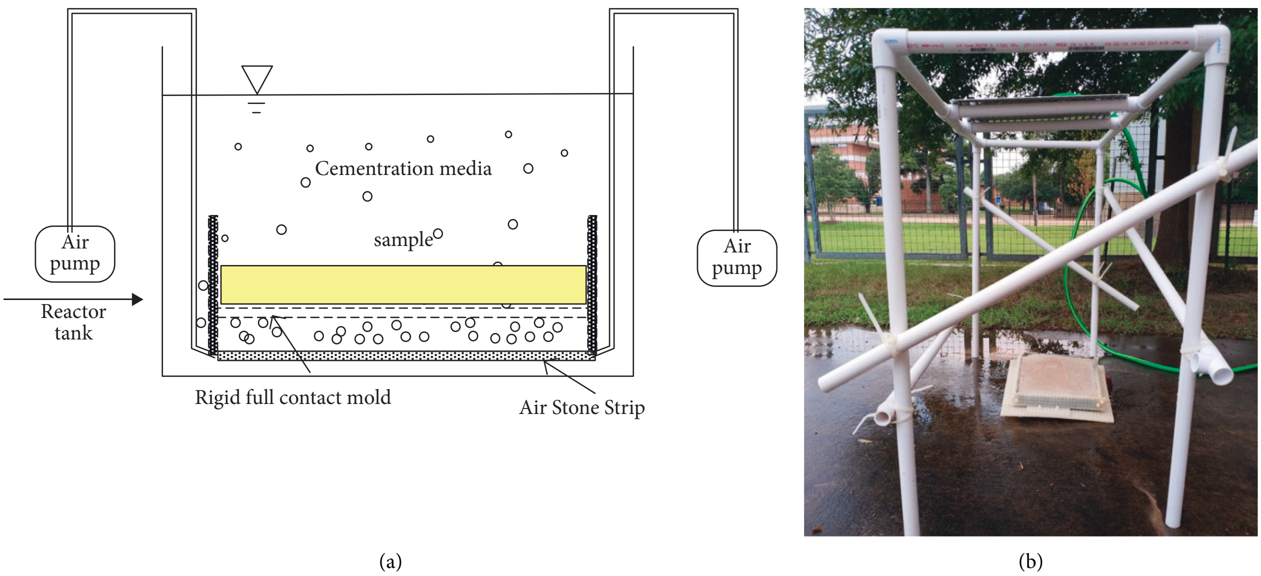


FIGURE 3: (a) Sketch of batch tank reactor and (b) photo of rainfall simulator and erosion flume.

where X_i is rainfall amount at location i, $\overline{X}$ is the average amount of rainfall, and N number of points where measurement cups are placed over the flume to collect rainfall. The CuC is a useful index of spatial uniformity of rainfall. The more uniform the pattern of rainfall is, the closer CuC approaches to 100%. Rainfall can be considered uniform when CuC is higher than 80% [17].

Table 1 shows the uniformity results. CuC was found higher than 80% for the four rainfall intensities. But CuC does not give any indication on the spatial pattern, which means that it is possible for different patterns to get the same CuC value. So, the spatial patterns of rainfall were examined, and the spatial relative rainfall intensity distribution maps are shown in Figure 4. The difference between the average rainfall intensity among the repetitions was less than 5%; thus, the average rainfall intensity can be considered as constant during the experiments with each flow rate we applied [18]. The spatial distribution of rainfall can be considered uniform enough over the flume.

2.7.3. Raindrop Size. The raindrop size was determined by the flour pellet method [19] supported by an image processing technique. A 12.5-cm diameter circular pan filled with wheat flour (Figure 5(a)) was exposed to rainfall for each rainfall intensity (Figure 5(b)). Exposure time was restricted to 2 s to minimize the coalescence of the pellets in the flour. Flour was dried for 12 h at 105°C, and then the pellets were sieved and photographed (Figure 5(c)). The photograph was then processed by an image processing software (Image-Pro Plus 6.0) to automatically distinguish and classify the raindrops based on the size of their surface area. Each raindrop was characterized by a circle area with a diameter to get the median diameter of raindrops.

Raindrop size determined as detailed above was compared to those found in the literature. An empirical equation fitted to data available in literature was given by [20] as

$$D_{50} = \alpha R^{\beta}, \quad (2)$$

where R is rainfall intensity given in mm h^{-1}. The parameter in (2) has ranges of $0.8 \le \alpha \le 1.28$ and $0.123 \le \beta \le 0.292$ with which envelope curves in Figure 6 were graphed. The determined median raindrop sizes of this study were found within this range, which shows the performance of the rainfall simulator in terms of drop size.

Mississippi local sand was used in this study to perform the rainfall-induced erosion of MICP-treated soil. Before the formal experiments, rainfall with four different intensity was examined by eroding the MICP-treated soil that was treated

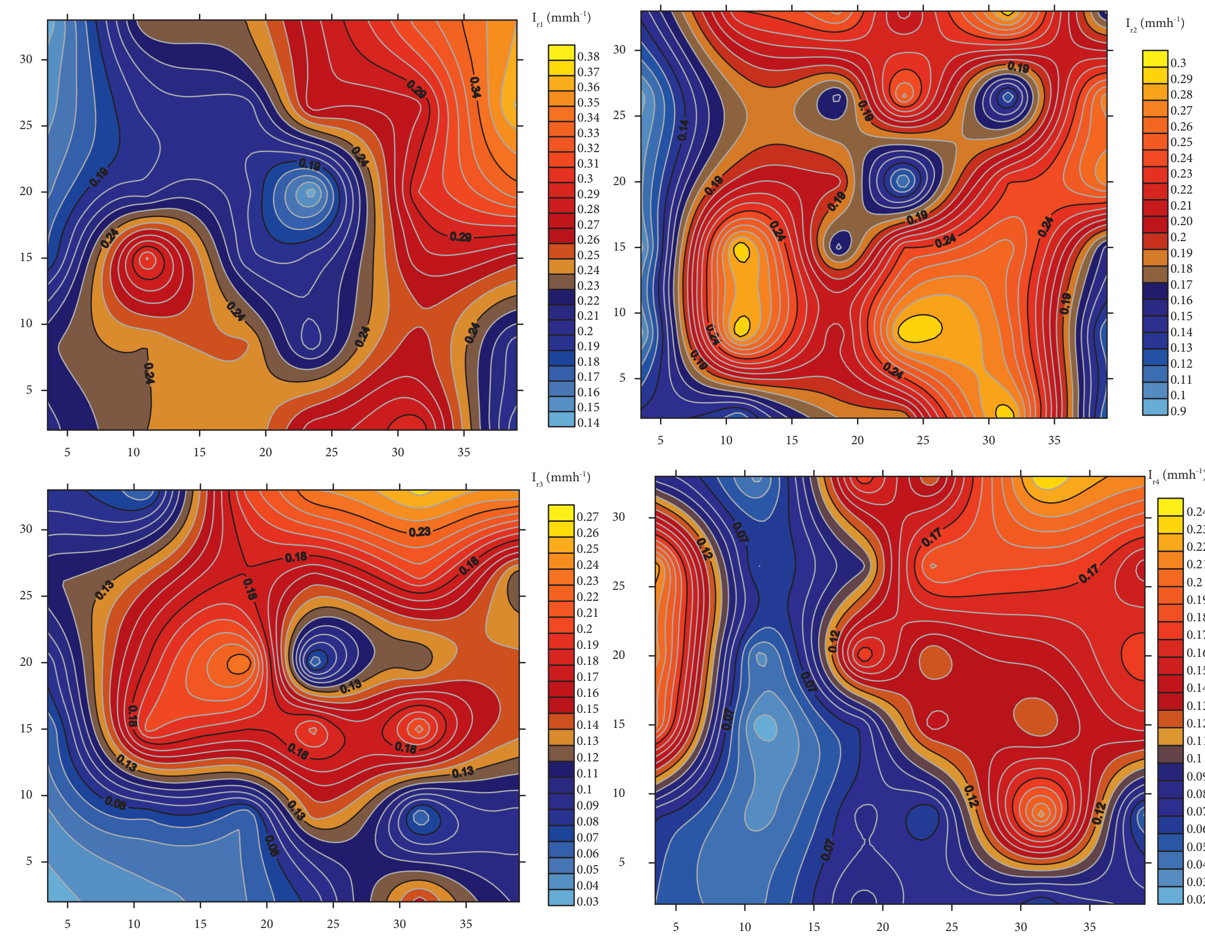


FIGURE 4: Spatial rainfall intensity distribution in the rainfall simulator with the different rainfall intensity (I = Relative rainfall intensity).

(a) (b) (c)

FIGURE 5: (a) Flour cup, (b) flour cup exposed to rainfall, and (c) flour pellets after oven drying.

with 0.25 M Ca cementation medium concentration for 24 h. No noticeable erosion could be observed on the MICP-treated soil under the rainfall with the intensity of 45 mm/h, 65 mm/h, and 85 mm/h. As shown in Figure 7, the 0.25 M Ca MICP-treated soil was eroded seriously by the rainfall with the intensity of 105 mm/h. To obtain noticeable erosion, the rainfall with the intensity of 105 mm/h was selected to perform the rainfall-induced erosion of MICP-treated soil in this study.

2.8. Unconfined Compressive Strength Testing. The unconfined compressive strength tests were conducted on MICP-treated and cement-treated samples under strain-controlled conditions at a uniform loading rate of 1.5%/min in accordance with ASTM D2166/D2166M-13 [21].

2.9. Roughness Testing. The LS-40 Portable 3D Surface Analyzer as shown in Figure 8(a) is a 3D surface measurement

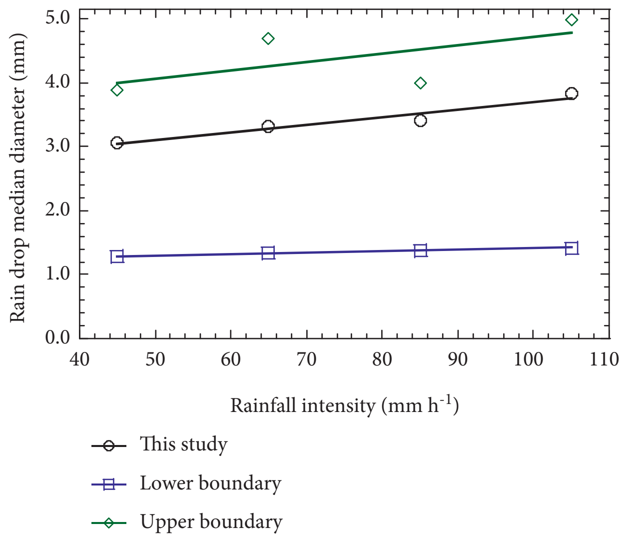


FIGURE 6: Changes in median diameter with rainfall intensity.

and analysis device, which scans 4.25″ by 6″ or 10″ areas and produces a high-resolution (0.01 mm) digital surface structure with an intensity image and a surface depth (height)-related range image.

LS-40 provides the data to calculate mean profile depth (MPD) and 3D views by processing profiles over the entire scanned surface according to ASTM E1845 [22] specifications.

As shown in Figure 8(b) [22], the measured profile is divided for analysis purpose into segments each having a base length of 100 mm. The segment is future divided into half, and the height peak in each half segment is determined. The difference between that height and the average level of the segment is calculated. The average value of these differences for all segments making up the measured profile is reported as the MPD. The MPD values were used to describe the roughness of the samples' surface in this study.

3. Results and Discussion

3.1. Visual Observation. The observed surface erosion pattern of 0.25 M Ca MICP-treated slopes under simulated rainfall at 0, 4, 6, 12, and 24 hours is shown in Figure 8. A hard surface calcite crust was induced on the entire surface of the soil sample by MICP treatment.

For the 0.25 M Ca MICP-treated sample, surface erosion was found to occur soon after the start of the rainfall erosion test (Figure 8). At 4 hours, eroded holes appeared on the soil surface, and soil fluidization and loss were observed at the slope toe. This gradually destabilized the slope, the hole came to a greater range, and more eroded holes were observed on the soil surface along with longer rainfall erosion. At 6 hours, the soil inside the slope was washed away, and the hard surface calcite crust was suspended above the surface. Finally, at 24 hours, almost a third of the slope was damaged, and the suspended surface crust was broken by rainfall erosion. The stability of soil slope was deteriorated by exposure to simulated rainfall.

For the 0.5 M Ca MICP-treated sample, no discernible surface erosion could be identified after 12 hours of rainfall impact. Even after exposure to the rainfall for 24 hours, only loose particles on the surface were washed away, while the slope surface remained intact.

After the rainfall-induced erosion test, the average thickness of the hard crust formed on the 0.25 M Ca and 0.5 M Ca MICP-treated surface of slopes was determined using a caliper. The 0.5 M Ca MICP-treated slope was artificially broken before the thickness measurement. For the 0.25 M Ca MICP-treated slope, the average thickness of the hard crust was 4.33 mm, whereas for the 0.5 M Ca MICP-treated slope, it was 9.82 mm, which was more than two times the 0.25 M Ca MICP-treated slope. The thicker hard crust of the 0.5 M Ca MICP-treated slope was primarily responsible for its better surface erosion resistance than the 0.25 M Ca MICP-treated slope.

Figure 9 shows the SEM images of surface soil samples in the 0.25 and 0.5 M Ca MICP-treated slopes before the rainfall erosion tests. From these SEM images, the morphology of $CaCO_3$ crystal can be clearly illustrated in these two cases. For the 0.25 M Ca MICP-treated soil, sporadic CaCO3 crystals were found on the surface of sand particles; however, lots of large void network remained open. While for the 0.5 M Ca MICP-treated soil, $CaCO_3$ crystals were found between particle contacts, even though not all adjacent particles were bridged. But most of the large pores were partially obstructed by $CaCO_3$ crystals. These phenomena observed from SEM images could also explain why the 0.5 M Ca MICP-treated slopes were better to resist rainfall-induced erosion.

3.2. Unconfined Compressive Strength of MICP-Treated and Cement-Treated Samples. Figure 10 showed a box plot of the unconfined compressive strength of MICP and cement-treated samples as a function of the concentration of cementation media and cement content. Each box showed the median value and ±25% of the unconfined compressive strength population as the top and bottom of the box. The lines extending from the top and bottom of each box mark the minimum and maximum unconfined compressive strength. The outlier was shown as an individual point. From Figure 10, the unconfined compressive strength of MICP-treated and cement-treated samples increased with a higher concentration of cementation media and cement content. And the 0.5 M Ca MICP-treated samples achieved 1300 kPa of the unconfined compressive strength which was roughly equivalent to 10% cement-treated samples. This result was similar to [4]. The 0.25 M Ca MICP-treated samples only got about 200 kPa unconfined compressive strength, which was much lower than the 0.5 M Ca MICP-treated samples.

3.3. Effect of Rainfall Erosion on the Roughness of MICP and Cement-Treated Slopes. To obtain the properties of MICP-treated soil under rainfall-induced erosion, the properties of MICP-treated samples were compared with soil samples made through cement modification. The proportion of cement in this part was 10% by weight of dry sand, and the concentration of cementation media for the MICP-treated samples was 0.5 M Ca. These two samples had similar unconfined compressive strength as described in Section 3.2.

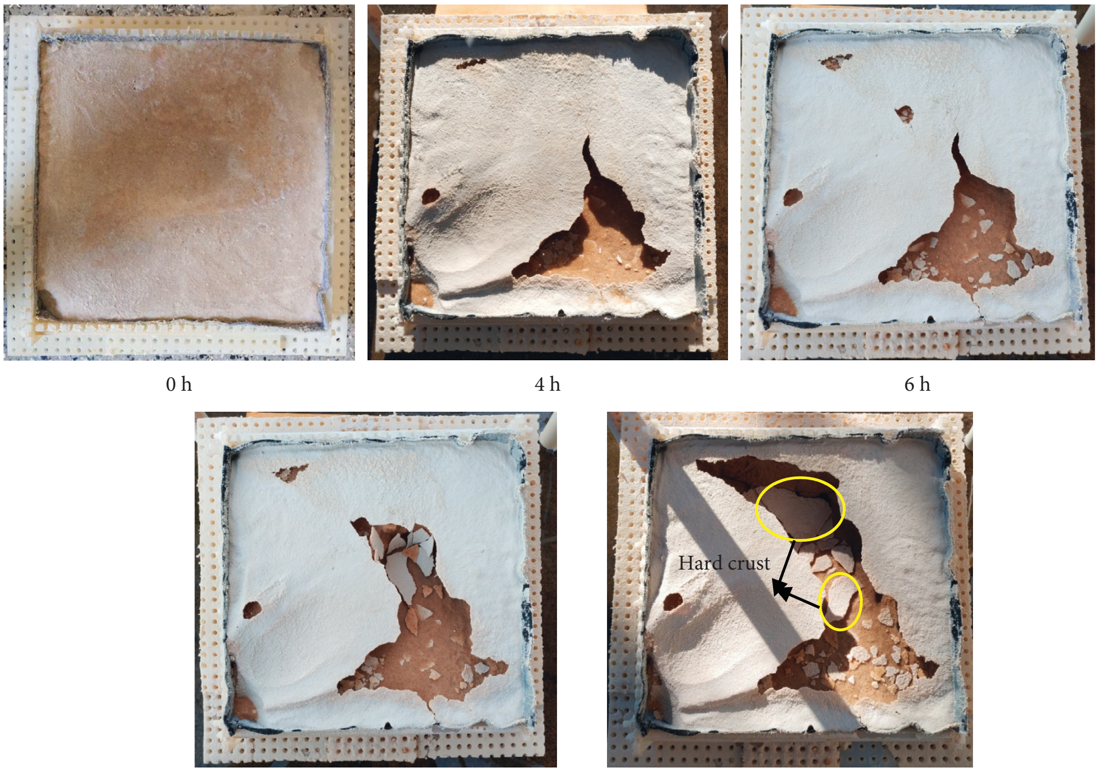
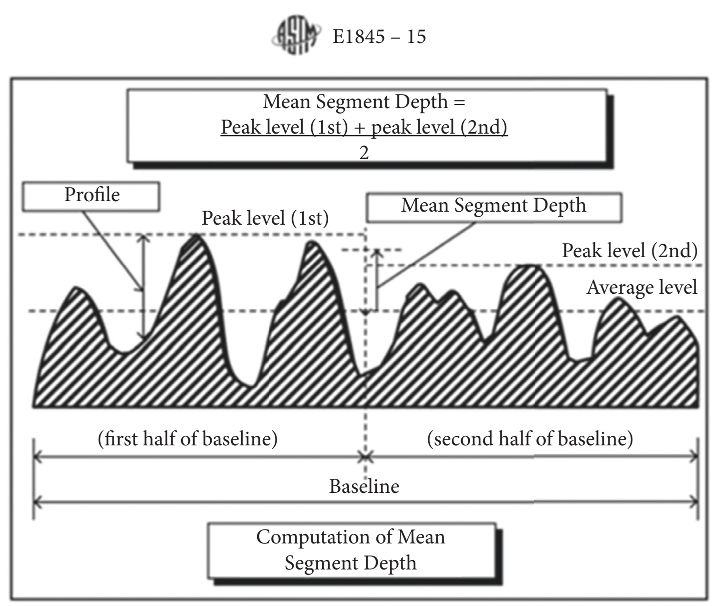


FIGURE 7: Photograph of 0.25 M Ca MICP-treated soil after 105 mm/h rainfall-induced erosion under different eroded times.

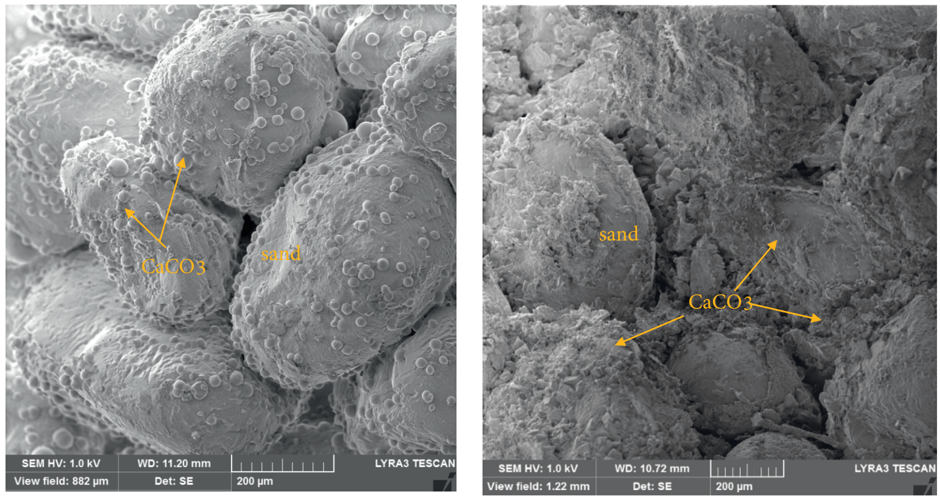
(a)



(b)

FIGURE 8: Surface analysis: (a) photograph of LS-40 Portable 3D Surface Analyzer and (b) computation procedure of mean segment depth (ASTM E1845).

No visible erosion could be observed on the surface of MICP-treated and cement-treated slopes after 24-h rainfall-induced erosion since roughness testing was conducted on samples to investigate the subtle erosion caused by rainfall-induced erosion. Soil surface roughness is an important parameter in understanding the mechanisms of soil erosion by water. Three-dimensional measurements were applied by a laser-scanner device in this study. The roughness of



(a) (b)

Figure 9: SEM images of (a) 0.25 M Ca and (b) 0.5 M Ca MICP-treated sand.

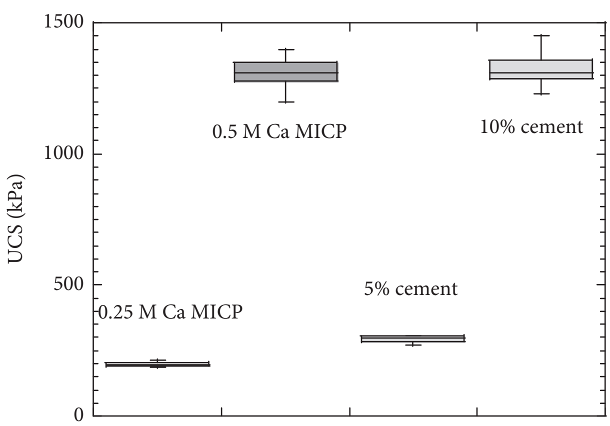


Figure 10: Unconfined compressive strength of MICP-treated and cement-treated samples.

samples was tested after the eroded time of 0 h, 1 h, 2 h, 4 h, 6 h, 12 h, and 24 h, respectively. To investigate the roughness of soil surface, 3D views and mean profile depth were analyzed.

For the 0.5 M Ca MICP-treated slope, Figures 11 and 11(b) show the 3D surface views before and after 24-h rainfall-induced erosion. The eroded surface looked smoother than the uneroded surface, maybe because the powdery bonds, unbonded minerals, or loosely bonded calcite were washed away by simulated rainfall.

Similar results could be obtained from Figure 11(c), which showed the MPD values of the MICP-treated sample as a function of rainfall-induced eroded time. A higher MPD value represented a textured surface, which means a rougher surface. The MPD values on the surface of the MICP-treated slope decreased gradually along with longer rainfall-induced eroded time. A 16.7% decrease in MPD value happened after 24-h rainfall-induced erosion. A smoother surface of the MICP-treated sample was caused by the simulated rainfall. When the soil slope was treated by MICP, a part of $CaCO_3$ precipitation was only attached to the surface of sand particles that may not bond the sand particles strongly, thus easily eroded by rainfall and resulted in a smoother surface.

For the cement-treated samples, the opposite results were induced by simulated rainfall. From Figures 11(d) and 11(e), the 3D views of the cement-treated sample became rougher after 24-h rainfall-induced erosion.

The same conclusion could be summarized from Figure 11(f). The MPD values on the surface of cement-treated samples kept increasing as the rainfall-induced eroded time growing. A 75% increase in MPD value happened because of 24-h rainfall-induced erosion. A rougher surface was induced by rainfall. This phenomenon could be caused by the hydraulic strength of cement during the rainfall-induced erosion process. The early strength of cement in this study gain allowed the various curing times ranged from 7 to 21 days. The cement-treated samples were cured for 7 days in a constant humidity of 100% before the rainfall-induced erosion test. Loosely bonded sand particles were washed away by rainfall at the early stage of the erosion; meanwhile, the strength of the cement-treated sample kept increasing during the erosion process to resist erosion. Afterward, a rougher surface was formed at the later stage of rainfall-induced erosion.

However, it has been reported that rough surfaces absorb raindrop impact on the soil surface and significantly modify water flow and soil surface interactions [23]. Moreover, Liu et al. [7] found that MICP-treated materials had short service life during wet-dry cycles. Especially in the wetting period, the water could penetrate and inundate the MICP-treated soil, the powdery bonds, unbonded minerals, or loosely bonded calcite that could be eroded by water erosion. This means the MICP-treated slope was weak to resist rainfall-induced erosion compared to the cement-treated slope. The ability of MICP-treated slopes against rainfall-induced erosion must be improved in the future.

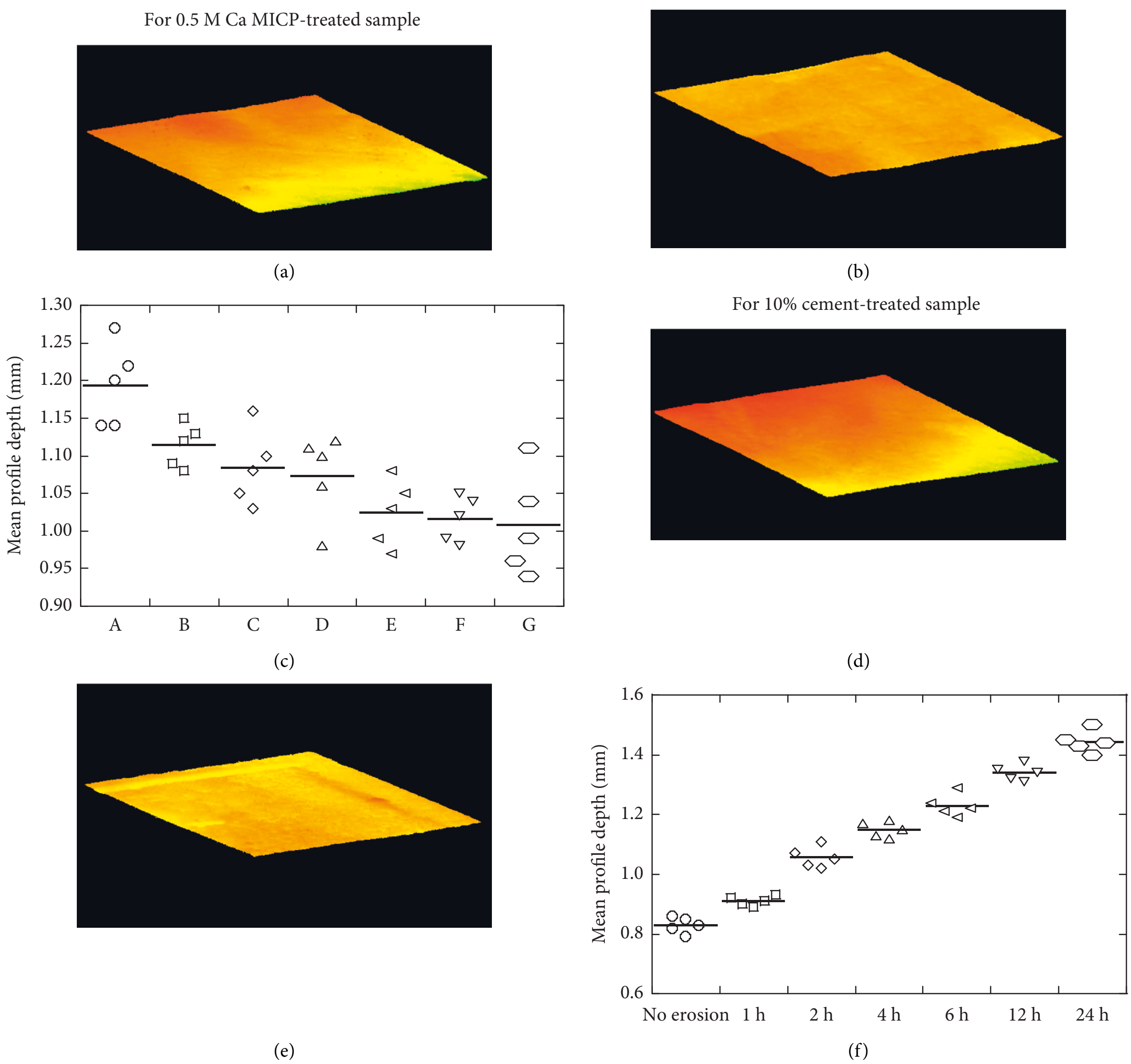


Figure 11: (a) and (c) 3D surface views of the sand surface before rainfall-induced erosion; (b) and (e) 3D surface views of sand surface after 24-h rainfall-induced erosion; (c) and (f) mean profile depth on the surface as a function of rainfall-induced eroded time. (a), (b), and (c) are for 0.5 M Ca MICP-treated sample, whereas (d), (e), and (f) are for 10% cement-treated sample.

4. Conclusion

It is apparent that the MICP treatment method could improve the surface erosion resistance of sandy slopes through the analysis of rainfall-induced erosion test results. The observation of the erosion pattern of low concentration (0.25 M Ca) and high concentration (0.5 M Ca) of MICP-treated slopes, the mechanical behaviors of MICP-treated and cement-treated samples, and the effects on the roughness of the 0.5 M Ca MICP-treated and 10% cement-treated slope were studied through visual observation, unconfined compressive tests, and roughness tests. For the 0.25 M Ca MICP-treated sample, surface erosion was found to occur soon after the start of the rainfall erosion test, while for the 0.5 M Ca MICP-treated sample, only loose particles on the surface were washed away after exposing to the rainfall for 24 hours, and the slope surface remained intact. Through unconfined compressive tests, it can be concluded that as an environmentally friendly method, the 0.5 M Ca MICP treatment achieved a high strength, which was similar to 10% cement-treated sand. The roughness test results showed that the surface of 0.5 M Ca MICP-treated slope looked smoother than the uneroded surface after 24-h rainfall-induced erosion. The MPD values on the surface of the MICP-treated slope decreased gradually along with longer rainfall-induced eroded time. A 16.7% decrease in MPD value happened after 24-h rainfall-induced erosion. On the contrary, the surface of the 10% cement-treated slope became rougher after 24-h rainfall-induced erosion. A 75% increase in MPD value happened because of 24-h rainfall-induced erosion. The MICP-treated sandy slope had lower resistance against rainfall-induced erosion compared to the cement-treated sandy slope.

Data Availability

The data are available on request to the corresponding author.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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