Journal of Rock Mechanics and Geotechnical Engineering xxx (xxxx) xxx

Contents lists available at ScienceDirect

Journal of Rock Mechanics and Geotechnical Engineering

journal homepage: www.jrmge.cn

Full Length Article

# Experimental study on mitigating wind erosion of calcareous desert sand using spray method for microbially induced calcium carbonate precipitation

Monika Dagliya [a], Neelima Satyam [a,*], Meghna Sharma [a], Ankit Garg [b,c]

[a] Department of Civil Engineering, Indian Institute of Technology Indore, Indore, India
[b] Department of Civil and Environmental Engineering, Shantou University, Shantou, China
[c] L.N. Gumilyov Eurasian National University, Nur-Sultan, Kazakhstan

ARTICLE INFO

*Article history:*
Received 2 July 2021
Received in revised form
8 November 2021
Accepted 2 December 2021
Available online xxx

*Keywords:*
Control wind erosion
Microbially induced calcium carbonate precipitation (MICP)
Surface strength
Wind tunnel
Calcite precipitation

ABSTRACT

Wind erosion is one of the significant natural calamities worldwide, which degrades around one-third of global land. The eroded and suspended soil particles in the environment may cause health hazards, i.e. allergies and respiratory diseases, due to the presence of harmful contaminants, bacteria, and pollens. The present study evaluates the feasibility of microbially induced calcium carbonate precipitation (MICP) technique to mitigate wind-induced erosion of calcareous desert sand (Thar desert of Rajasthan province in India). The temperature during biotreatment was kept at 36 °C to stimulate the average temperature of the Thar desert. The spray method was used for bioaugmentation of *Sporosarcina* (*S.*) *pasteurii* and further treatment using chemical solutions. The chemical solution of 0.25 pore volume was sprayed continuously up to 5 d, 10 d, 15 d, and 20 d, using two different concentration ratios of urea and calcium chloride dihydrate viz 2:1 and 1:1. The biotreated samples were subjected to erosion testing (in the wind tunnel) at different wind speeds of 10 m/s, 20 m/s, and 30 m/s. The unconfined compressive strength of the biocemented crust was measured using a pocket penetrometer. The variation in calcite precipitation and microstructure (including the presence of crystalline minerals) of untreated as well as biotreated sand samples were determined through calcimeter, scanning electron microscope (SEM), and energy-dispersive X-ray spectroscope (EDX). The results demonstrated that the erosion of untreated sand increases with an increase in wind speeds. When compared to untreated sand, a lower erosion was observed in all biocemented sand samples, irrespective of treatment condition and wind speed. It was observed that the sample treated with 1:1 cementation solution for up to 5 d, was found to effectively resist erosion at a wind speed of 10 m/s. Moreover, a significant erosion resistance was ascertained in 15 d and 20 d treated samples at higher wind speeds. The calcite content percentage, thickness of crust, bulk density, and surface strength of biocemented sand were enhanced with the increase in treatment duration. The 1:1 concentration ratio of cementation solution was found effective in improving crust thickness and surface strength as compared to 2:1 concentration ratio of cementation solution. The calcite crystals formation was observed in SEM analysis and calcium peaks were observed in EDX analysis for biotreated sand.



## 1. Introduction

Sandstorm is a serious global natural calamity as it causes land degradation in arid and semi-arid areas which results in the erosion of loose sand and fugitive dust particles. Nearly 41% of the Earth's land surface is covered by deserts. Approximately 38% of the world's population gets affected due to this disaster (Miao et al., 2020a, b). Desertification is a threat to an ecosystem that declines economic development and stability in arid and semi-arid regions (Le Houérou, 2001).

Northwestern part of India is severely affected by desertification. Out of 32 million hectares of hot and arid land in India, Rajasthan province shares the maximum 62% of the desert,

* Corresponding author.
*E-mail address:* neelima.satyam@iiti.ac.in (N. Satyam).
Peer review under responsibility of Institute of Rock and Soil Mechanics, Chinese Academy of Sciences.

https://doi.org/10.1016/j.jrmge.2021.12.008

followed by 19% in Gujarat, 10% in Karnataka and Andhra Pradesh, and 9% in Punjab and Haryana (Moharana et al., 2016). The Thar desert is located 27°N latitude and 71°E longitude between the Aravali mountain range in the East and the Indus river in the West. It covers 170,000 km$^2$ land area which is approximately 5% of the total geographic area of the country. It is the 20th largest desert and the 9th largest hot subtropical desert in the world. Despite extreme temperatures in summer (50 °C) and winter (−4 °C), the population density of Thar is around 83 people per km$^2$ comprising about 40% of the total population of Rajasthan. Approximately 70% of the Rajasthan area is seriously affected by wind erosion (Roy and Singhvi, 2016).

Mitigation of sandstorms and controlling land degradations are one of the worldwide challenges (Miao et al., 2020a). The techniques, which are conventionally used for wind erosion control to prevent desertification, i.e. vegetation, sand fences, barriers, chemical stabilization, and engineering approaches are likely to be ineffective with time (Goudie and Middleton, 2006). There are performance and application limitations associated with each conventional method. In the case of vegetation, roots help to keep soil particles intact through reinforcement and soil matric potential, but non-availability of suitable soil temperature and nutrient conditions is the major issue of vegetation (Gadi et al., 2016). The fences and barriers cannot be reset and moved according to the condition of sand accumulation and the surface formed in the field (Miao et al., 2020a). The chemical stabilizers create environmental issues mainly related to groundwater contamination as it releases toxic and synthetic materials, hence their usage are banned for ground improvement (Karol, 2003). Engineering methods are not feasible as they require a lot of manpower and material resources (Verdoodt et al., 2009; Deléglise et al., 2011; Zomorodian et al., 2019).

In recent years, the microbially induced calcite precipitation (MICP) method has arisen as a potential technique for strengthening soil properties (Chou et al., 2011; Sun et al., 2019; Sharma et al., 2021a) as compared to various other ground improvement practices, which uses agricultural waste, industrial waste, ashes, and fibers (Tiwari et al., 2020a, b, c, 2021a; Tiwari and Satyam, 2019, 2020, 2021). MICP is developed as an effective strength enhancement approach not only for sand but also for clay (Tiwari et al., 2021b). Moreover, the treatment methodology should be different due to the lower permeability of clay. MICP process essentially induced metal ions to bind with acid radical ions to form calcium carbonate minerals (Mitchell and Santamarina, 2005; DeJong et al., 2006; Sun et al., 2018). The hydrolysis of urea by introducing highly active urease-producing bacteria (e.g. *Sporosarcina pasteurii* and *Bacillus megaterium*) is one of the most popular methods to induce carbonate precipitation (DeJong et al., 2006; Soon et al., 2013; Sharma et al., 2021b). In the MICP technique, calcium carbonate crust formation strengthens the soil and protects it against wind impact. Hence, it is well explored that carbonate precipitation has significant potential as an effective method for biomineralization (Sharma et al., 2019, 2021a, c). Moreover, the cost of this method can be optimized by regulating the nutrient and cementation solutions. A study on the optimization of cementation solution was conducted by Sharma et al. (2021b), which showed that the injection or spraying frequency of 0.5 pore volume cementation solution every 24 h resulted in effective calcite precipitation and strength improvement. Agricultural grade urea and lower-grade calcium chloride dihydrate can also be used to achieve economy in the MICP method (Gowthaman et al., 2021a). The nutrient broth used in the MICP method for bacterial growth is more expensive, however, few studies applied the substitute of nutrient broth such as corn steep liquor, vinasse and molasses, which leads to economic biotreatment (Maleki et al., 2016; Nikseresht et al., 2020).

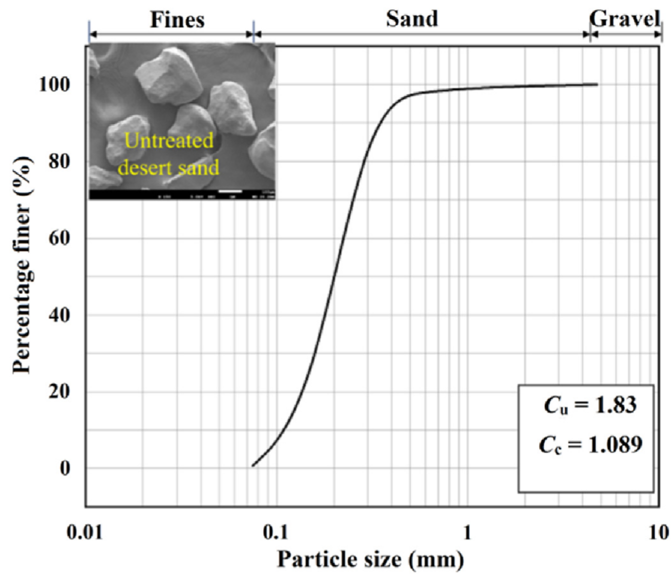


**Fig. 1.** Grain size distribution curve for desert sand.

The MICP technique has been used by various researchers in different environmental conditions for strengthening the sandy soil. It was found effective for enhancing stiffness, liquefaction resistance, bearing capacity, slope stabilization, and contamination immobilization (DeJong et al., 2006; Mwandira et al., 2017; Simatupang et al., 2018; Gowthaman et al., 2019a, b; Sharma et al., 2020). The MICP technique is not likely to cause environmental pollution as compared to the traditional methods that use lime, fly ash, and cement (Wang et al., 2018; Sharma et al., 2021d). Some recent studies have also demonstrated that the calcite precipitated sand shows sandstone-like properties and durability against various environmental conditions, i.e. freezing-thawing, wetting-drying, and ageing (Gowthaman et al., 2020, 2021b; Sharma and Satyam, 2021; Sharma et al., 2021e, f, g).

The treatment of the top layer of the sand surface by bacteria and cementation solution through the MICP technique made an integrated thin stiff layer, which covered up dust and prevented wind erosion. However, untreated particles lying below the layer are not integrated, which consequently results in the displacement of a thin layer in presence of water and increases the chances of erosion (Poulsen et al., 2020). Wang et al. (2018) tested the MICP treated sample (at temperature of 20 °C) in the wind tunnel and found that the erosion rate was less than 0.4%. A study on wind erosion rate was performed by some of the researchers; however, the surface strength of crust and thickness of the layer are under explored (Sun et al., 2018; Wang et al., 2018). Hence, the surface strength of crust and thickness of the layer should be explored to investigate the effectiveness of treatment beyond maximum wind speed.

The objective of the present study is to study the intactness of the surface soil layer induced due to MICP for minimizing the wind induced erosion. The experimental study was conducted in the laboratory for the treatment of the top layer of sand to control wind erosion. The spray method for MICP treatment was used with different cementation solution concentration ratios (2:1 and 1:1) and at a constant temperature of 36 °C to simulate field conditions. Cementation solution of 2:1 indicates that the concentration of urea was 0.5 mol/L and calcium chloride dehydrate was 0.25 mol/L, and in 1:1 cementation solution, the concentration of both urea and calcium chloride dihydrate was 0.5 mol/L. The wind tunnel test was conducted to evaluate erosion of untreated and biotreated soils, at

Please cite this article as: Dagliya M et al., Experimental study on mitigating wind erosion of calcareous desert sand using spray method for microbially induced calcium carbonate precipitation, Journal of Rock Mechanics and Geotechnical Engineering, https://doi.org/10.1016/j.jrmge.2021.12.008

different wind velocities. The unconfined compressive strength test was performed to assess surface stiffness (i.e. intactness) of bio-treated sand samples using a pocket penetrometer. Percentage of calcite content, crust layer thickness, and bulk density were measured to analyze the treatment effectiveness. Calcium carbonate precipitated crystals were analyzed using SEM and EDX methods.

## 2. Materials and methods

### 2.1. Properties of desert sand

The desert sand used in this study was collected from Tinwari village, located in Osian tehsil of Jodhpur district in Rajasthan province of India. Soil can be classified as poorly graded sand as per Indian standard IS:1498−1970 (2002). Fig. 1 shows the particle size distribution curve for desert sand. The mean grain size ($D_{50}$), uniformity coefficient ($C_u$), and coefficient of curvature ($C_c$) were 0.212 mm, 1.83, and 1.089, respectively. The specific gravity of sand was 2.75. The minimum ($e_{min}$) and maximum ($e_{max}$) void ratios were 0.616 and 0.903, respectively.

### 2.2. Preparation of bacterial solution

Fig. 2 shows the cultivation process of *S. pasteurii* bacterial culture which was stored at −20 °C. 25 g nutrient broth powder was mixed with distilled water to prepare 1 L nutrient broth solution. The nutrient broth was autoclaved for 20 min at temperature of 121 °C and pressure of 15 psi (1 psi = 6.895 kPa). Inoculation of strain was performed in a laminar airflow cabinet under sterile conditions, and to initiate the growth of bacteria, an orbital shaking incubator was used. The inoculated solution was kept in an incubator at a rotating speed of 200 r/min at 30 °C temperature under aerobic conditions for 24 h. Cotton plugs were used as a cap for jars to maintain aerobic conditions. The optical density (OD) value of 1.182 was measured using a spectrophotometer at 600 nm wavelength (Bu et al., 2018; Sharma et al., 2019).

**Table 1**
Mass of each component in 1 L cementation solution.

| Series No. | Material | Mass (gm/L) | |
|---|---|---|---|
| | | 2:1 cementation solution | 1:1 cementation solution |
| 1 | Urea | 30.03 | 30.03 |
| 2 | Calcium chloride dihydrate | 36.75 | 73.5 |
| 3 | Ammonium chloride | 10 | 10 |
| 4 | Sodium bicarbonate | 2.12 | 2.12 |
| 5 | Nutrient broth | 3 | 3 |

The following equation was used to calculate the bacteria cell concentration ($Y$) in 1 mL solution, which shows the direct relation between $OD$ and $Y$ (Sharma et al., 2021d):

$$Y = 8.59 \times 10^7 OD^{1.3627} \tag{1}$$

The bacteria concentration ($Y$) was calculated using the above equation as $1.07 \times 10^{11}$ cells/L. This proves that the bacteria cell concentration was significant for successful urease activity in biogeochemical reactions, as the active range of $OD$ for higher urease activity is 0.8−1.2 (Okwadha and Li, 2010).

### 2.3. Components of cementation solution

A cementation solution was prepared using urea, calcium chloride dihydrate, ammonium chloride, sodium bicarbonate, and nutrient broth. The mass of each component for different cementation media concentrations was summarized in Table 1 (Sharma et al., 2019). Sodium bicarbonate and ammonium chloride act as a buffer in cementation media (Bu et al., 2018; Sharma et al., 2019). Two different proportions of urea and calcium chloride dihydrate were used for analyzing and comparing the effect of concentrations as shown in Table 1. To replicate field conditions, autoclaving was not conducted for different components of cementation media.

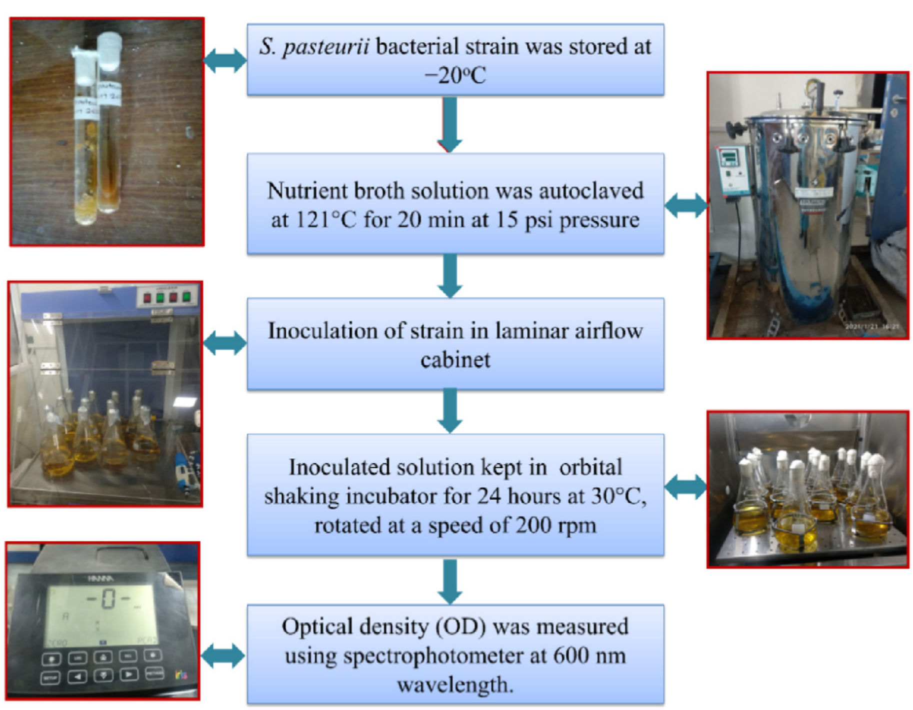


**Fig. 2.** Systematic diagram for the preparation of bacterial solution.

### 2.4. Sample preparation and biotreatment process

Sand sample of 980 g was filled at 50% relative density (as observed in deserts) (Fig. 3b) in a polypropylene (PP) plastic disposable tray, which weighed 13.8 g and had dimensions of 160 mm × 120 mm × 35 mm (Fig. 3a). 200 mL bacterial solution was sprayed using a spray device for each sample surface at the rate of 15 mL/min and left for 24 h for bacterial attachment, as presented in Fig. 3c (Wang et al., 2018). After 24 h of attachment period, cementation solution (equal to 0.25 pore volume) without calcium chloride dihydrate was sprayed. Less pore volume was used to target treatment of top exposed surface only (Maleki et al., 2016). The sample was left again for 24 h and the duration was termed as a simulation period (Fig. 3d). The simulation period here refers to the formation of carbonate ions in the soil matrix during urea hydrolysis, as in this period, cementation solution was injected without calcium source, hence, only urea hydrolysis took place during the simulation period. After the attachment and simulation period, the cementation solution was sprayed and calcium ion source reacted with carbonate ions and calcite precipitation occurred. The sand was biotreated for 5 d, 10 d, 15 d and 20 d, as shown in Fig. 3e. Treatment was started with the spraying of cementation solution with different molar concentrations (solution of cementation media was prepared every day) and all samples were kept in the oven for maintaining an average temperature of 36 °C (Gupta, 1986) to simulate field condition. All sample trays were taken out for spraying the solution and kept back in the oven at 24 h intervals. After 5 d of treatment, one-fourth of samples were kept out from the oven, and treatment for 10 d, 15 d, and 20 d continued. The same process was followed till 20 d of treatment.

### 2.5. Wind tunnel experimental setup

Erosion was simulated using a wind tunnel experimental setup (Fig. 4). Wind tunnel setup has a total length (distance between upwind entry and exhaust of the tunnel) of 1.5 m, out of which 0.6 m was a working section. The cross-section dimension of the duct was 0.3 m × 0.3 m (Maleki et al., 2016; Zomorodian et al., 2019; Almajed et al., 2020; Miao et al., 2020b). To calculate wind erosion resistance of the treated and untreated sand samples, wind tunnel testing was performed at different wind velocities of 10 m/s, 20 m/s, and 30 m/s for a 1-min duration (Miao et al., 2020b). To achieve different wind velocities in the duct, the flapper position of the air inlet to blower was adjusted. The air velocity of this complete setup has been measured and verified using an anemometer (Poulsen et al., 2020). Before starting the test, the sample was placed and fixed in the test section to avoid the movement of the tray (Wang et al., 2018). However, the in-house wind tunnel setup had a few limitations that included poor airflow speeds along with a challenge to reflect natural wind flow conditions, which could only be maintained by using an anemometer (Strong et al., 2016). The tunnel had limitations in the evaluation of the erodibility of natural soil surfaces and their dust emissions (Van Pelt et al., 2010). The size of the sample to be used was decided according to the test section of the wind tunnel to achieve efficiency in results. However, the spatial variability of the MICP crust regarding the homogeneity of the treated soil surface in the field could not be captured by the testing of samples in the laboratory wind tunnel setup (Strong et al., 2016). In the present study, wind erosion was assessed by mass difference and visual operation. Pre and post weighing of the sample was conducted to obtain mass loss that occurred during wind tunnel testing (Fattahi et al., 2020).

### 2.6. Surface strength test

The surface strength of the biotreated crust was measured using a pocket penetrometer, as shown in Fig. 5a. The pocket penetrometer was used to determine the penetration resistance of biotreated sand surface both in the field and in the laboratory. The instrument is widely used because of its easy operation and instant results (Cheng and Cord-Ruwisch, 2012; Omoregie et al., 2018; Fick et al., 2020; Kou et al., 2020). However, the limitation of the instrument is its range of measuring strength (0–441.29 kPa). The least count of pocket penetrometer is 24.51 kPa (0.25 kg/cm$^2$),

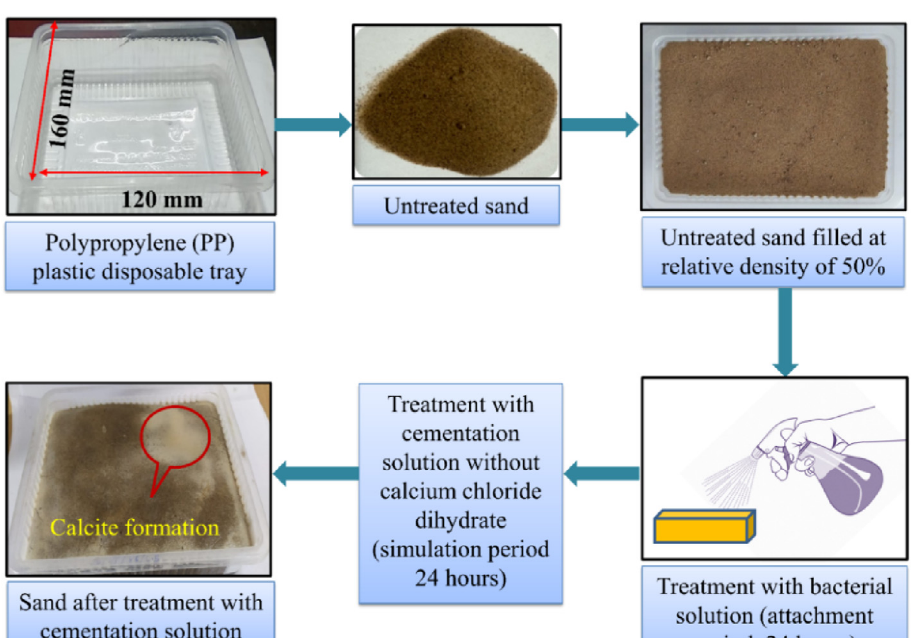


**Fig. 3.** Sample preparation and biotreatment process.

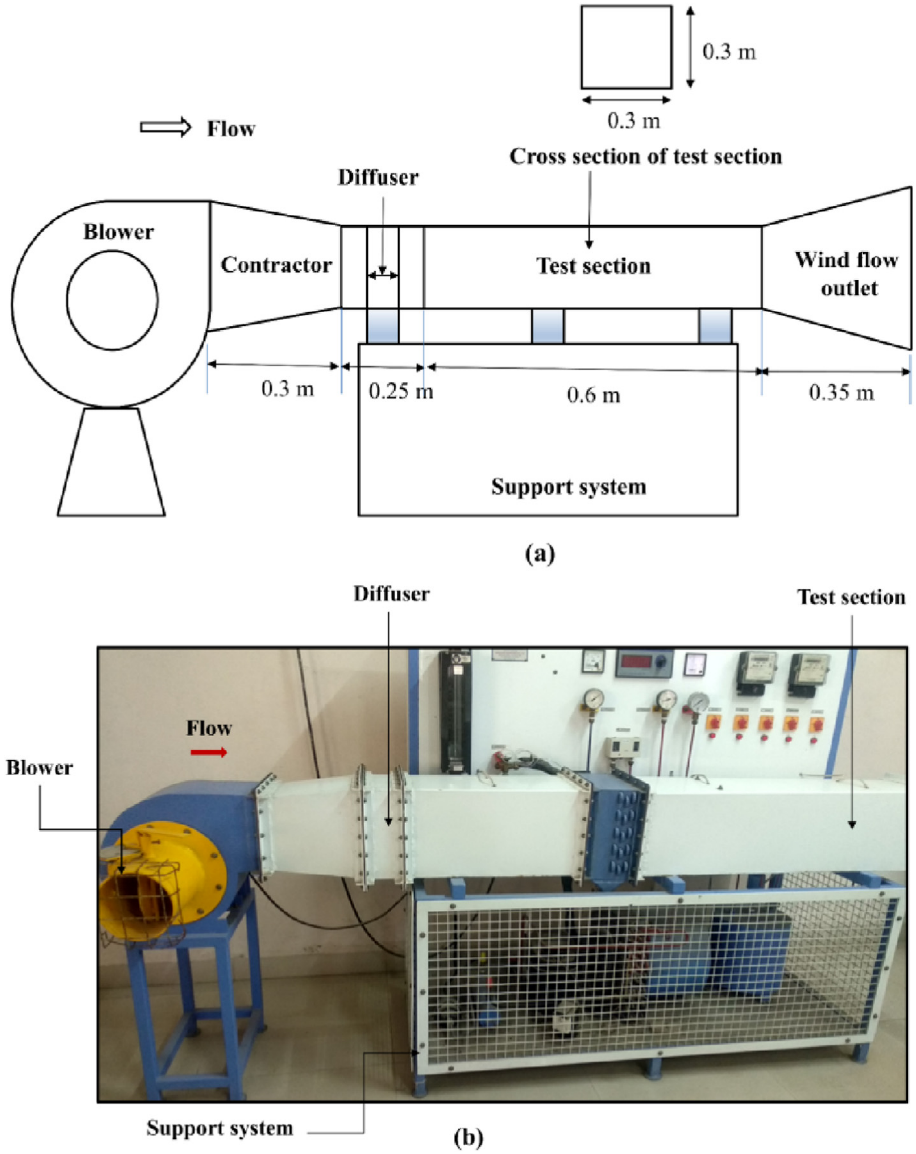


**Fig. 4.** (a) Schematic diagram of the wind tunnel setup; and (b) Wind tunnel experimental setup.

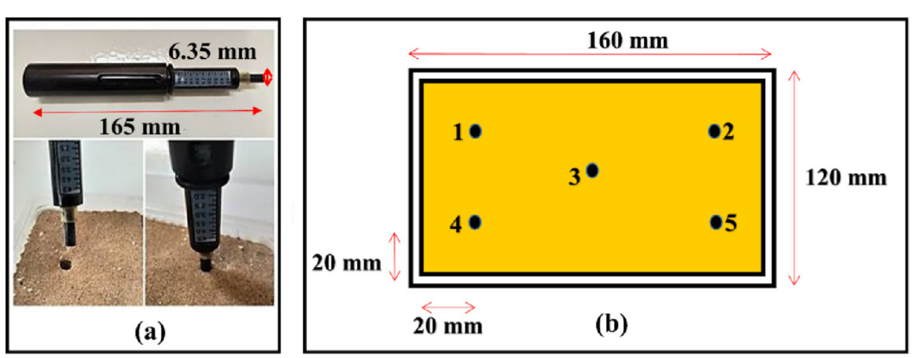


**Fig. 5.** (a) Measurement of unconfined compressive strength using pocket penetrometer; and (b) Five test locations for biotreated sample.

hence error up to 1/2 division on the scale is permissible. To measure the unconfined compressive strength of the biotreated sample surface, a pocket penetrometer was pushed into the top surface at five different locations (four at corners and one at center), as shown in Fig. 5b.

### 2.7. Measurement of calcium carbonate content

Calcimeter was used to determine the calcite precipitation percentage of the treated sand sample obtained from 0.5 cm depth from the top layer. The amount of carbon dioxide ($CO_2$) produced was measured after completing the reaction between carbonates and hydrochloric acid. An increase in pressure inside the calcimeter cylinder was measured using a pressure gage. The pressure reading was used to calculate the calcium carbonate content (Kalantary et al., 2019; Sharma et al., 2019; Almajed et al., 2020).

### 2.8. Bulk density

The weight of each tray of the sand sample was measured after the completion of each treatment cycle to check for an increase in the mass of the sample. As volume remains constant, bulk density was calculated using the following formula (Wang et al., 2018):

$$\rho = \frac{M - m}{V} \tag{2}$$

where $\rho$ is the bulk density of sand sample (g/cm$^3$), $M$ is the mass of treated sand sample including tray weight (g), $m$ is the empty weight of tray (g), and $V$ is the volume of the tray (cm$^3$).

### 2.9. Microscale identification analysis

SEM and EDX tests were performed to calculate the amount of calcite precipitation in the treated soil samples. The precipitation concentration was more at the top layer due to spraying on the top surface. Subsequently, the sample was collected from the top layer (at 0.5 cm depth). A piece from the biocemented sand sample was obtained for micro-characterization and kept in the oven for 24 h at 105 °C. The dried sample was grinded to fine powder using an agate mortar and pestle. For analysis of the presence of calcite precipitation, SEM images of gold sputter-coated samples were taken at 15 kV at different beam intensities (Wang et al., 2018; Sharma et al., 2019, 2021a). Analytical method EDX was used for the chemical characterization of materials. The calcium peak of the investigated samples was obtained from the spectrum, which was the output of EDX analysis.

## 3. Results and discussion

### 3.1. Analysis of treated sample surface thickness

The objective of the study was to minimize wind erosion by making an integrated layer at the top surface of the sample. The range of thickness for each sample was measured and is summarized in Table 2. Fig. 6 shows the measured thicknesses of the top layer with different cementation solutions and treatment times. The significant crust thickness was achieved in the case of 1:1 cementation solution treatment up to 15 d and 20 d. The crust thickness ranged in 10–21 mm with an average calcite content of 3.5%–3.8%, which was found effective to control wind erosion in the biotreated sample. The higher crust thickness shows that the calcite formation occurred between the sand grains due to deeper penetration of cementation solution from the top surface. The samples treated with 2:1 cementation solution for 5 d resulted in minimum thickness up to 2.5 mm, which shows binding of top surface particles only due to lack of deeper connectivity of particles. In the 2:1 cementation solution, the molarity of urea was twice that of the calcium chloride dihydrate, which resulted in a greater number of carbonate ions during the urea hydrolysis process and simultaneously increased the rate of reaction. Due to an increase in the rate of reaction, the calcite crystal formation occurred rapidly at the top surface only. On the other hand, treated samples for 5 d using 1:1 cementation solution showed 6.5 mm crust thickness, which confirms the effectiveness of solution towards cementation with the depth as compared to 2:1 cementation solution. Similar reaction kinetics and non-uniform precipitation of calcite in 2:1 cementation solution treated samples were observed by Sharma et al. (2019). It can also be interpreted from the results that the improvement in soil crust thickness with an increase in the treatment time was due to more calcium carbonate precipitation.

A similar range of crust thickness was achieved by Almajed et al. (2020) using enzyme induced calcite precipitation method. Li et al. (2018) investigated the bioremediation of aeolian sand using the MICP technique and observed the formation of bio-crust with suitable unconfined compressive strength improvement of 0.66 MPa with an average friction angle of 36° after 7 d of treatment. It was concluded that the crust formed after biotreatment of aeolian sand significantly showed resistance towards wind erosion. The results of the present study were consistent with the field study of Meng et al. (2021), which also showed that the crust thickness up to 12.5 mm resulted in an efficient reduction of wind erosion. Hence, a similar treatment strategy using 1:1 cementation solution and treatment up to a minimum of 15 d can be adopted for field applications.

### 3.2. Wind erosion resistance analysis

Wind erosion resistance of treated samples was measured in terms of mass losses at 0.01 g accuracy before and after wind tunnel testing at varying wind speeds. The weight loss in percentage for untreated sand was estimated as 8.2%, 34%, and 54.5% at 10 m/s, 20 m/s, and 30 m/s speeds, respectively. An increase in wind speed has led to more weight loss which was an indication of sandstorm disaster.

Fig. 7 shows images of the sand sample before and after wind tunnel testing. No visible changes were observed. It was found that the biotreated sample had cracks on the top surface, which may be due to excessive evaporation at the treatment temperature. Table 3 shows the percentage of weight loss after wind tunnel testing at different wind speeds of 10 m/s, 20 m/s, and 30 m/s during a 1-min duration. It was observed that the weight loss at 10 m/s speed with all treatment combinations (i.e. 5 d, 10 d, 15 d and 20 d with 2:1 and 1:1 cementation solutions) was almost negligible. It was also observed that the maximum loss in the weight was 0.14% at 20 m/s wind speed and 0.22% at 30 m/s wind speed for 5 d treatment with 2:1 cementation solution. Treatment with 1:1 cementation solution for 5 d resulted in weight loss of 0.01% at 20 m/s wind speed and

**Table 2**
Experimental result showing crust thickness, unconfined compressive strength, calcite content, and bulk density of biotreated sand samples.

| Sample No. | Cementation solution | Treatment time (d) | Crust thickness (mm) | Unconfined compressive strength (kPa) | Calcite content (%) | Bulk density (g/mL) |
|---|---|---|---|---|---|---|
| 1 | 2:1 | 5 | 0.5–2.5 | 0–24.51 | 1.76 | 1.515 |
| 2 | 2:1 | 10 | 2–7.5 | 49.03–73.54 | 1.89 | 1.544 |
| 3 | 2:1 | 15 | 3.5–9 | 49.03–122.58 | 2.17 | 1.546 |
| 4 | 2:1 | 20 | 8–17 | 98.06–147.1 | 2.46 | 1.549 |
| 5 | 1:1 | 5 | 2–6.5 | 24.5–49.03 | 2.1 | 1.536 |
| 6 | 1:1 | 10 | 7–12 | 122.58–171.62 | 2.44 | 1.575 |
| 7 | 1:1 | 15 | 10–16 | 171.62–220.64 | 3.52 | 1.583 |
| 8 | 1:1 | 20 | 15–21 | 196.13–269.68 | 3.84 | 1.618 |

Please cite this article as: Dagliya M et al., Experimental study on mitigating wind erosion of calcareous desert sand using spray method for microbially induced calcium carbonate precipitation, Journal of Rock Mechanics and Geotechnical Engineering, https://doi.org/10.1016/j.jrmge.2021.12.008

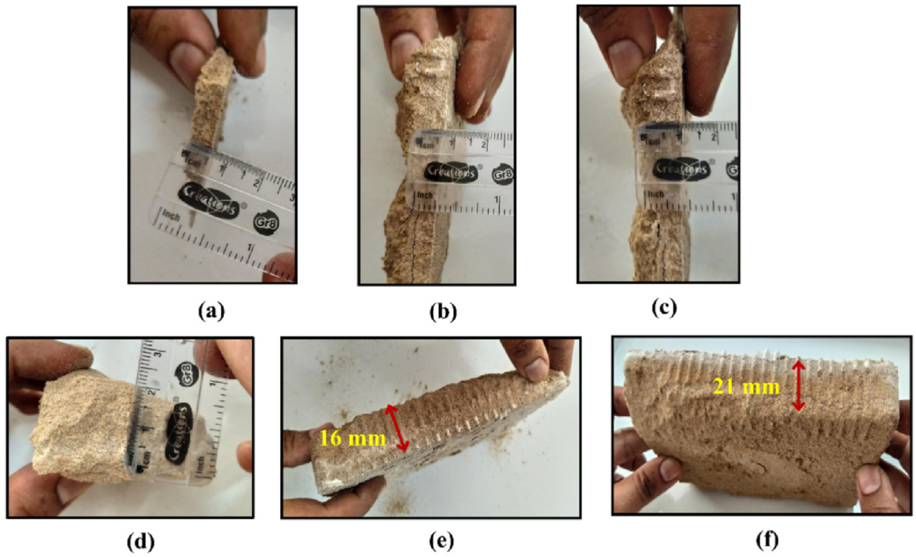


**Fig. 6.** Crust thickness formation for different cementation solutions and treatment times: (a) 1:1 cementation solution with 5 d treatment; (b) 2:1 cementation solution with 15 d treatment; (c) 1:1 cementation solution with 10 d treatment; (d) 2:1 cementation solution with 20 d treatment; (e) 1:1 cementation solution with 15 d treatment; and (f) 1:1 cementation solution with 20 d treatment.

0.02% at 30 m/s wind speed, which was negligible. Furthermore, with an increase in the treatment time (i.e. 10 d, 15 d and 20 d with both cementation solutions), the weight loss was almost negligible for 20 m/s and 30 m/s wind speeds.

The results of the present study are consistent with that of Zomorodian et al. (2019), as the MICP treated crust layers were found stable at the stimulated wind speed of 20 m/s at 20 cm above the surface layer. However, a different treatment method was adopted as the samples were cured up to 28 d with a single MICP spray. Meng et al. (2021) also demonstrated that the biotreated surface was found intact even after the exposure of 30 m/s wind speed for up to 2 min.

Fig. 8 shows that calcite content increases and wind erosion reduces (refer to Table 3) with an increase in treatment days. The 2:1 cementation solution for 5 d treatment was useful where the wind speed was low, but it was not applicable in the case of moving loads such as vehicles, persons, and animals. In the case of moving load, higher crust strength was required. For this purpose, a surface strength test should be conducted as the crust strength cannot be checked using wind tunnel testing. Consequently, wind erosion resistance of sand can effectively be improved using the spray method for the MICP treatment with an increasing number of treatment cycles.

### 3.3. *Surface strength analysis with the amount of precipitated calcite*

Fig. 8 shows the variation of calcite content at the top and bottom layers under different biotreatment conditions. It was noted that the calcite content percentage was greater at the top layer (i.e. directly treated layer) than the bottom layer. It was also observed that calcite content (after 20 d) percentage of the bottom layer for 1:1 treatment solution was almost the same as the top layer for 2:1 treatment solution (10 d after treatment). Similarly, the calcite content of the bottom layer for 2:1 solution (after 20 d of treatment) was almost the same as the top layer for 2:1 solution (5 d treatment). In summary, the intactness of the top and bottom layers was enhanced with an increase in the treatment time and treatment ratio. Fig. 8 shows that there is no significant variation in calcite content percent at different locations in the bottom layer for different biotreatment conditions.

Table 2 and Fig. 9 summarize the values of unconfined compressive strength and calcite content percentage for different treatment cycles. As evident from Fig. 9, for the top layer, 2:1 cementation solution after 20 d treatment had an average surface strength of 117.6 kPa, which was even less in comparison to 1:1 cementation solution after 10 d treatment (152.2 kPa). Interestingly, calcite content at the bottom layer was similar between the former and the latter as 2.46% and 2.44%, respectively. It could be due to higher calcite formation during the initial stage, which reacts fast and achieves more strength. It is reasonable to assume that calcium chloride dihydrate is similar for 2:1 and 1:1 solutions after 20 d and 10 d, respectively.

Table 2 shows that the upper and lower limits for the calcite content were overlapping with previous results for both ratios. For 2:1 solution, the increase in calcite content was 0.13% between 5 d and 10 d of treatment. The increase is mor than twice ($\sim$0.28) between 10 d and 15 d and also between 15 d and 20 d after treatment. For 1:1 solution, an increase in calcite content was 0.34% from 5 d to 10 d after treatment. However, it increased by 1.08% for 10–15 d and by 0.32% for 15–20 d. The increase in calcite content was higher during 10–15 d in both treatments. This proves that an increase in calcite content was much higher in 1:1 solution as compared to 2:1 solution. The result indicates that the effectiveness of treatment is higher between 10 d and 15 d after biotreatment. Pocket penetrometer was used to check the effectiveness of treatment for unconfined compressive strength of top layer under higher strain. Pocket penetrometer was pushed in the treated sample at five different locations (Fig. 5b) at 1 cm depth to know uniformity in surface strength. Fig. 10 shows the influence of various biotreatment conditions on the unconfined compressive strength at five different test locations. It was observed that there was no significant difference in strength. It was also observed that the unconfined compressive strength at the center location was higher in all the cases. Strength uniformity was observed on the sample treated with both cementaion solutions for 5 d. However, as the treatment time increases, the strength variation also increases at different test locations. Further studies are needed to

Please cite this article as: Dagliya M et al., Experimental study on mitigating wind erosion of calcareous desert sand using spray method for microbially induced calcium carbonate precipitation, Journal of Rock Mechanics and Geotechnical Engineering, https://doi.org/10.1016/j.jrmge.2021.12.008

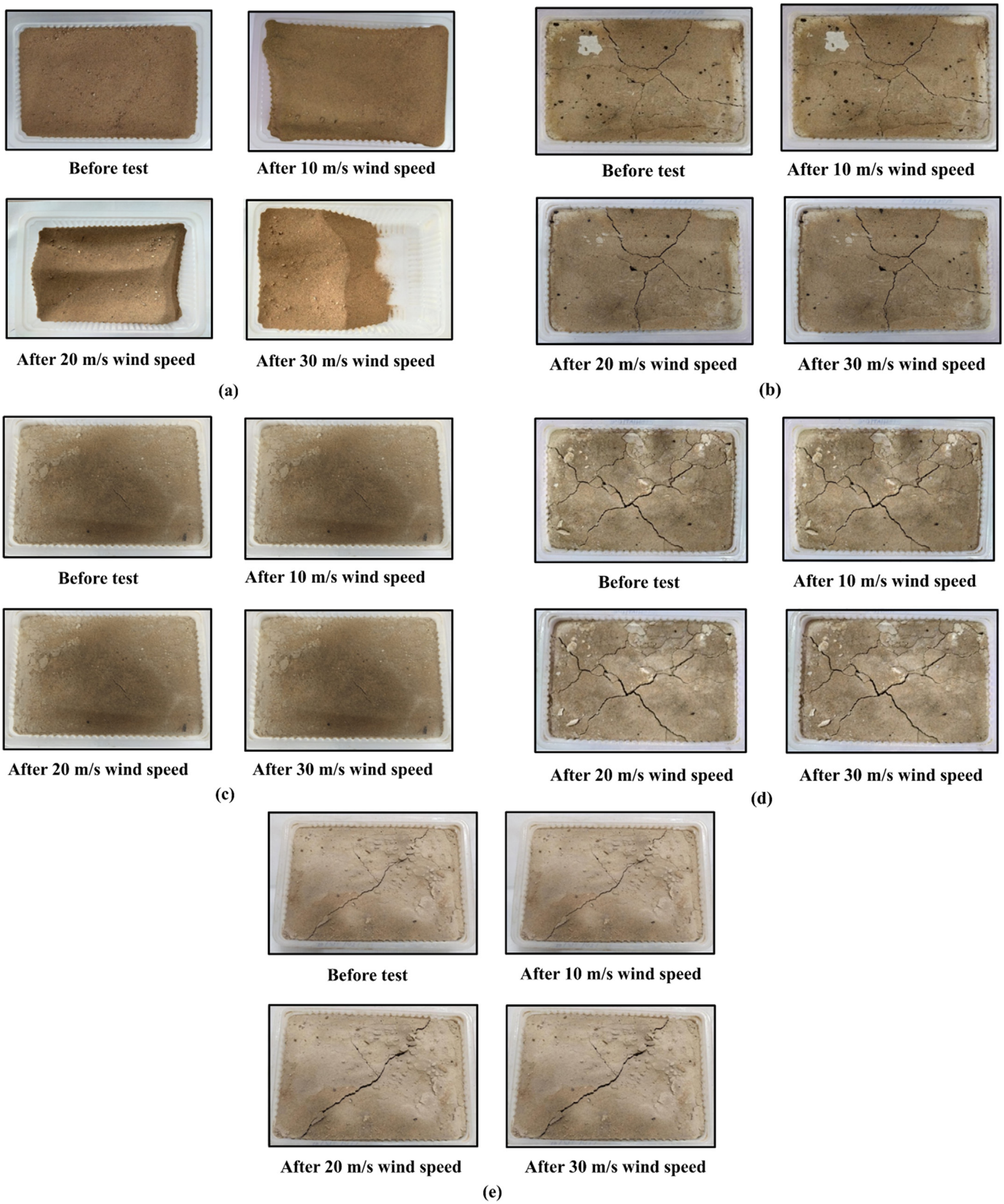


**Fig. 7.** Images of untreated and biotreated sand samples before and after wind tunnel testing at different wind speeds: (a) Untreated samples; (b) Biotreated sample with 2:1 cementation solution for 5 d; (c) Biotreated sample with 1:1 cementation solution for 5 d; (d) Biotreated sample with 2:1 cementation solution for 20 d; and (e) Biotreated sample with 1:1 cementation solution for 10 d.

Please cite this article as: Dagliya M et al., Experimental study on mitigating wind erosion of calcareous desert sand using spray method for microbially induced calcium carbonate precipitation, Journal of Rock Mechanics and Geotechnical Engineering, https://doi.org/10.1016/j.jrmge.2021.12.008

**Table 3**
Weight loss after wind tunnel testing at different wind speeds.

| Sample | Weight loss (%) | | |
|---|---|---|---|
| | 10 m/s wind speed | 20 m/s wind speed | 30 m/s wind speed |
| Untreated | 8.2 | 34 | 54.5 |
| 2:1/05 days | 0 | 0.14 | 0.22 |
| 2:1/10 days | 0 | 0.05 | 0.18 |
| 2:1/15 days | 0 | 0.03 | 0.06 |
| 2:1/20 days | 0 | 0.02 | 0.03 |
| 1:1/05 days | 0 | 0.01 | 0.02 |
| 1:1/10 days | 0 | 0.04 | 0.07 |
| 1:1/15 days | 0 | 0.02 | 0.04 |
| 1:1/20 days | 0 | 0.01 | 0.03 |

investigate the uniformity of treatments, especially in large scale testing.

The top surface of the treated sample with 1:1 cementation solution becomes stiffer as treatment days increase due to an increase in calcite content. For 1:1 cementation solution with 20 d of treatment, average surface strength and calcite content were 240.1 kPa and 3.84%, respectively. The results of the present study are consistent with that of Nikseresht et al. (2020). Calcium carbonate formation is the only factor that results in the formation of soil surface which provides resistance against penetration.

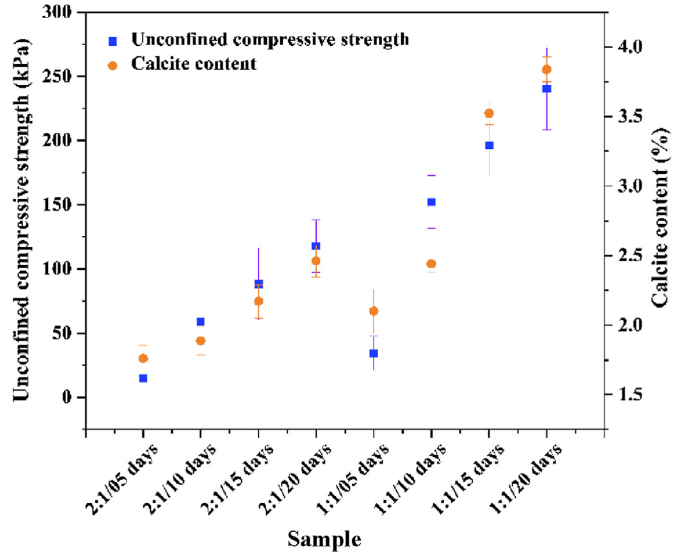


**Fig. 9.** Effect of various biotreatment conditions on unconfined compressive strength and calcite content of the top layer (i.e. 0.5 cm from the top layer) of biotreated sand samples.

### 3.4. Bulk density

The sand samples were treated for 5 d, 10 d, 15 d and 20 d with different cementation solutions. As the treatment duration was increased, it was noted that the calcite content also increased and the maximum value was obtained for 20 d of treatment (Fig. 11). It was also observed that for 1:1 cementation solution, bulk density was higher due to more calcite formation as compared to 2:1 solution. The mechanism of improving the bulk density of biocemented sand includes the important role of initial soil density in calcium carbonate crystal formation between the soil grains. The initial soil density significantly affects the effectiveness of calcite crystal formation and strength enhancement in the MICP technique. The mechanism of crystal formation between sand grains depends on the initial density of sand. Tsukamoto et al. (2013) explored the biocementation efficiency with three different initial relative densities of soil, i.e. 30%, 65%, and 85%. The results demonstrated higher calcite content at lower relative densities, but lower strength was observed as compared to higher initial relative density for biocemented samples. A similar influence of initial density was investigated by Cheng et al. (2014), and it was concluded that under the same calcium carbonate content, the samples with high initial density resulted in higher strength than the biotreated samples with lower initial density. The major reason behind the higher strength at the high initial density of biocemented sample was the compactness of sand grains. The sand particles are closed together in compacted sand columns, thus the

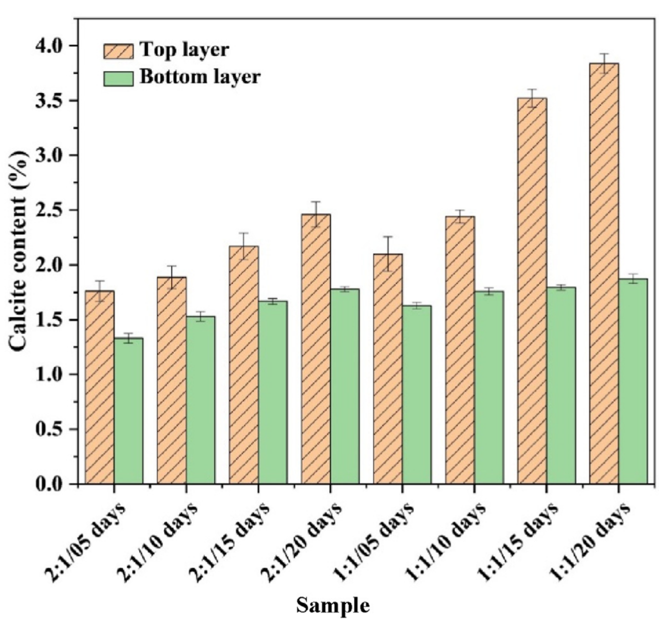


**Fig. 8.** Calcite content variation with different biotreatment conditions for top and bottom layers of biotreated sand samples.

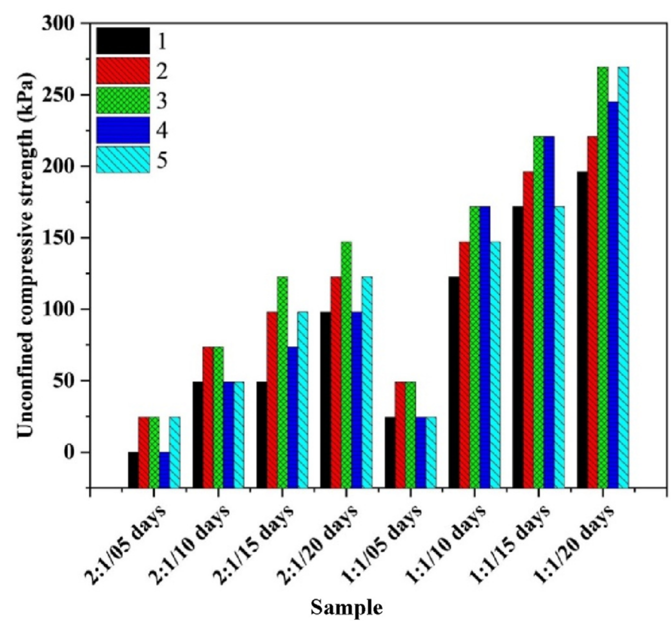


**Fig. 10.** Effect of various biotreatment conditions on unconfined compressive strength at different test locations.

Please cite this article as: Dagliya M et al., Experimental study on mitigating wind erosion of calcareous desert sand using spray method for microbially induced calcium carbonate precipitation, Journal of Rock Mechanics and Geotechnical Engineering, https://doi.org/10.1016/j.jrmge.2021.12.008

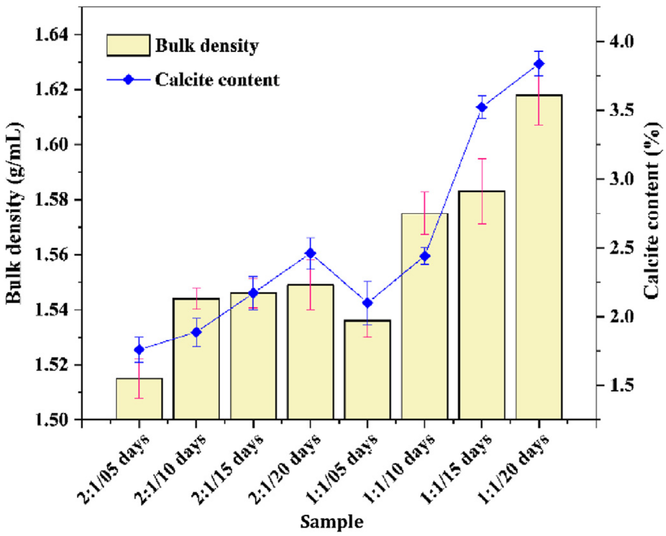


**Fig. 11.** Variation of bulk density and calcite content of the top layer (i.e. 0.5 cm from the top layer) with different biotreatment combinations.

calcium carbonate crystal formation occurs for shorter distances and creats intact bond between the sand grains. This proves that the MICP crust formation and strength improvement depend on the initial soil density. The bulk density of biotreated soil rises with the increase in calcium carbonate content. The results of present study are consistent with that of Wang et al. (2018), which also demonstrated the increase of bulk density with calcium carbonate formation in every treatment cycle.

### 3.5. *Microscale identification analysis*

Figs. 12 and 13 show the micro and chemical characterization of materials showing the SEM images and peaks of investigated samples from EDX analysis for untreated and biotreated sand samples. Untreated sand was calcareous sand as the presence of calcium was observed in EDX spectra (Fig. 12a). The presence of calcite content after solidification of the top surface of the sample was also analyzed on the micro-scale using SEM analysis. After analyzing the SEM image for untreated sand (Fig. 13a), it was observed that untreated sand has no bond between the particles and had a relatively smooth surface. SEM analysis was also performed at 900 × and 1800 × magnifications for treated samples taken at 0.5 cm depth from the top surface to observe calcite crystal formation. It was found that pore space was reduced between particles and bonding was observed among particles in the form of calcite precipitation, as shown in Fig. 13b.

## 4. Conclusions

This study focused on using the spray method for MICP treatment to control wind erosion of sandy soil. The treatment was conducted with 2:1 and 1:1 cementation solutions for 5 d, 10 d, 15 d and 20 d. The treated samples were tested for wind erosion resistance, unconfined compressive strength, calcite content, EDX, and SEM. The following conclusion can be drawn from the present study:

(1) The spray method for MICP treatment with 2:1 and 1:1 cementation solutions enhanced stiffness at the top layer and also showed satisfactory results in controlling wind

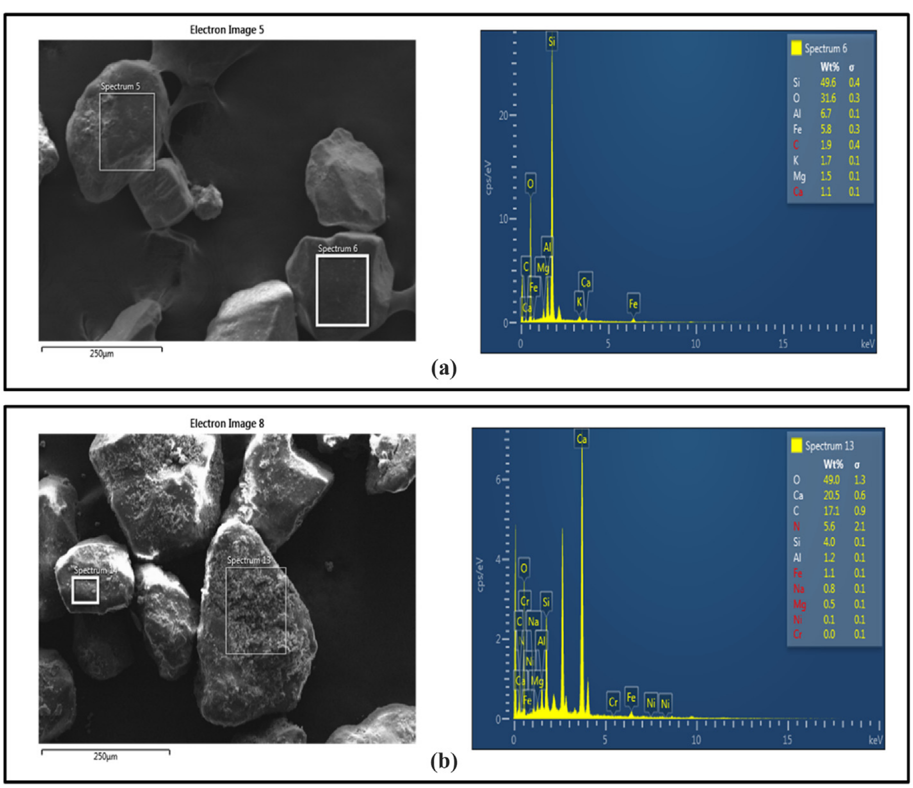


**Fig. 12.** EDX analysis: (a) Untreated and (b) biotreated sands.

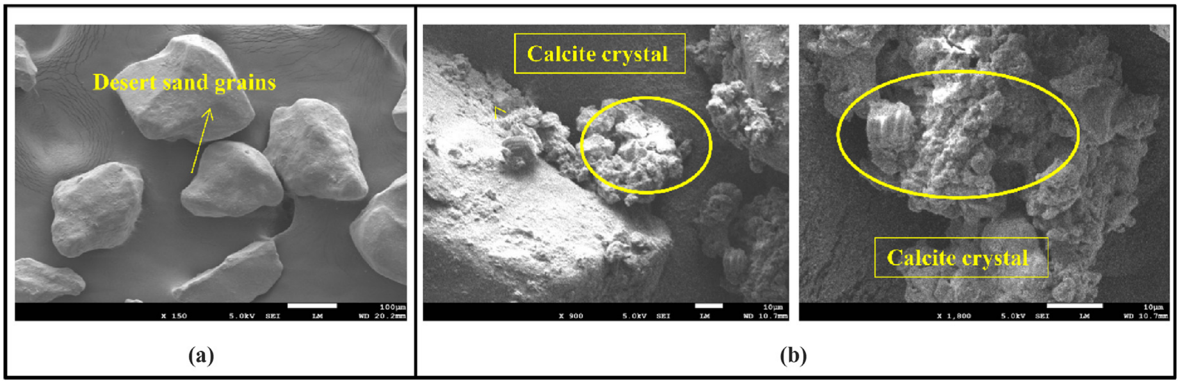


**Fig. 13.** SEM images: (a) untreated sand and (b) calcite crystal formation after biotreatment.

erosion. The possible mechanism for this is the formation of calcium carbonate, which was found present between the sand particles. MICP catalyzed the bonding of particles in a very firm manner, and hence resulted in the reduction of wind erosion.

(2) Wind erosion corresponding to 10 m/s wind speed was nearly negligible for soil treated with 1:1 cementation solution for 5 d. However, for higher wind speeds, 1:1 cementation solution after 15 d was more desirable in controlling erosion. The weight loss percentage at the wind speed of 30 m/s for untreated sand was more than 50%, whereas for biotreated sand, it was only 0.22%.
(3) The values of calcite content, crust thickness, and unconfined compressive strength were enhanced with an increase in treatment days. It was noted that the result obtained by 2:1 cementation solution with 20 d treatment and 1:1 cementation solution with 10 d treatment at 36 °C temperature was almost the same. The 1:1 cementation solution was effective as compared to the 2:1 cementation solution.
(4) It was also observed that as treatment days increased, calcite crystal formation growth along with bonding between soil particles also improved. Thus, the spray method for MICP treatment was effective for the formation of calcite crystals in the desert soil media to mitigate wind erosion.

It should be noted that the conclusions are based on given experimental conditions. The soil samples were tested at a short interval of duration, i.e. 1 min, during the wind tunnel testing. The performance of biocemented sand while exposed to higher wind speeds for longer duration needs to be investigated. The current study does not include the strength of the crust developed for moving loads such as vehicles, people, and animals. Further studies are needed for scaling up the technology to the field level.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Acknowledgment

The first is grateful to Prestige Institute of Engineering, Management, and Research, Indore, India for their support throughout the research work. The second and fourth authors are also grateful to the Guangdong Department of Science and Technology, China for “Overseas Famous Teacher Project” (Grant No. 2020A1414010268).

## References

Almajed, A., Lemboye, K., Arab, M.G., Alnuaim, A., 2020. Mitigating wind erosion of sand using biopolymer-assisted EICP technique. Soils Found. 60 (2), 356–371.
Bu, C., Wen, K., Liu, S., Ogbonnaya, U., Li, L., 2018. Development of bio-cemented constructional materials through microbial induced calcite precipitation. Mater. Struct. 51, 30.
Cheng, L., Cord-Ruwisch, R., 2012. In situ soil cementation with ureolytic bacteria by surface percolation. Ecol. Eng. 42, 64–72.
Cheng, L., Shahin, M., Cord-Ruwisch, R., Addis, M., Haranto, T., Elms, C., 2014. Soil stabilisation by microbial-induced calcite precipitation (MICP): investigation into some physical and environmental aspects. In: 7th International Congress on Environmental Geotechnics. Engineers Australia, Melbourne, Australia, pp. 1105–1112.
Chou, C.W., Seagren, E.A., Aydilek, A.H., Lai, M., 2011. Biocalcification of sand through ureolysis. J. Geotech. Geoenviron. Eng. 137 (12), 1179–1189.
DeJong, J.T., Fritzges, M.B., Nüsslein, K., 2006. Microbially induced cementation to control sand response to undrained shear. J. Geotech. Geoenviron. Eng. 132 (11), 1381–1392.
Deléglise, C., Loucougaray, G., Alard, D., 2011. Effects of grazing exclusion on the spatial variability of subalpine plant communities: a multiscale approach. Basic Appl. Ecol. 12 (7), 609–619.
Fattahi, S.M., Soroush, A., Huang, N., 2020. Biocementation control of sand against wind erosion. J. Geotech. Geoenviron. Eng. 146 (6), 04020045.
Fick, S.E., Barger, N., Tatarko, J., Duniway, M.C., 2020. Induced biological soil crust controls on wind erodibility and dust (PM10) emissions. Earth Surf. Process. Landforms 45 (1), 224–236.
Gadi, V.K., Bordoloi, S., Garg, A., Kobayashi, Y., Sahoo, L., 2016. Improving and correcting unsaturated soil hydraulic properties with plant parameters for agriculture and bioengineered slopes. Rhizosphere 1, 58–78.
Goudie, A.S., Middleton, N.J., 2006. Desert Dust in the Global System. Springer, New York, USA.
Gowthaman, S., Iki, T., Nakashima, K., Ebina, K., Kawasaki, S., 2019a. Feasibility study for slope soil stabilization by microbial induced carbonate precipitation (MICP) using indigenous bacteria isolated from cold subarctic region. SN Appl. Sci. 1, 1480.
Gowthaman, S., Mitsuyama, S., Nakashima, K., Komatsu, M., Kawasaki, S., 2019b. Biogeotechnical approach for slope soil stabilization using locally isolated bacteria and inexpensive low-grade chemicals: a feasibility study on Hokkaido expressway soil. Jpn. Soils. Found. 59 (2), 484–499.
Gowthaman, S., Nakashima, K., Kawasaki, S., 2020. Freeze-thaw durability and shear responses of cemented slope soil treated by microbial induced carbonate precipitation. Soils Found. 60 (4), 840–855.
Gowthaman, S., Nawarathna, T.H.K., Nayanthara, P.G.N., Nakashima, K., Kawasaki, S., 2021a. The amendments in typical microbial induced soil stabilization by low-grade chemicals, biopolymers and other additives : a review. In: Achal, V., Chin, C.S. (Eds.), Building Materials for Sustainable and Ecological Environment. Springer, Singapore, pp. 49–72.
Gowthaman, S., Nakashima, K., Kawasaki, S., 2021b. Effect of wetting and drying cycles on the durability of bio-cemented soil of expressway slope. Int. J. Environ. Sci. Technol. https://doi.org/10.1007/s13762-021-03306-1.
Gupta, J.P., 1986. Moisture and thermal regimes of the desert soils of Rajasthan, India, and their management for higher plant production. J. Hydrol. Sci. 31, 347–359.
IS:1498-1970, 2002. Classification and Identification of Soils for General Engineering Purposes. Bureau of Indian Standards, New Delhi, India.

Kalantary, F., Abbasi Govanjik, D., Safdari Seh Gonbad, M., 2019. Stimulation of native microorganisms for improving loose salty sand. Geomicrobiol. J. 36 (6), 533–542.
Karol, R.H., 2003. Chemical Grouting and Soil Stabilization. Marcel Dekker, New York, USA.
Kou, H., Wu, C., Ni, P., Jang, B., 2020. Assessment of erosion resistance of biocemented sandy slope subjected to wave actions. Appl. Ocean Res. 105, 102401.
Le Houérou, H.N., 2001. Biogeography of the arid steppeland north of the Sahara. J. Arid Environ. 48 (2), 103–128.
Li, C., Yao, D., Liu, S., Zhou, T.J., Bai, S., Gao, Y., Li, L., 2018. Improvement of geomechanical properties of bio-remediated aeolian sand. Geomicrobiol. J. 35 (2), 132–140.
Maleki, M., Ebrahimi, S., Asadzadeh, F., Emami Tabrizi, M., 2016. Performance of microbial-induced carbonate precipitation on wind erosion control of sandy soil. Int. J. Environ. Sci. Technol. 13, 937–944.
Meng, H., Gao, Y., He, J., Qi, Y., Hang, L., 2021. Microbially induced carbonate precipitation for wind erosion control of desert soil: field-scale tests. Geoderma 383, 114723.
Miao, L., Wu, L., Sun, X., 2020a. Enzyme-catalysed mineralisation experiment study to solidify desert sands. Sci. Rep. 10 (1), 10611.
Miao, L., Wu, L., Sun, X., Li, X., Zhang, J., 2020b. Method for solidifying desert sands with enzyme-catalysed mineralization. Land Degrad. Dev. 31 (11), 1317–1324.
Mitchell, J.K., Santamarina, J.C., 2005. Biological considerations in geotechnical engineering. J. Geotech. Geoenviron. Eng. 131 (10), 1222–1233.
Moharana, P.C., Santra, P., Singh, D.V., Kumar, S., Goyal, R.K., Machiwal, D., Yadav, O.P., 2016. ICAR-central arid zone research Institute, Jodhpur: erosion processes and desertification in the Thar desert of India. Proc. Indian Natl. Sci. Acad. 82 (3), 1117–1140.
Mwandira, W., Nakashima, K., Kawasaki, S., 2017. Bioremediation of lead-contaminated mine waste by *Pararhodobacter* sp. based on the microbially induced calcium carbonate precipitation technique and its effects on strength of coarse and fine grained sand. Ecol. Eng. 109, 57–64.
Nikseresht, F., Landi, A., Sayyad, G., Ghezelbash, G., Schulin, R., 2020. Sugarcane molasse and vinasse added as microbial growth substrates increase calcium carbonate content, surface stability and resistance against wind erosion of desert soils. J. Environ. Manag. 268, 110639.
Okwadha, G.D.O., Li, J., 2010. Optimum conditions for microbial carbonate precipitation. Chemosphere 81 (9), 1143–1148.
Omoregie, A.I., Siah, J., Pei, B.C.S., Yie, S.P.J., Weissmann, L.S., Enn, T.G., Rafi, R., Zoe, T.H.Y., Mkwata, H.M., Sio, C.A., Nissom, P.M., 2018. Integrating biotechnology into geotechnical engineering: a laboratory exercise. Trans. Sci. Technol. 5 (2), 76–87.
Poulsen, T.G., Cai, W., Garg, A., 2020. Water evaporation from cracked soil under moist conditions as related to crack properties and near-surface wind speed. Eur. J. Soil Sci. 71 (4), 627–640.
Roy, P.D., Singhvi, A.K., 2016. Climate variation in the Thar desert since the last glacial maximum and evaluation of the indian monsoon. TIP 19 (1), 32–44.
Sharma, M., Satyam, N., 2021. Strength and durability of biocemented sands : wetting-drying cycles, ageing effects, and liquefaction resistance. Geoderma 402, 115359.
Sharma, M., Satyam, N., Reddy, K.R., 2021a. Rock-like behavior of biocemented sand treated under non-sterile environment and various treatment conditions. J. Rock Mech. Geotech. Eng. 13 (3), 705–716.
Sharma, M., Satyam, N., Reddy, K.R., 2019. Investigation of various gram-positive bacteria for MICP in Narmada Sand, India. Int. J. Geotech. Eng. 15 (2), 220–234.
Sharma, M., Satyam, N., Reddy, K.R., 2021b. Hybrid bacteria mediated cemented sand: microcharacterization, permeability, strength, shear wave velocity, stress-strain, and durability. Int. J. Damage Mech. https://doi.org/10.1177/1056789521991196.
Sharma, M., Satyam, N., Reddy, K.R., 2021d. Comparison of Improved Shear Strength of Biotreated Sand Using Different Ureolytic Strains and Sterile Conditions. Soil Use Manag. https://doi.org/10.1111/sum.12690.
Sharma, M., Satyam, N., Reddy, K.R., 2020. Strength enhancement and lead immobilization of sand using consortia of bacteria and blue-green algae. J. Hazard. Toxic Radioact. Waste 24 (4). https://doi.org/10.1061/(ASCE)HZ.2153-5515.0000548.
Sharma, M., Satyam, N., Reddy, K.R., 2021e. State of the art review of emerging and biogeotechnical methods for liquefaction mitigation in sands. J. Hazard. Toxic Radioact. Waste 25 (1). https://doi.org/10.1061/(ASCE)HZ.2153-5515.0000557.
Sharma, M., Satyam, N., Reddy, K.R., 2021f. Effect of freeze-thaw cycles on engineering properties of biocemented sand under different treatment conditions. Eng. Geol. 284, 106022.
Sharma, M., Satyam, N., Tiwari, N., Sahu, S., Reddy, K.R., 2021c. Simplified biogeochemical numerical model to predict pore fluid chemistry and calcite precipitation during biocementation of soil. Arabian J. Geosci. 14, 807.
Sharma, M., Satyam, N., Reddy, K.R., 2021g. Liquefaction resistance of biotreated sand before and after exposing to weathering conditions. Indian Geotech. J. https://doi.org/10.1007/s40098-021-00576-x.
Simatupang, M., Okamura, M., Hayashi, K., Yasuhara, H., 2018. Small-strain shear modulus and liquefaction resistance of sand with carbonate precipitation. Soil Dynam. Earthq. Eng. 115, 710–718.
Soon, N.W., Lee, L.M., Khun, T.C., Ling, H.S., 2013. Improvements in engineering properties of soils through microbial-induced calcite precipitation. KSCE J. Civ. Eng. 17, 718–728.
Strong, C.L., Leys, J.F., Raupach, M.R., Bullard, J.E., Aubault, H.A., Butler, H.J., McTainsh, G.H., 2016. Development and testing of a micro wind tunnel for on-site wind erosion simulations. Environ. Fluid Mech. 16, 1065–1083.
Sun, X., Miao, L., Tong, T., Wang, C., 2019. Study of the effect of temperature on microbially induced carbonate precipitation. Acta. Geotech. 14, 627–638.
Sun, X., Miao, L., Tong, T., Wang, C., 2018. Improvement of microbial-induced calcium carbonate precipitation technology for sand solidification. J. Mater. Civ. Eng. 30 (11), 04018301.
Tiwari, N., Satyam, N., 2020. An experimental study on the behavior of lime and silica fume treated coir geotextile reinforced expansive soil subgrade. Eng. Sci. Technol. 23 (5), 1214–1222.
Tiwari, N., Satyam, N., 2019. Experimental study on the influence of polypropylene fiber on the swelling pressure expansion attributes of silica fume stabilized clayey soil. Geosciences 9 (9), 377.
Tiwari, N., Satyam, N., 2021. Coupling effect of pond ash and polypropylene fiber on strength and durability of expansive soil subgrades: an integrated experimental and machine learning approach. J. Rock Mech. Geotech. Eng. 13 (5), 1101–1112.
Tiwari, N., Satyam, N., Shukla, K.S., 2020a. An experimental study on micro-structural and geotechnical characteristics of expansive clay mixed with EPS granules. Soils Found. 60 (3), 705–713.
Tiwari, N., Satyam, N., Patva, J., 2020b. Engineering characteristics and performance of polypropylene fibre and silica fume treated expansive soil subgrade. Int. J. Geosynth. Ground Eng. 6, 18.
Tiwari, N., Satyam, N., Puppala, A.J., 2021a. Strength and durability assessment of expansive soil stabilized with recycled ash and natural fibers. Transp. Geotech. 29, 100556.
Tiwari, N., Satyam, N., Sharma, M., 2021b. Micro-mechanical performance evaluation of expansive soil biotreated with indigenous bacteria using MICP method. Sci. Rep. 11, 10324.
Tiwari, N., Satyam, N., Singh, K., 2020c. Effect of curing on micro-physical performance of polypropylene fiber reinforced and silica fume stabilized expansive soil under freezing thawing cycles. Sci. Rep. 10 (1), 7624.
Tsukamoto, M., Inagaki, T., Sasaki, Y., Oda, K., 2013. Influence of relative density on microbial carbonate precipitation and mechanical properties of sand. In: Proceedings of the 18th International Conference on Soil Mechanics and Geotechnical Engineering. Presses des Ponts, Paris, France, pp. 2613–2616.
Van Pelt, R.S., Zobeck, T.M., Baddock, M.C., Cox, J.J., 2010. Design, construction, and calibration of a portable boundary layer wind tunnel for field use. Trans. ASABE (Am. Soc. Agric. Biol. Eng.) 53, 1413–1422.
Verdoodt, A., Mureithi, S.M., Ye, L., Van Ranst, E., 2009. Chronosequence analysis of two enclosure management strategies in degraded rangeland of semi-arid Kenya. Agric. Ecosyst. Environ. 129, 332–339.
Wang, Z., Zhang, N., Ding, J., Lu, C., Jin, Y., 2018. Experimental study on wind erosion resistance and strength of sands treated with microbial-induced calcium carbonate precipitation, 2018 Adv. Mater. Sci. Eng. 3463298.
Zomorodian, S.M.A., Ghaffari, H., O'Kelly, B.C., 2019. Stabilisation of crustal sand layer using biocementation technique for wind erosion control. Aeolian Res. 40, 34–41.

Please cite this article as: Dagliya M et al., Experimental study on mitigating wind erosion of calcareous desert sand using spray method for microbially induced calcium carbonate precipitation, Journal of Rock Mechanics and Geotechnical Engineering, https://doi.org/10.1016/j.jrmge.2021.12.008