MICP Based Indian Desert Sand Stabilization

Monika Dagliya[1][0000-0001-5267-5294] and Neelima Satyam[2][0000-0002-5434-0671]

[1]Doctoral Student, Department of Civil Engineering, Indian Institute of Technology Indore, India
phd2001204003@iiti.ac.in

[2]Associate Professor, Department of Civil Engineering, Indian Institute of Technology Indore, India
neelima.satyam@iiti.ac.in

Abstract: The present experimental work assesses the practicability of the MICP (microbial induced calcite precipitation) method to enhance resistance against wind generated sand erosion of Indian desert sand. A 45°C temperature was maintained during biotreatment. The sand treatment was performed using the spray method for both *S. pasteurii* bacterial solution and 0.5 M cementation solution. The treatment was performed for 7, and 14 days cycles using a 0.25 pore volume solution. Wind-induced sand erosion was measured at different wind speeds (5 m/s, 15 m/s, and 25 m/s) using wind tunnel testing (WTT). A pocket penetrometer (PP) was used to measure the crust's strength. Calcite formation was measured using a calcimeter. Micro characterization of untreated and biotreated sand samples was performed using SEM, and EDX analysis. The results confirmed that sand erosion increased as the wind speed increased for untreated sand, but negligible erosion was observed for biotreated sand. Compressive strength and percentage calcite content were measured and it was found that both increase with treatment duration. Calcium peaks of biotreated sand samples were observed in EDX analysis. Through SEM pictures, the formation of the bond among sand particles was seen.

K**eywords:** Sand erosion, MICP, Crust strength, Wind tunnel, Pocket penetrometer

Introduction

A sandstorm is a severe global natural catastrophe. Sandstorms affect fugitive dust particles and loose sand to erode, which degrades the ground in dry and semi-arid regions. Approximately 41% of the Global land surface is under desertification, which affects around 39% of the world's population and it is a serious menace to the ecosystem as it hinders stability and economic growth in desert areas (Miao et al., 2020a).

In India, around 32 million hectares of land are severely distressed by desertification. The North-western part of India i.e., Rajasthan state alone contributes 62% part of the desert (Moharana et al., 2016). Around 70% of the area and 40% of the population of Rajasthan are suffering from wind induced soil erosion (Roy and Singhvi, 2016). Thar desert of Rajasthan is among the top 20 deserts in the world. It alone covers 170000 km² land area (Dagliya et al., 2022c).

The MICP approach has emerged as a viable strategy for increasing soil properties in recent years. The soil is bound and restrained against wind pressure by a calcium carbonate crust in the MICP process. The benefits of carbonate precipitation as a biomineralization technique are widely explained. However, by altering the nutrition and cementation solutions, the cost of this procedure can be changed. The MICP technique, which encourages bacterial growth, includes an expensive component called nutrient broth. According to a study on cementation solution optimization by Sharma et al. (2021b), high calcite precipitation and therefore greater strength were produced by injecting or spraying 0.5 pore volumes of cementation solution at a regular interval of 24 hours.

An integrated thin stiff layer was produced after the sand crust was treated using the MICP approach. By limiting dust, this layer stopped wind induced sand erosion. It must be noted that particles lying below the layer are untreated and unintegrated. Subsequently, the movement of the thin layer leads to erosion

(Poulsen et al., 2020). Also, strength of crust and thickness of the layer is under explored (Sun et al., 2018; Wang et al., 2018). Both must be investigated post treatment, for evaluating the how well the treatment worked at different wind speed.

The purpose of the current investigation is to examine the effect of MICP treatment on soil crust strength and hence reduction in wind induced sand erosion. 2:1 and 1:1 cementation solution were used in MICP treatment spray method and to replicate field environment, 45˚C temperature was maintained. 2:1 cementation solution, where concentration of urea (0.5M) was double to that of calcium chloride dehydrate (0.25M). similarly, 1:1 cementation solution where calcium chloride dehydrate and urea were same (0.5M) were used. The wind tunnel test was conducted at varying wind speeds and erosion of untreated and biotreated soil were analysed. The UCS test was applied, using a pocket penetrometer (PP), to assess top crust intensity of biotreated sand samples. EDX and SEM tests were performed to analyse $CaCo_3$ formation among sand particles.

Materials and Methods

Untreated Desert sand properties

For the current study, poorly graded desert sand as per IS:1498–1970, 2002 was collected from Tinwari village, of Jodhpur district, Rajasthan, India. Figure 1 shows the particle size distribution curve for sand sample. The D_{50} (mean grain size), specific gravity, e_{max} and e_{min} for sand sample were 0.212 mm, 2.75, 0.903, and 0.616 respectively.

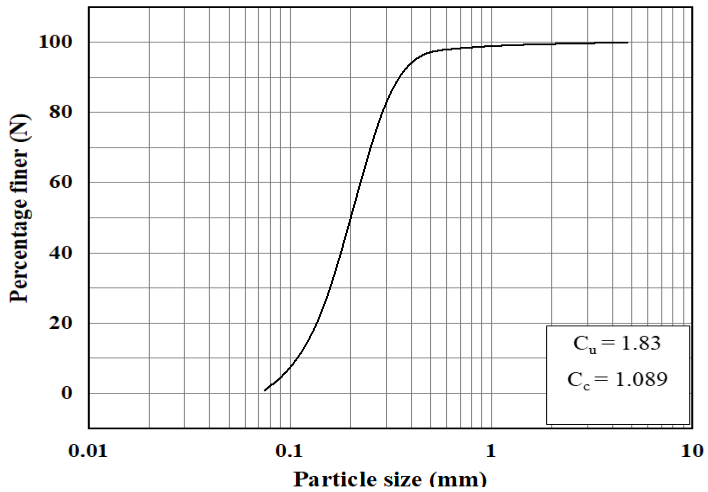

Figure 1. particle size distribution curve

Bacterial solution

Figure 2 shows the bacterial cultivation process. One litre nutrient broth solution was prepared by mixing 25-gram powder nutrient broth along with water. Autoclaving was performed for 20 minutes at 121˚C temperature and pressure was maintained at 15 psi. Inoculation of strain was performed in a laminar airflow cabinet. The inoculated solution was kept in an incubator. Rotation speed 200 rpm and 30˚C temperature were maintained for one day so that bacteria growth could be started. With the help of spectrophotometer optical density (OD) was measured. Optical Density observed as 1.18 at wavelength of 600 nm (Sharma et al., 2019).

The following equation can be used to compute the bacteria cell concentration (Y) in a per-ml solution, which exhibits a direct relationship with OD. (Sharma et al., 2021a).

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

Y was observed as 1.07×10^{11} cells/litre using the above equation.

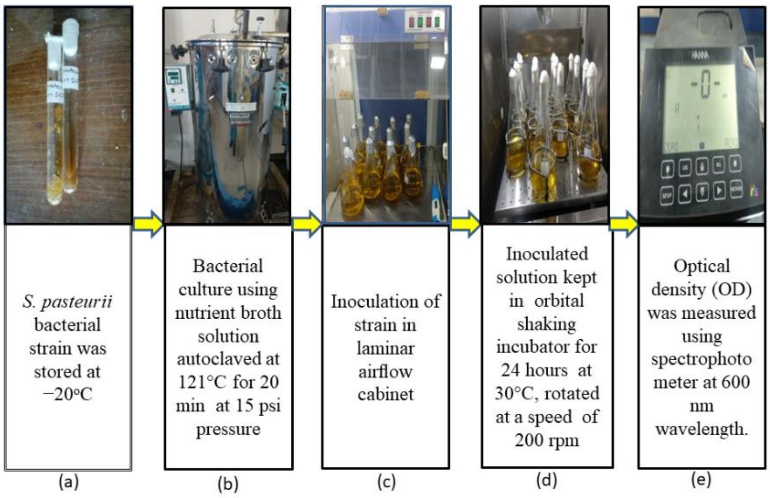

Figure 2. Bacterial solution preparation process (Dagliya et al., 2022a)

Cementation solution

Urea, sodium bicarbonate, ammonium chloride, calcium chloride dihydrate and nutrient broth (NB) were used to prepare cementation solution. Table 1 provides a summary of the various masses of the individual component for varying cementation media concentrations. Sodium bicarbonate and ammonium chloride performs the screen role in cementation media (Sharma et al., 2019).

Table 1 Mass of cementation solution components (Sharma et al., 2020)

S. No.	Components	Concentration of urea: calcium chloride dehydrate (2:1) gm/l	Concentration of urea: calcium chloride dehydrate (1:1) gm/l
1	Calcium chloride dihydrate	36.75	73.50
2	Urea	30.03	30.03
3	Nutrient broth	3	3
4	Sodium bicarbonate	2.12	2.12
5	Ammonium chloride	10	10

Biotreatment process

Figure 3 explained the biotreatment process. 980 gm sand sample was filled in a polypropylene plastic tray. For bacterial attachment, 200 ml bacterial solution at the rate of 15 ml/min was sprayed over filled sample and left for 1 day (Sharma et al., 2021b; Wang et al., 2018). Next day, 0.25 PV cementation solution without calcium chloride dihydrate was sprayed over the sample surface and again left for 1 day called simulation period. Less pore volume was used so that only upper crust gets treatment (Maleki et al., 2016). The 0.25 PV cementation solution was sprayed for treatment duration, after attachment and the simulation period. The sand was biotreated for 7 and 14 days treatment duration. All samples were stored in the oven at a uniform temperature of 45°C throughout treatment duration to replicate field condition. All specimen was taken out, solution was sprayed and put back in the oven. After 7 days of treatment, 50% specimens were removed from the oven, and treatment for 14 days continued with the same process for remaining specimen.

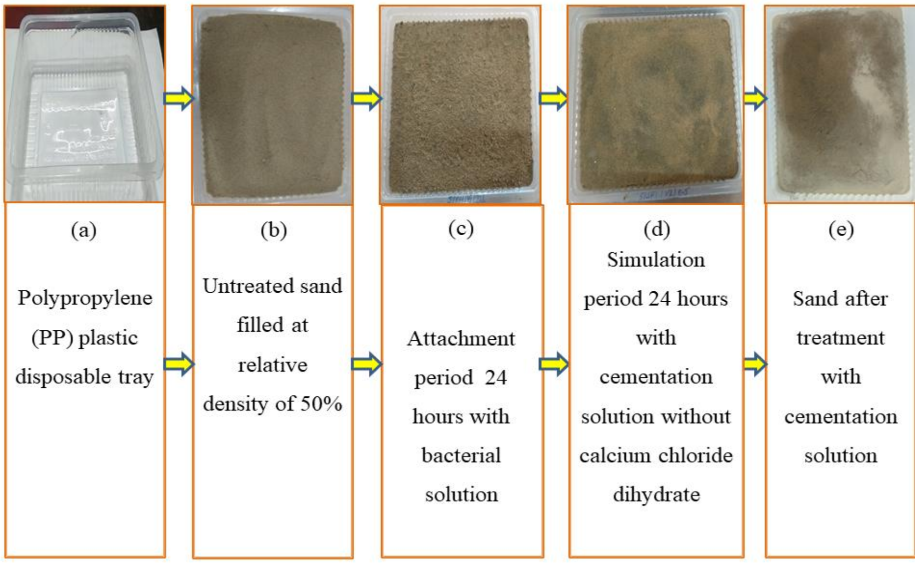

Figure 3. Biotreatment process

Sand erosion testing experimental set up (Wind tunnel)

WTT was performed for the treated and untreated sand samples to know resistance to wind induced sand erosion. The wind tunnel setup (Figure 4) has cross-section of 30 cm x 30 cm in size (Dagliya et al., 2022b), was used to performed testing at various wind speeds of (5, 15, and 25 meter/second) for a single minute span (Miao et al., 2020b). Anemometer was used to cross check the wind velocity of the set up (Poulsen et al., 2020). In the current study, visual operation and mass difference were used to measure wind induced sand erosion. Pre and post WTT, samples were weighed to calculate mass loss (Fattahi et al., 2020).

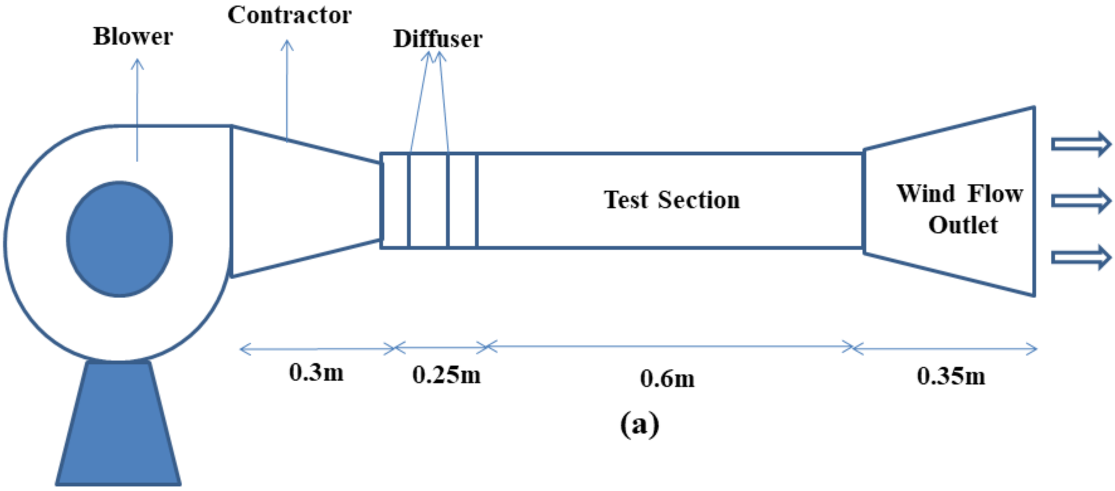

Figure 4. Wind tunnel test setup (Dagliya et al., 2022c)

unconfined compressive strength (UCS) test using Pocket penetrometer (PP)

A PP was used to assess the surface strength of the biotreated sand samples, as demonstrated in Figure 5. The ease in use and quick results make PP quite popular. (Fick et al., 2020; Kou et al., 2020). It was used to quantify the UCS values at five distinct locations (corners and centre) on the biotreated sample surface. However, the restriction of the instrument is that it can measure strength only in the range of 0 kg/cm^2 to 4.5 kg/cm^2.

Figure 5. Pocket penetrometer

Measurement of $CaCO_3$ using calcimeter

Using a calcimeter, the amount of calcite precipitation was measured in the treated and untreated sand samples (Figure 6). When the reaction between carbonates and hydrochloric acid was finished, the amount of CO_2 produced was calculated. The increase in pressure inside the calcimeter cylinder was measured using a pressure gauge. The pressure reading was applied to the $CaCO_3$ content calculation. (Almajed et al., 2020; Kalantary et al., 2019).

Figure 6. Calcimeter

Microscale identification analysis

Calcite precipitation presence was measured using SEM and EDX for biotreated and untreated soil samples. The treated samples were collected from the top crust, as there is more precipitation concentration at the top layer. Collected samples were kept for drying in oven for 1 day at 105°C. The oven dried samples were crushed to fine powder. Representative sample were coated with gold sputter and put in SEM Machine for SEM images and EDX analysis.

Results and discussion

Surface thickness measurement

The study aimed at restricting wind erosion by developing a stiff thin layer on the crust of the specimen. The thickness range for every sample was quantified and briefed in Table 2. The significant thickness of the top layer was analyzed in case of cementation solution 1:1 along with treatment up to 14 days. The crust thickness range was attained between 8-13 mm with an average content of calcite as 2.5%. This ratio worked well to prevent wind erosion. Due to greater crustal cementation solution penetration, the deeper crust thickness demonstrates that calcite production occurred in the intermediate layer sand grains. The specimens treated with cementation solution 2:1 for 7 days developed minimum thickness of range 0.7-2.8 mm. In cementation solution 2:1, the molarity of calcium chloride dehydrate was half of urea, which formed additional carbonate ions during the process of urea hydrolysis. Due to this rate of reaction increased and calcite crystal formed more swiftly at the crust. Conversely, cementation solution 1:1 for 7 days treatment showed 2.2 mm crust thickness, which interpreted that with higher number of days of treatment more calcium carbonate precipitation occurred and hence more thick crust gets developed. Thus, replicating this treatment strategy using cementation solution 1:1 and more number of treatment days (minimum 14 days) can be suggested for field applications.

An equivalent top surface thickness range was attained by Almajed et al. (2020) using EICP method. (Li et al., 2017) investigated using the MICP technique for aeolian sand for 7 days and examined that the top layer thickness developed after biotreatment, which significantly restricted wind erosion. The UCS test also performed and strength was found 0.66 MPa with an average 36° friction angle. The outcomes of the given study were consistent with (Meng et al., 2021) field study, which demonstrated crust thickness range upto 12.5 mm and hence found effective in restricting wind erosion.

Table 2 Different values of biotreated sand samples for unconfined compressive strength (UCS), Crust thickness, and calcite content percentage

S.No.	Cementation solution / no. of days	Unconfined compressive strength (kg/cm^2)	Calcite content (%)	Crust thickness (mm)
1	2:1/7	0-0.25	1.86	0.7-2.8
2	2:1/14	0.5-0.75	2.1	2.3-7.9
3	1:1/7	0.5-0.75	2.3	2.2-6.8
4	1:1/14	1.55-1.75	2.5	8-13

Analysis of wind induced sand erosion resistance

Wind induced sand erosion resistance of biotreated samples were observed through visual observation. Calculation of for pre and post WTT, mass loss was performed at 0.01 gm accuracy, at changing wind speeds. Figure 7 demonstrates pictures of tested specimen for pre and post WTT. Not much change was observed. Table 3 displayed percentage weight loss of pre and post WTT at varying wind speed of 5, 15, and 25 m/s during a one-minute time interval. With all treatment combinations, it was noted that weight loss occurred at a speed of 5 m/s (i.e., 7, and 14 days with 2:1 and 1:1 cementation solution) was almost negligible. Furthermore, the highest weight loss was 0.2%. In contrary to this, percentage of weight loss in case of untreated sand was observed as 4.2%, 26%, and 42.2 % at 5, 15, and 25 m/s speed, respectively. More the wind speed, higher the weight loss which can be termed as sandstorm disaster.

Table 3 Weight loss in percentage after WTT at different wind speed

Cementation solutions	Weight loss % (5 m/s wind speed)	Weight loss % (15 m/s wind speed)	Weight loss in % (25 m/s wind speed)
Untreated	4.2	26	42.2
2:1/07 days	0.0	0.1	0.2
2:1/14 days	0.0	0.03	0.1
1:1/ 07 days	0.0	0.02	0.2
1:1/ 14 days	0.0	0.01	0.05

Figure 8 demonstrates that when the number of treatment day rises, the amount of calcite increases, and wind induced sand erosion decreases (refer to Table 3). Considering the practical application of this test, higher crust strength is required in case of moving loads like automobiles, humans, and animals which can be enhanced by applying the MICP treatment approach using multiple treatment cycles.

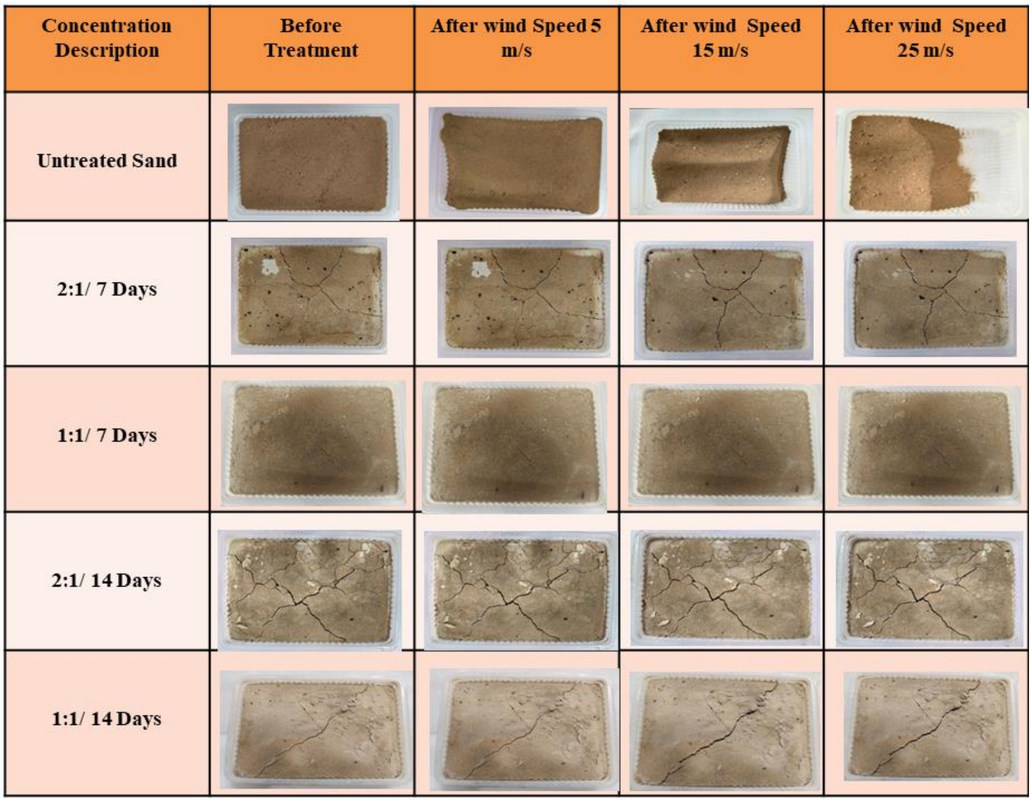

Figure 7. Pictures of treated and biotreated sand samples before and after WTT at varying wind speeds

Analysis of surface strength and calcite formation

Figure 8 shows the comparison of top and bottom layers calcite formation for different treatment combinations. Calcite content percentage of the top crust was comparatively more (i.e., confronting treated layer) than the lower layer. After 14 days of treatment, it was noticed that the bottom layer for 2:1 had a calcite content percentage that was nearly identical to the top layer for 2:1. (7 days' treatment). In summary, for various biotreatment settings and day counts, there was not any appreciable variance in the bottom layer's calcite content percent value.

PP was used to check the UCS of top layer under advanced strain. PP was pressed in the treated specimen at four corners and one centre for 10 mm depth to ensure surface strength evenness. Strength uniformity was observed on 7th day of treatment for both ratios. No significant difference was observed in strength. However, the strength variation enhanced with increase in number of treatment days. Additional research is required to examine the homogeneity of treatments, particularly in large-scale testing. Table 2 and figure 9 summarizes the percentage of calcite content and UCS values for various treatment cycles. Table 2 reveals that the top layer after 14 days treatment with the 2:1 cementation solution's and 7 days treatment with 1:1 solution was almost same.

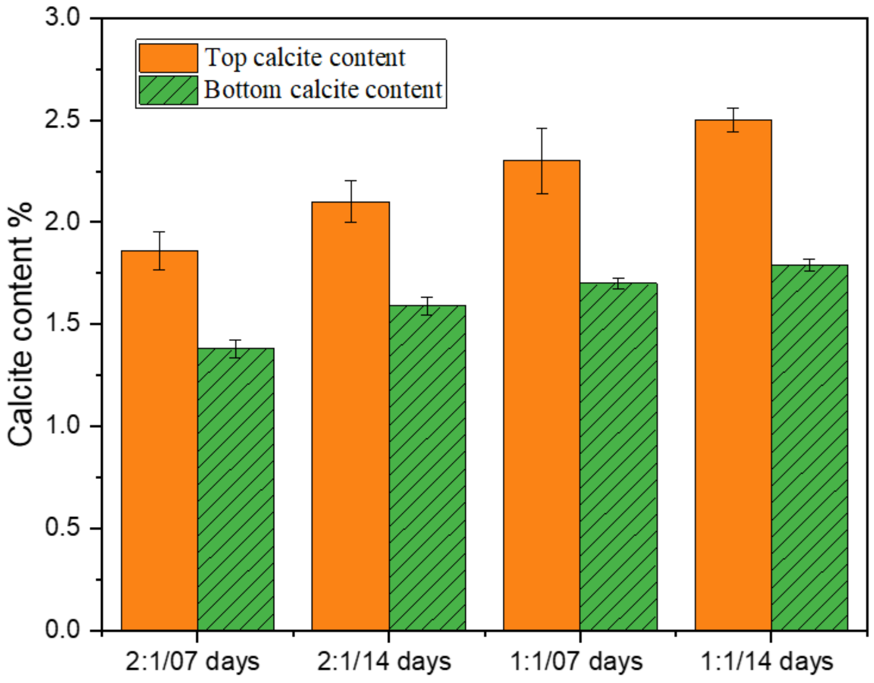

Figure 8. Top and bottom calcite content for varying treatment conditions

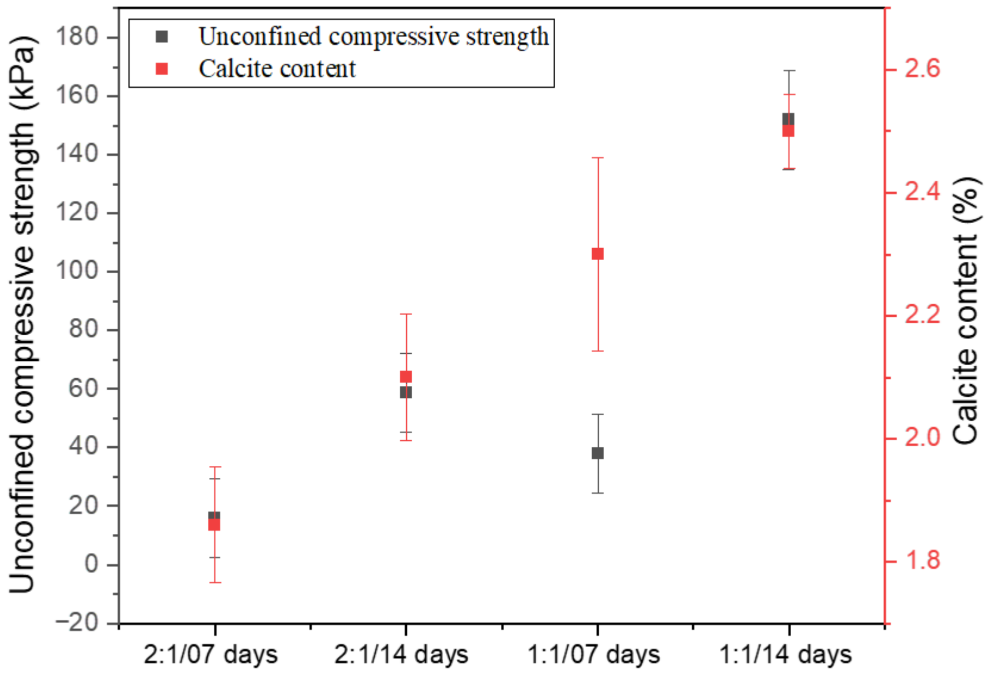

Figure 9. UCS values measured with pocket penetrometer with calcite formation for varying treatment conditions

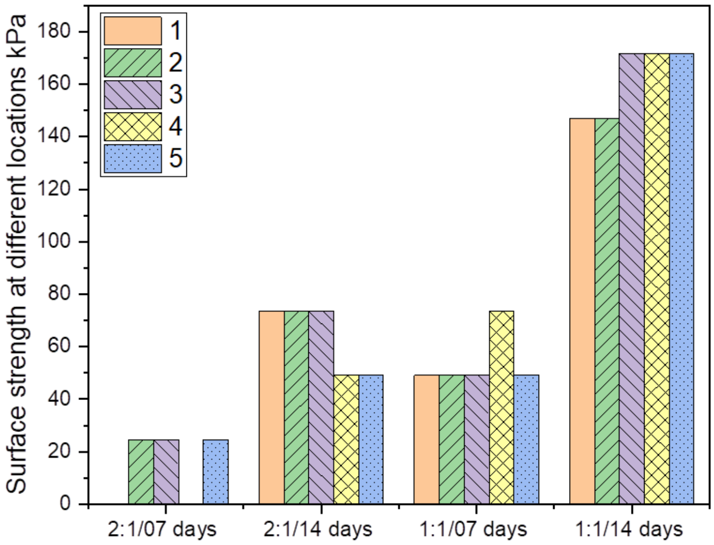

Figure 10. UCS at different test locations (corners and centre)

Microscale identification analysis

Figure 11 and figure 12 showed SEM and EDX analysis observation. It represents the micro and chemical characterization for both untreated and biotreated sand samples. Calcite picks were observed through EDX analysis. SEM analysis was used to conduct a micro-scale examination through images of the specimens for particles bonding through calcite content. After analysing the SEM images figure 12(a), untreated sand was found to have a comparatively soft surface and no apparent link between the particles while 12(b), treated specimen had reduced pore space and strong attachment amongst sand particles in the form of calcite precipitation.

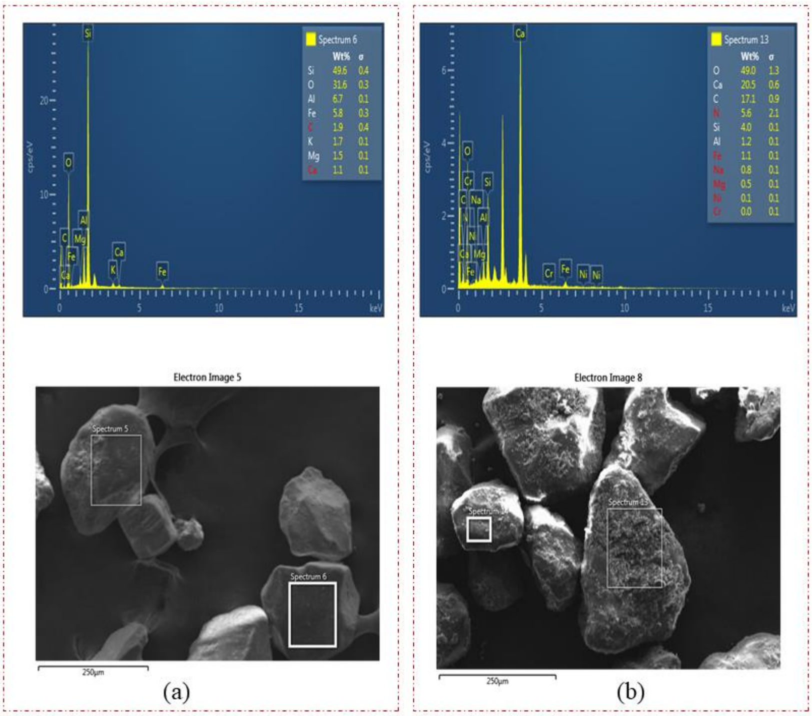

Figure 11. EDX analysis

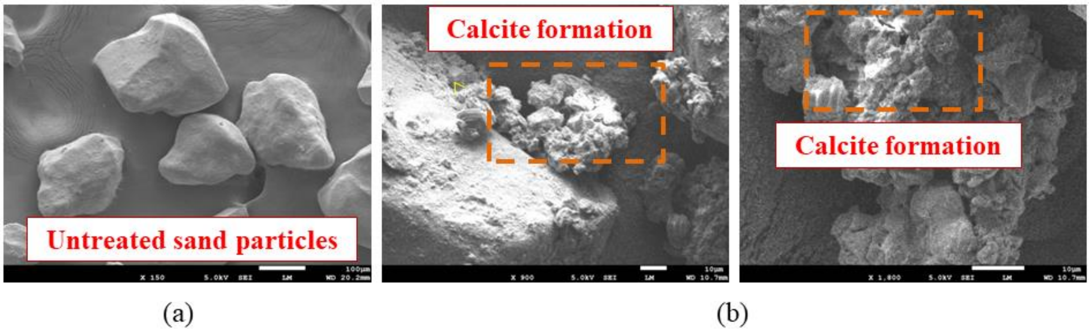

Figure 12. SEM images

Conclusions

This study focused on restricting wind induced sand erosion using the MICP spray method treatment. The treatment was conducted with cementation solution 2:1 and 1:1 for 7, and 14 days. The treated specimens were tested for wind induced sand erosion resistance, unconfined compressive strength (UCS), calcite content percentage, EDX, and SEM. The following conclusions have been drawn from the present study:

1. Both cementation solutions (2:1 and 1:1) stipulated improved top layer stiffness and shown successful results in reducing wind erosion. This is due to production of $CaCO_3$ in the spaces between the sand grains.
2. At a wind speed of 25 m/s, the untreated sand had lost nearby half of its weight, whereas it was barely noticeable for biotreated sand.
3. In terms of calcite formation, crust thickness, and UCS, the cementation solution 1:1 performed better than the cementation solution 2:1. It was observed that the results of 2:1 with 14 days of treatment and 1:1 with 7 days of treatment at a temperature of 45°C were nearly identical.
4. Wind induced sand erosion at 5 m/s was essentially nonexistent for soil treated with a cementation solution 1:1 and 7-day treatment period. However, for greater wind speeds, more treatment days are desirable in controlling erosion.
5. Additionally, it was shown that as the number of treatment days grew, calcite crystal development and soil particle bonding both got better. In order to reduce wind induced sand erosion, the spray approach for MICP treatment proved successful for desert soil.

It should be mentioned that the conclusions are predicated on the assumptions of the experiments. During the WTT, a brief period of time one minute was spent in testing the soil samples. However, it is necessary to explore how bio cemented sand performs when exposed to stronger winds for an extended period of time. The strength measurement of the crust built for moving loads like people, vehicles, and animals is also not included in the current study. For the technology to be scaled up to the field level, more research is required.

References

1. Almajed A, Lemboye K, Arab MG, Alnuaim A. Mitigating wind erosion of sand using biopolymer-assisted EICP technique. Soils Found 2020;60:356–71. https://doi.org/10.1016/j.sandf.2020.02.011.
2. Dagliya M, Satyam N, Garg A. Experimental Study on Optimization of Cementation Solution for Wind-Erosion Resistance Using the MICP Method 2022a:1–17.
3. Dagliya M, Satyam N, Garg A. Biopolymer based stabilization of Indian desert soil against wind - induced erosion. Acta Geophys 2022b. https://doi.org/10.1007/s11600-022-00905-5.
4. Dagliya M, Satyam N, Sharma M, Garg A. Experimental Study on Mitigating Wind Erosion of Calcareous Desert Sand using Spray Method for MICP. J Rock Mech Geotech Eng 2022c. https://doi.org/10.1016/j.jrmge.2021.12.008.
5. Fattahi SM, Soroush A, Huang N. Biocementation Control of Sand against Wind Erosion. J Geotech

Geoenvironmental Eng 2020;146:04020045. https://doi.org/10.1061/(asce)gt.1943-5606.0002268.
6. Fick SE, Barger N, Tatarko J, Duniway MC. Induced biological soil crust controls on wind erodibility and dust (PM10) emissions. Earth Surf Process Landforms 2020;45:224–36. https://doi.org/10.1002/esp.4731.
7. Kalantary F, Abbasi Govanjik D, Safdari Seh Gonbad M. Stimulation of Native Microorganisms for Improving Loose Salty Sand. Geomicrobiol J 2019;36:533–42. https://doi.org/10.1080/01490451.2019.1579876.
8. Kou H lei, Wu C zhou, Ni P peng, Jang BA. Assessment of erosion resistance of biocemented sandy slope subjected to wave actions. Appl Ocean Res 2020;105:102401. https://doi.org/10.1016/j.apor.2020.102401.
9. Li C, Yao D, Liu S, Zhou T, Bai S, Gao Y, et al. Improvement of geomechanical properties of bio-remediated aeolian sand. Geomicrobiol J 2017;35:132–40. https://doi.org/htps://doi.org/10.1080/01490451.2017.1338798.
10. Maleki M, Ebrahimi S, Asadzadeh F, Emami Tabrizi M. Performance of microbial-induced carbonate precipitation on wind erosion control of sandy soil. Int J Environ Sci Technol 2016;13:937–44. https://doi.org/10.1007/s13762-015-0921-z.
11. Meng H, Gao Y, He J, Qi Y, Hang L. Microbially induced carbonate precipitation for wind erosion control of desert soil: Field-scale tests. Geoderma 2021;383. https://doi.org/10.1016/j.geoderma.2020.114723.
12. Miao L, Wu L, Sun X. Enzyme-catalysed mineralisation experiment study to solidify desert sands. Sci Rep 2020a;10:1–13. https://doi.org/10.1038/s41598-020-67566-6.
13. Miao L, Wu L, Sun X, Li X, Zhang J. Method for solidifying desert sands with enzyme-catalysed mineralization. vol. 31. 2020b. https://doi.org/10.1002/ldr.3499.
14. Moharana PC, Santra P, Singh D V., Kumar S, Goyal RK, Machiwal D, et al. ICAR-Central Arid Zone Research Institute, Jodhpur: Erosion processes and desertification in the Thar Desert of India. Proc Indian Natl Sci Acad 2016;82:1117–40. https://doi.org/10.16943/ptinsa/2016/48507.
15. Poulsen TG, Cai W, Garg A. Water evaporation from cracked soil under moist conditions as related to crack properties and near-surface wind speed. Eur J Soil Sci 2020;71:627–40. https://doi.org/10.1111/ejss.12926.
16. Roy PD, Singhvi AK. CLIMATE VARIATION IN THE THAR DESERT SINCE THE LAST GLACIAL MAXIMUM AND EVALUATION OF THE INDIAN MONSOON. TIP 2016;19:32–44. https://doi.org/10.1016/j.recqb.2016.02.004.
17. Sharma M, Satyam N, Reddy KR. Comparison of improved shear strength of biotreated sand using different ureolytic strains and sterile conditions. Soil Use Manag 2021a. https://doi.org/10.1111/sum.12690.
18. Sharma M, Satyam N, Reddy KR. State of the Art Review of Emerging and Biogeotechnical Methods for Liquefaction Mitigation in Sands 2021b;25. https://doi.org/10.1061/(ASCE)HZ.2153-5515.0000557.
19. Sharma M, Satyam N, Reddy KR. Strength Enhancement and Lead Immobilization of Sand Using Consortia of Bacteria and Blue-Green Algae 2020;24. https://doi.org/10.1061/(ASCE)HZ.2153-5515.0000548.
20. Sharma M, Satyam N, Reddy KR. Investigation of various gram-positive bacteria for MICP in Narmada Sand, India. Int J Geotech Eng 2019;15:220–34. https://doi.org/10.1080/19386362.2019.1691322.
21. Sun X, Miao L, Tong T, Wang C. Improvement of Microbial-Induced Calcium Carbonate Precipitation Technology for Sand Solidification. J Mater Civ Eng 2018;30:04018301. https://doi.org/10.1061/(asce)mt.1943-5533.0002507.
22. Wang Z, Zhang N, Ding J, Lu C, Jin Y. Experimental Study on Wind Erosion Resistance and Strength of Sands Treated with Microbial-Induced Calcium Carbonate Precipitation. Adv Mater Sci Eng 2018;2018. https://doi.org/10.1155/2018/3463298.