Geoderma 429 (2023) 116183

Contents lists available at ScienceDirect

Geoderma

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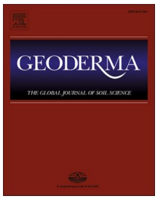

Soil stabilization for dunes fixation using microbially induced calcium carbonate precipitation

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ARTICLE INFO

Handling Editor: Morgan Cristine L.S.

Keywords:
Wind erosion potential
Wind threshold detachment velocity
MICP
Sand

ABSTRACT

Climate change and desertification caused increases in sandstorms and sand movements due to the erosive force of the wind. Wind erosion is a phenomenon depending on the climatic components and surface roughness in arid and semi-arid regions responsible for health and economic loss. The phenomenon is controlled by increasing the resistance of soils using chemical, physical and biological methods. Due to the high cost and environmental issues of conventional techniques, the use of alternative green stabilization methods is inevitable. Therefore, in the present study, the effect of microbially induced calcium carbonate precipitation (MICP) on the fixation of in situ dunes in north-east of Iran was assessed. The cementation solution of 0.1–0.5 M was sprayed and evaluated after 7, 15, and 30 days. The MICP treated samples were exposed to wind tunnel for the variation of wind threshold detachment velocity (TDV) as well as other macro/micro evaluation such as unconfined compressive strength, seed germination, scanning electron microscope (SEM), and energy-dispersive X-ray spectroscope (EDX). The results suggested the critical impact of both geotechnical and geoenvironmental parameters for the selection of soil stabilizers on the fixation of dunes. It can be stated that the bio-crust formation with 0.3 M showed 123 kPa and no wind erosion potential after 30 days under the wind speed of 30 m/s. The results of the germination of *H. persicum* demonstrated that the contemporaneous of MICP treatment with native plants positively affect the TDV.

1. Introduction

Soil erosion by the wind in arid and semi-arid regions is a threat to the sustainability of the land and the viability and quality of life for rural and urban communities. It is a serious threat to food security and contributes to the degradation of sustainable agriculture in the world. Some soil from damaged land enters suspension and becomes part of the atmospheric dust load. Dust storms affect air quality, while airborne dust has significant economic, health (Watanabe et al., 2011), ecological, and hydrological impacts (Namdari et al., 2018).

Wind erosion is resulting from agricultural lands, cultivated organic soils, sandy coastal areas, alluvial soils along river bottoms, mining sites, construction sites, and unpaved roads (Almajed et al., 2020). The susceptible areas in the world to wind erosion include much of North Africa and the Near East; parts of southern, central, and eastern Asia; the Siberian Plains; Australia; northwest China; southern South America; and North America. In the middle-east, two-thirds of Iran is located in an arid and semi-arid zone (Zamani and Mahmoodabadi, 2013) as shown in Fig. 1b, while more than half of the Iranian provinces are suffering from critical wind erosion (Cao et al., 2015).

Wind erosion is not only closely related to geo-ecological factors but also to land changes (Rezaei et al., 2016). The threshold velocity (the minimum velocity required to move soil particles) is crucial for wind erosion controlling. However, the threshold velocity for each specific soil is dependent upon the soil characteristics such as particle size distribution, water content (Sirjani et al., 2019) and surface soil shear strength (Zhang et al., 2017). Considering the importance of soil improvement in dust control and increasing attention to various types of additives, it is very important to address this issue.

A vast host of soil stabilizing methods have been addressed to mitigate wind erosion of desert soils. Previously, the use of natural approaches, mechanical barriers, and conventional/modern chemical additives was investigated. For example, the application of natural approaches such as wetting has limitation, including rapid evaporation, and the scarcity of water in the focused area. Moreover, the cost and labor investment on the vegetation which is all dependent to the rainfall

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https://doi.org/10.1016/j.geoderma.2022.116183
Received 25 April 2022; Received in revised form 13 September 2022; Accepted 19 September 2022

in desert regions and considering the decrease trend of rainfall due to climate change (Naeimi, 2020) is not economical; while vegetation is not practical for construction sites and the border of roads in desert regions. The application of sand barriers such as straw checkerboard barriers (Li et al., 2006) also requires too much material and labor force (Peng et al., 2017). Conventional additives and synthetic polymers were also showed adverse impacts to human health, vegetation, environment, equipment, and vehicles. Some modern environmentally-friendly biopolymers, has been introduced, whereas their water-soluble properties may lose strength and be washed away from the soil when exposed to water (Lo, 2020). On the hand, the fragile and weak BSCs in the initial stage trend to be destroyed by the interfere of climate parameters as well as environmental deterioration (Peng et al., 2017; Zhang et al., 2006). Therefore, the wind erosion control could be reachable by the development of an alternative sustainable green soil stabilization techniques which elevated the previous techniques drawbacks.

In recent years, a number of studies focusing on the application of bio-mediated techniques including microbially induced calcium carbonate precipitation (MICP) for wind erosion control and dust mitigation (Hamdan and Kavazanjian, 2016; Song et al., 2019; Naeimi and Chu, 2017). MICP induces carbonate precipitation between the soil particles via hydrolysis catalyzed by the urease enzyme from bacteria (Chu et al., 2014; Dejong et al., 2013; Ivanov and Chu, 2008).

It was found that a higher fines content and higher temperature and humidity helped form the soil crust that resisted fugitive dust emission after the application of ureolytic bacteria in MICP process (Meyer, et al., 2011), whereas makes it an alternative choice for desert management. Moreover, the cost of this method for sand dune fixation due to vast areas can be optimized by regulating the application method, and concentration of cementation solutions. The optimization of cementation solution (Sharma et al., 2021; Naeimi, 2014) showed an effective calcite precipitation by the application of 0.5 pore volume cementation solution with either injection or spraying method. Considering a very low dosage of spraying of biocemntation solution for wind erosion mitigation due to biocrust formation demonstrated the applicability of the method technically and economically. Hence, industrial and lower grade of materials (Gowthaman et al., 2022); industrial waste carbide sludge and urine (Yang et al., 2022); and natural materials extracted from soya been for urease activity (Maleki et al., 2016; Nikseresht, 2020; Ming-JuanCui, xxxx) can also be used to make it cost effective in desert management. Additionally, the surface strength, wind erosion potential, and thickness of the layer under different cementation solution was stated in various studies (Meng, 2021; Dagliya et al., 2022; Wang et al., 2018; Sun et al., 2018).

Notably, stabilization techniques for controlling the blowing soil are impacting the vegetation of dunes. It can reduce seedling survival and growth, resulting in the susceptibility of plants to certain types of stress, including diseases, and contribute to the transmission of some chemicals and ions increases. (Pointing and Belnap, 2014; Jones and Barbetti, 2012). In the long run, the costs of wind erosion control practices can offset the cost of replanting native vegetation. Regarding the importance of the vegetation in regions encountered with sand movements issues, such as dunes on the area near cities, the cementation solution is still requiring to be more adaptable with a fragile desert ecosystem and investigation on its impact on the vegetation and germination is unclear.

Hence, the purpose of the present study was to evaluate the effectiveness of MICP on near surface soil stabilization for wind erosion control of samples from dunes demonstrating the importance of geotechnical vs environmental parameters. Throughout the study, the effectiveness of MICP for sand fixation of dunes in desert regions was explored using the observation and measurements of biocrust thickness, wind erosion potential, surface strength, and environmental impact of the MICP on germination.

2. Materials

2.1. Soil characteristics

The soil sample used in the experiment was collected from the surface (0.0–15.0 cm) of a desert sandy soil from a wind-erosion area in the

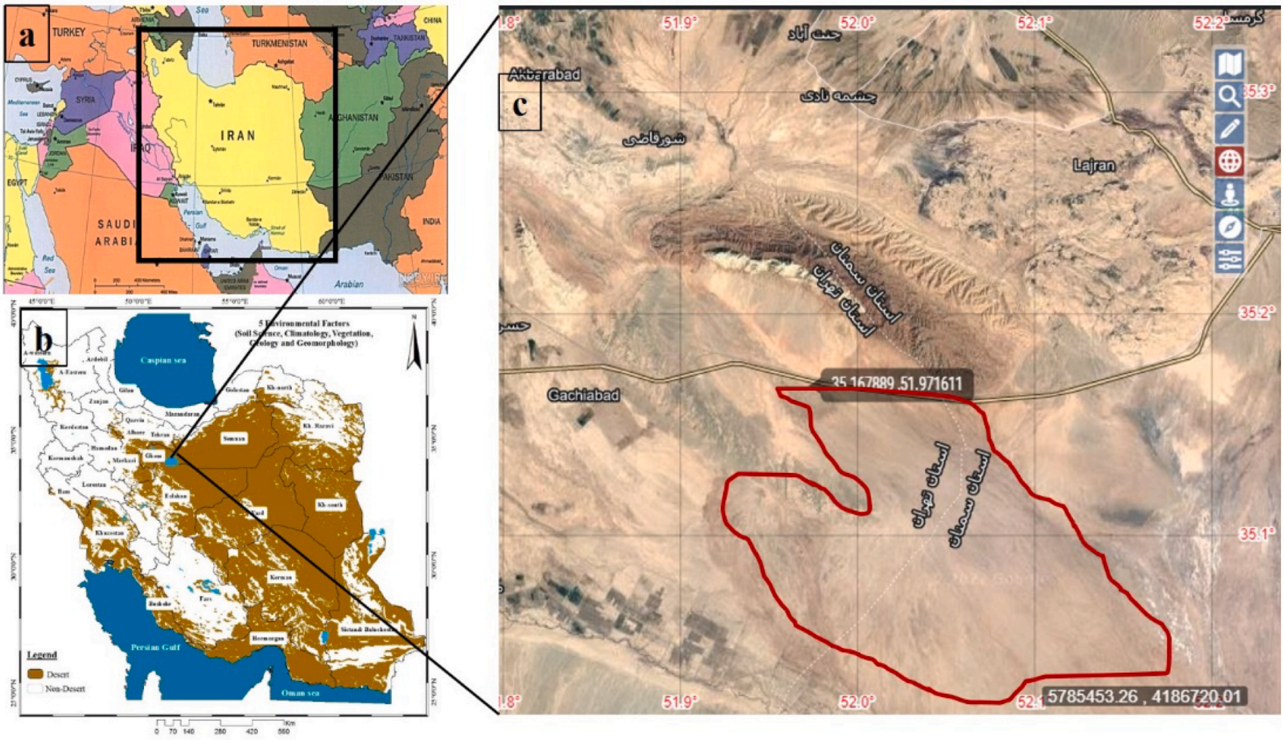

Fig. 1a. Map of the Islamic Republic of Iran: (a) distribution of desert in the country (Khosroshahi and Morteza, 2017); (b) extent of desert and the threat of sand movements around the highway of the capital.

northeast of Iran called Garmsar (Fig. 2a) located in the coordinates of 35°09′58.7″N and 51°58′12.0″E. Due to its proximity to urban areas, railway and busiest freeway transportation from the capital to the second crowded city of the country, terms of preventing wind erosion as well as dust is a priority of study and implementation. The average monthly velocity of the strongest winds during a 24-year statistical period (1990–2015) fluctuates from 11.7 m/s in September to 19 m/s in April.

After natural air drying after 30 days, the grain soil particles test was carried out in the soil laboratory of the Desert Research Department at RIFR according to ASTM-D422. The result obtained from the granulation experiment shows that the sand sample is uniformly and poorly granulated. The result of particle size analysis showed that the soil sample consisted of 92.7 % sand (>0.05 mm), 2 % silt (0.002 mm to 0.05 mm), and 5.4 % clay (<0.002 mm) and the average particle diameter of the soil samples was determined to be 0.3 mm (Fig. 2b). The soil texture is sandy soil according to the USDA classification. The sand was categorized as SP based on its characteristics with a specific gravity of 2.07 g/cm3. Moreover, the minimum and maximum porosity were 0.5 and 0.8 respectively.

2.2. Testing program

The program concentrated on the investigation of the engineering properties and behavior of the stabilized dune sand using microbial treatments. A set of series samples were treated using Microbial Induced Calcium Precipitation (MICP) method by the application of urease-producing bacteria (UPB), and a solution of urea and CaCl$_2$. The procedure for the cultivation of bacterial cells of *S. pasteurii* was described previously by Naeimi and Chu (Naeimi and Chu, 2017) (Naeimi and Chu, 2017). 100 ml of cultivated UPB suspension was centrifuged at 1000 g at 4 °C for 10 min to separate the bacteria cells from the culture liquid. Note that the OD, conductivity, and urease activity of *S. pasteurii* was equal to 2.4, 3.19 (μs), and, 3.19 IU, respectively. Therefore, in this study as reported in Table 2, the supply of 100 ml of urease activity with 1 % NaCl was stirred with 1.5 M cementation solution for 10 s as previously the effectiveness of pretreatment (Chu et al., 2014) was reported. Later, the cementation solution was sprayed on top of the sand samples. Note that the calcium chloride and urea content was set in a way to be in the range of 0.1 – 0.5 M with the same biomass concentration of UPB (Table 1). Note that the sufficient rate required to cover the entire sample's surface area was pre-determined, to be 2.5 L/m^2. All the samples were manually sprayed using a 1000 ml handheld plastic spray bottle. The spray was done at approximately 500 mm above each sample. Two samples were also set to be water treated (at the same volume as the other treated samples) and controlled. Note that for all the measurements after casting, the treated dune sand samples were maintained at room temperature of around 25∘C to keep the moisture content almost constant and the experiments were measured for 7, 15, and 30 days.

3. Methods

3.1. Wind erosion tests

A wind tunnel test was employed to evaluate the improving effect of treatments on the dust resistance of samples. A sufficient number of metal trays with dimensions of 500*300*50 mm were prepared. Then, a thin layer of aerated sand (50 mm) around 15 kg, loosely packed in its initial state, was placed over the trays. The surface is controlled to be completely smooth and uniform, as shown in Fig. 2a.

An existing wind tunnel in the laboratory of the RIFR, Iran, was used for monitoring the weight loss of samples. The wind tunnel has 8 test rooms, each with a length of 2 m, dimensions of 80 × 80 cm, with four electric motors, each with a power of 16 kW, and has several pitchers, an electronic sphygmomanometer, and a speed control device using engine speed control to adjust wind speed. It is from at least 6.28 to 30 m/s (Fig. 2b). Note that the TDV (TDV) for the untreated sample was 6.28 m/s. TDV is the minimum friction velocity required to initiate detachment of soil particles, representing the strength of forces among soil particles

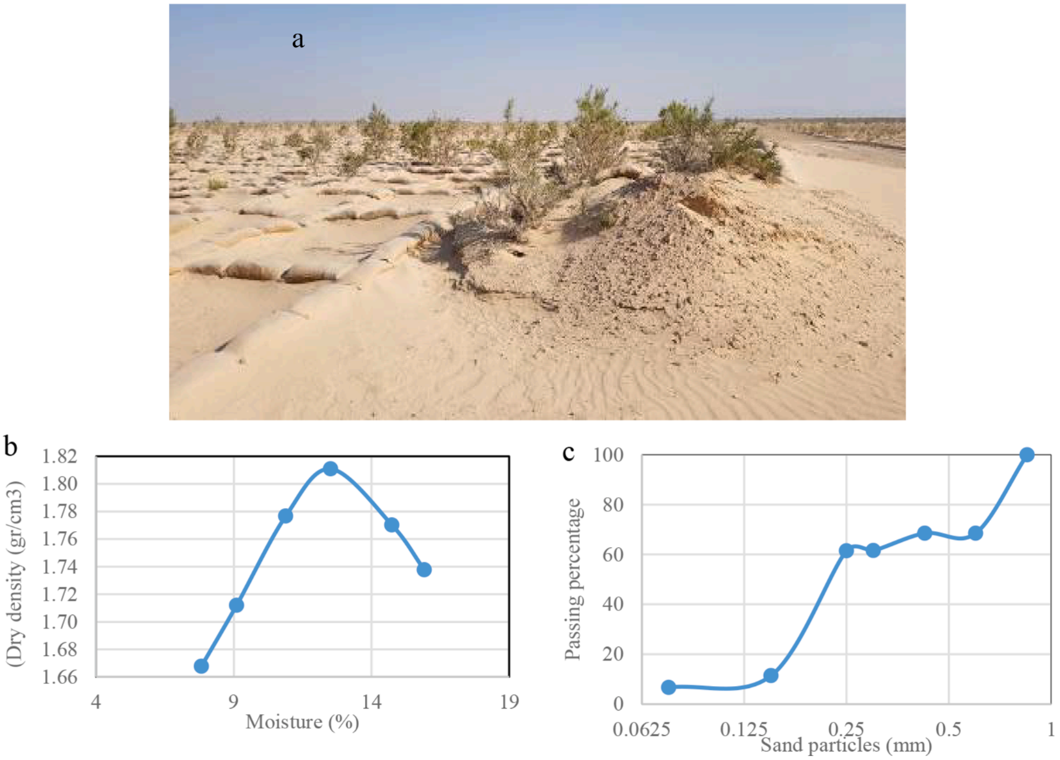

Fig. 1b. a) picture of place that the sand samples were taken, b) moisture density curve, c) soil distribution curve.

Fig. 2. a) Control test model in the tray, and b) pictures of the wind tunnel set up.

Table 1
Testing program.

Test models (#)	1	2	3	4	0
Cementation solution (M)	0.1	0.2	0.3	0.5	0
Treatment days	7–15 − 30				

and capacity of an aeolian surface to resist wind erosion (Batt and Peabody, 1999; Shao and Lu, 2000). Nearly all wind erosion and dust flux models require the specification of TDV (Marticorena and Bergametti, 1995; Okin et al., 2008; Shao et al., 1993).

Furthermore, the wind speeds were chosen after careful consideration of the TDV. Each of the treated samples was exposed to distinct wind speeds up to 30 m/s at intervals of 5 mins, to evaluate the TDV of sand with stabilizers. At the end of each step, the trays were weighed again to determine the amount of sand removed by the wind.

3.2. *Surface strength*

A hand penetrometer also called a pocket penetrometer was used to estimate the unconfined compressive strength of the MICP treated in the present study. As shown in Fig. 3a, It was used in the present study due to the insensitivity and low concentration of cementation solution and thus low resistance. The 6.4 mm diameter penetration piston is pushed into the soil surface. Penetration resistance from the calibrated spring is registered on an integrated scale engraved on the penetrometer barrel. Note that the average announcements are from 6 different locations, as shown in Fig. 3b.

3.3. *Calcium carbonate content analysis and microstructure identification*

The calcite precipitation concentration was more at the top surface (at 0.3 cm depth) as intended by the the spraying method adopted. Therefore, the topsoil of the treated samples was collected and analyzed for calcite precipitation using two methods: EDTA titration and EDX.

For the titration method, at first, the soil was mixed with a known amount of hydrochloric acid (HCl). Then, the amount of acid left was measured by titrating it with sodium hydroxide to produce sodium chloride and water, adding phenolphthalein indicator to the solution caused it to turn pink when all the acids had reacted (Chu et al., 2014).

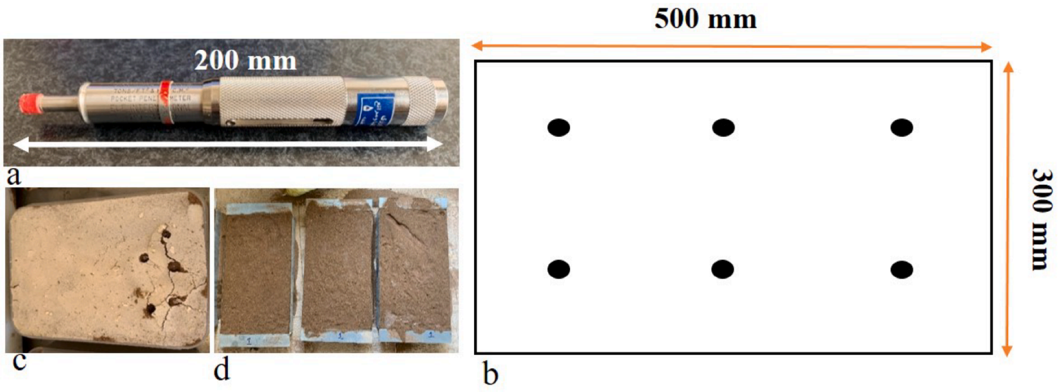

Fig. 3. (a) Measurement of UCS using pocket penetrometer; and (b & c) samples characteristics and the locations of UCS on the crust of treated samples after curing and, (d) three set for each treatment to be tested after 7, 15 and 30 days.

Then, the content of calcium carbonate in the specimen was calculated, with three parallel tests per specimen.

The microstructure identification of treated samples was analyzed using FESEM consisting of the SEM and EDX. Therefore, at first, the samples were kept under 105 °C for 24 h to be dried and then powdered. Later, determination of the chemical peak (calcite) of the treated samples was obtained from the output of EDX analysis, using the spectrums on the SEM images, which were taken at 15 kV at different beam intensities.

3.4. Seed germination tests

A series of tests were conducted to evaluate the effect of MICP treatment with various concentrations of cementation solution on the seed germination of *Haloxylon persicum* in the presence of bio grout. Note that, the chosen species is a hardy tree, drought tolerated that can grow in nutritionally poor soil of sandhills and sand ridges. The quantification and mechanism analysis of seed germination experiments was adopted from literature along with field experiments where the seeds spread in the desert regions by wind. Previous studies showed that temperature along with some other elements such as water absorbance strongly influences physiological and biochemical processes (Kigel, 1995). A seed must absorb a certain amount of water to germinate, the critical hydration level being species-specific (Hadas and Stibbe, 1973). Hence, in the present study the quantification and mechanism analysis of seed germination experiments was set up in a way to cover the germinations concern such as water absorbance in the presence of biocrust.

In an attempt to speed up germination, different scarification and stratification experiments were previously carried out, which is out of the scope of this paper. Germination of *H. persicum* was evaluated in the same condition for MICP treated and control samples with fifteen repetitions using equal seeds in each vase. The results of germination were recorded after 21 days. Control set was used because all experiments ran simultaneously.

A coefficient of germination rate (CRG) was calculated considering the percent of germination in each set of experiments to total seeds. Therefore, the data of the germination experiments of *H. persicum* in each set were analyzed using the total number of germinated to the total seeds. All statistical tests were performed using the statistical program SPSS 21. A 95 % confidence interval was adopted. Continuously, the results were statistically analyzed using the Paired T-Test method, at a 95 % confidence level ($P < 0.05$). In paired samples, the results of the same items in two different conditions were compared. This test is more powerful than regular T-test since the same "lab rat" for both samples, instead of different lab rats for each sample were used, thus limiting noise.

The null hypothesis in the study assumes that the known difference between the groups is correct. When the known difference is zero, the null hypothesis assumes the Means of the groups are identical. Degrees of freedom equal number of items minus one (or number of observations divided by 2 minus 1).

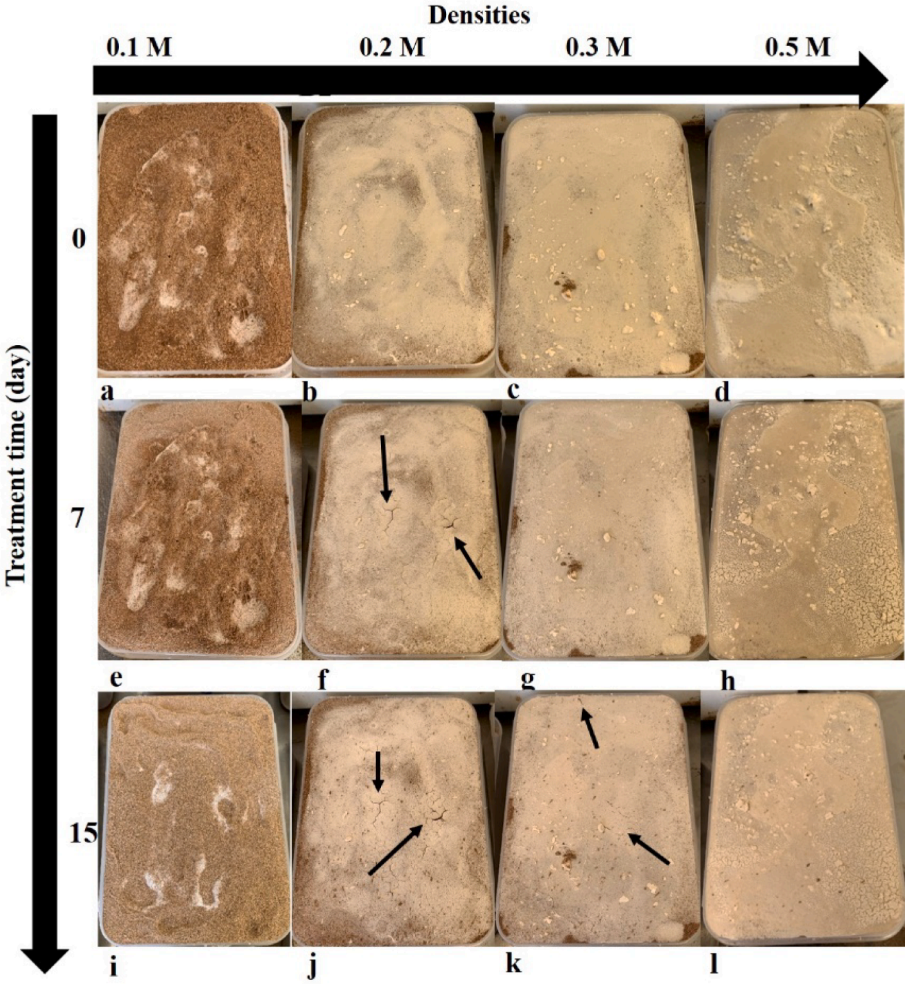

Fig. 4. Variation the surface of samples treated with 0.1 to 0.5 treated through MICP process with different densities at various curing time. The arrows shows the cracks 7 and 15 days after treatment.

4. Results and discussion

4.1. Surface thickness analysis

The objective of the study was to form a protective crust for sand fixation. Data obtained from observation as shown in Fig. 4, indicated the variation of biocrust formation in the range of 0.5–22 mm with different dosages of cementation solutions after 30 days of treatment.

As all the samples were treated with the same method of application, the higher crust thickness shows the impact of a higher concentration of calcium chloride solution, pre-treatment of cells which leads to the calcite formation occurring between the sand grains on the top surface of the sand. Chu et al., (Chu et al., 2014) also mentioned the optimization of calcium carbonate precipitation by pretreatment of the bacterial cells with calcium chloride. The pretreatment resulted in a superlative number of available calcium ions and simultaneously increased the rate of carbonate reaction during urea hydrolysis.

The effect of treatment time and ratio on the crust consistency was also observed, while by increasing the calcium concentration and treatment time the crust was settled through the soil matrix and has not stayed as a detachable crust. Moreover, the presence of the precipitated calcite and its penetration gives cohesiveness to the soil grains; As shown in Figs. 4, 7 days after treatment, the cracks appeared on the top of MICP treated samples treated with 0.2 and 0.3 M. Continuously, 15 days after treatment, the cracks on samples treated with 0.2 and 0.3 M were extended. However, there were no cracks observed in samples treated with 0.1 and 0.5.

The formation of crust with various thicknesses was confirmed by observation. As shown in Fig. 5, the thickness of the crust varied from 0.5 to 22 mm in samples after 30 days, respectively. However, the ranges of crust on variously treated samples were observed, and the averages are stated in Fig. 5. The crust thicknesses on the surface of the MICP treated sample with the cementation solution of 0.1, 0.2, 0.3, and 0.5 M after 30 days, are equal to 0.5–2 mm, 4–6 mm, 8–10 mm, and 20–24 mm, respectively. The results of this study show that the cracks are depending on the crust formation and cementation solution. Test model treated with 0.1 M cementation solution did not show any cracks which can be explained by the low amount of cementation solution that adsorbed through the soil matrix and as a consequence less formrd crust to be cracked. On the other hand, test model treated with 0.5 M cementation solution showed enough crust that did not cracked.

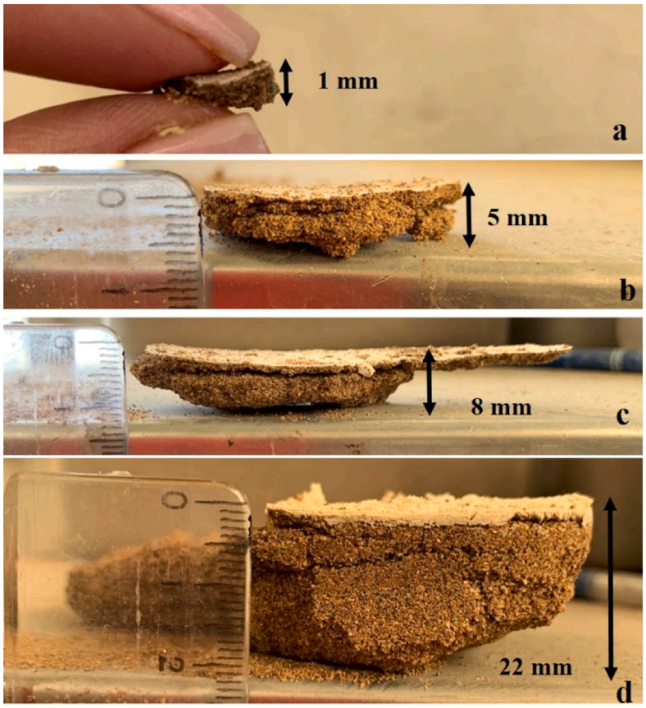

Fig. 5. Crust thickness in different concentration of calcium chloride after 30 days treated with a) 0.1, b) 0.2, c) 0.3 and, d) 0.5 M of calcium chloride.

On the other hand, samples treated using 0.5 M calcium chloride showed a very thin crust with the thickness of 4 mm of calcium carbonate precipitation while it forms an average of 21 mm of sand particles as a clump. The white crust on the surface of the MICP treated crust confirms the effectiveness of crust formation with higher calcium contents. However, the thickness of the crust was similar to the range previously reported by other studies (Naeimi and Chu, 2017; Dagliya et al., 2022; Buikema et al., 2018). Hence, the cementation solution was less than that of a range of solutions that were previously reported as 0.8 M by Almajed et al. (Almajed et al., 2020) and 0.5 M by Li et al. (2018). However, the mentioned studies was also concluded the efficiency of the MICP treatment in reduction of wind erosion.

4.2. Wind erosion potential analysis

Wind tunnel experiments to indicate the mass loss alteration was carried out for wind erosion potential determination. Therefore, firstly the TDV of untreated soil was measured and then was compared to the MICP treated samples. As shown in Fig. 6, the untreated sample of dunes started to move at 6.28 m/s (As arrowed in Fig. 6). However, the sand loss started at 10.33 m/s. The experiments will continue to achieve the fit curve on the sand loss to 30 m/s. The weight loss for untreated sand in kg/m2/min was shown in Fig. 6, equal to 9.56, 34.13, and 49.80 % at 10.13, 22.09, and 30.01 m/s speeds, respectively.

As shown in Fig. 7, the MICP treated samples showed the range of 0 to 0.3 kg/m2/min of wind erosion which was comparable to 0 to 1.5 % of the sand loss. The sample treated with 0.1 M showed the maximum weight loss of 0.5 and 1.5 % at 20 and 30 m/s wind speed after 30 d, respectively. Hence, accelerating the cementation solution resulted in weight loss of 0.75 % at 30 m/s wind speed. Considering the 50 % of sand lost in the untreated sample exposed to the wind with a wind speed of 30 m/s, the effectiveness of the adopted method can be concluded.

Additionally, although in the sample treated with 0.3 M, there were some cracks on parts of the surface, these cracks did not extend during the wind storm. Hence, it can be concluded that the cracks caused did not necessarily affect the strength of the surface. Additionally, with no cracks on the surface of the sample treated with 0.1 M, the precipitated calcite was not enough to stay cohesive against the erosive force of the wind.

It is worthwhile to mention that what is crucial as a stabilizer of sand is the changes in the TDV. Therefore, from a geotechnical point of view, increasing the TDV or less sand loss will be desirable after treatment. The results of Fig. 7 show that 30 days after treatment the TDV was changed from 6.25 m/s for untreated sand (Fig. 6) to 14.33 and 18.09 m/s for MICP treated samples with 0.1 and 0.2 M $CaCl_2$, respectively. This is a meaningful result in sand fixation. However, it also can be seen that the sample treated with 0.5 M did not show any changes and any TDV even after 30 days. Simultaneously, the sample treated with 0.1 M $CaCl_2$ shows a reduction of TDV 30 days after treatment from 15.8 to 14.33 m/s. This established the idea that the effectiveness of crust formation will be changed if the low percentage of calcium carbonate precipitated.

Moreover, significant dependence on treatment time due to surface soil moisture on sand loss was established in all the MICP treated crust in comparison to water treated as shown in Fig. 7, which suggested that the minimum of 0.1 M cementation solution created 0.5–2 mm of biocrust after 30 days, while losses 1.5 % of sand against wind speed by a factor of 5 than the TDV. However, increasing the concentration of the cementation solution four times resulted in 10 times less soil loss.The results of the this study are consistent with that of Meng et al. (Meng, 2021) demonstrated that the MICP treated surface with 0.2 M

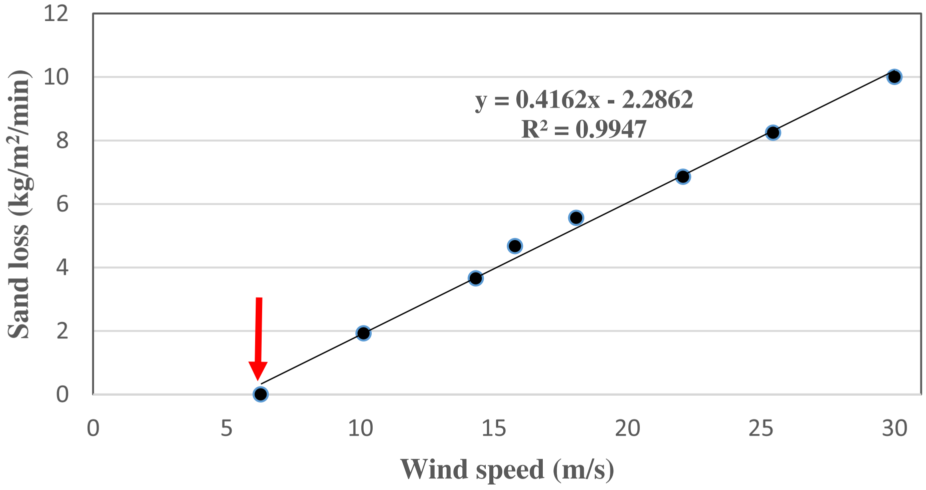

Fig. 6. Wind erosion potential and the TDV of the untreated sand.

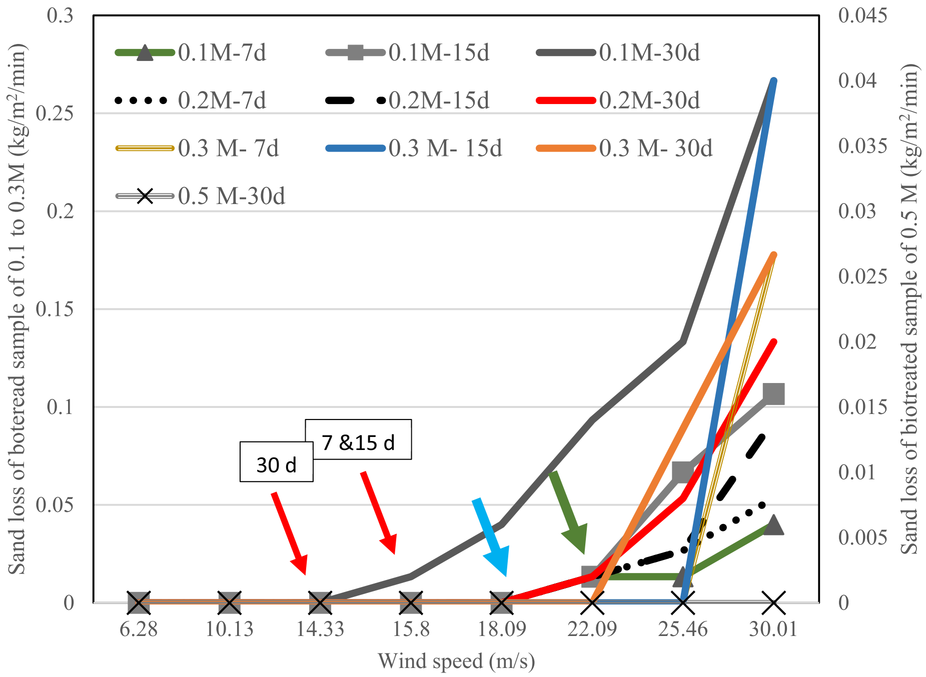

Fig. 7. Sand loss (kg/m2/min) in treated samples with various cementation solution as well as time (7, 15,and 30 days) after treatment. The red, blue and green arrow shows the TDV in samples #1 to #3, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

cementation solution, 4 L/m^2 and 12.5 mm crust was capable of controlling erosive force of wind of 30 m/s for up to 2 min. Note that the same results of sand fixation toward wind erosion at 30 m/s for 5 mins in the present study with 0.3 M and 2.5 L/m^2 spraying volume was reported. Moreover, the spraying volume in the present study for near surface soil stabilization toward wind erosive soil is almost 3 times less that what Song et al., (Song et al., 2019) was reported with the same results.

On the other hand, Fig. 8 shows the change of wind erosion threshold velocity of water treated sample which was 10.13 m/s after 7 days with sand loss of 0.3 %. However, 15 and 30 days after water treatment the sand loss are 39 and 50 % respectively; while the TDV also moved to the 6.25 m/s. Continueseley, comparing the results of MICP-treated sand with water treatment aslo reveals the effectiveness of 0.2 M cementatioin solution after 30 days with the TDV of 18.09 m/s and below 1 % of sand loss.

Fig. 9 shows images of the sand sample after wind tunnel testing, which can be comparable with Fig. 4 before treatment. No visible changes were observed for samples treated with 0.3 and 0.5 M. The cracks on the top surface of MICP-treated samples after 28 days can be explained by evaporation, along with movement disturbance. Continuously, as shown in Fig. 9, the reduction in wind erosion potential is due to the increase in the concentration of the cementation solution.

4.3. Surface strength analysis

The unconfined compressive strength of MICP treated samples was measured using the average of six points of pocket penetrometer. The solid strength among the six points was not observed. However, increasing the concentration of the cementation solution resulted in strength uniformity due to impenetrable crust formation. Continuously, samples showed raising in strength variation, as the treatment time

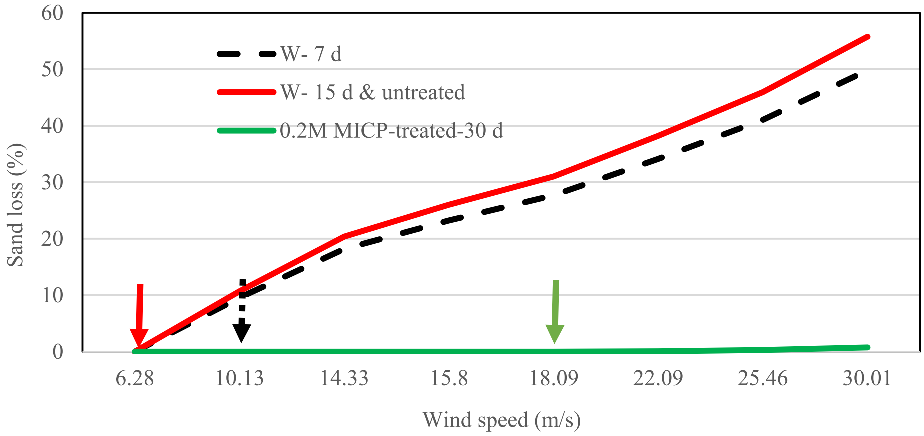

Fig. 8. Wind erosion potential and the TDV of the untreated, water treated and MICP-treated sand. Dash and plain arrow is the TDV after 7 and 15 days, respectively. The green arrow shoes the TDV od MICP treated sand after 28 days. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

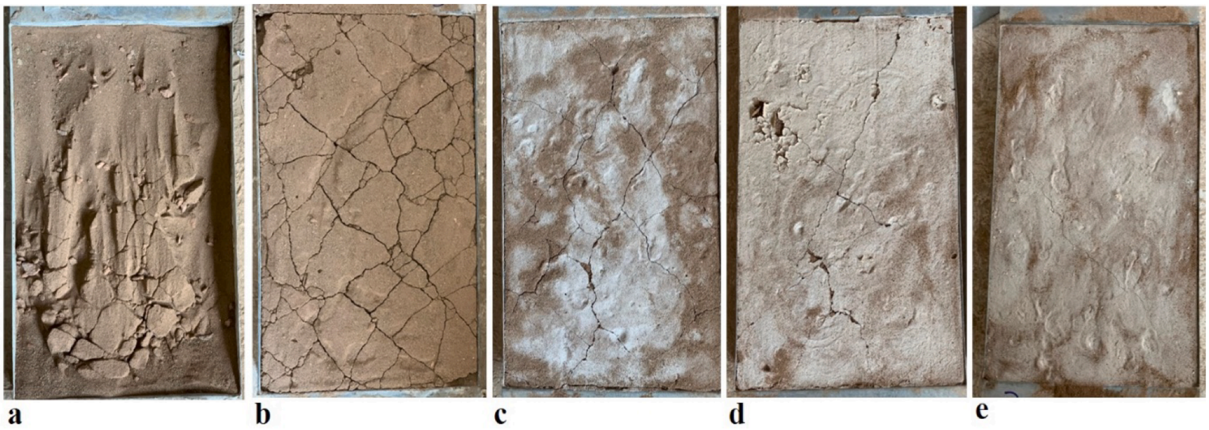

Fig. 9. Untreated and MICP treated sand samples before and after wind tunnel testing at 30.1 m/s wind speeds after 30 d: (a) Untreated; (b) 0.1 M; (c) 0.2 M; (d) 0.3 M; and (e) 0.5 M.

increases depending on the cementation ratio (as confirmed by observation and shown in Fig. 5). It can be attributed to the decrease in moisture content, as previously mentioned by (Chu, 2011) (Chu, 2011), that the dry MICP samples were stronger than wet samples.

As shown in Fig. 10, the maximum compression is obtained for the sample treated with 0.5 M as expected based on the crust thickness (148 kPa) while the minimum was for the sample treated with 0.1 M (35 kPa) after 30 days. However, comparing the results of samples treated with 0.1 and 0.2 M showed that, there is no such difference. Though, using double materials and more cracks on the surface of the sample treated with 0.2 M make it susceptible to wind erosion. Note that the data in Fig. 10 was the avearge of 6 penetrometers points showing in various times vs various cementation solutions. However, due to the MICP treatment, the large variations in UCS can be explained by the method of application (spraying) in which the edges are less treated than the main body. Additionally, due to the bacterial presence the large variations in biotreatments are inevitable explained earlier by other researchers (Mahawish et al., 2018; Stabnikov et al., 2011).

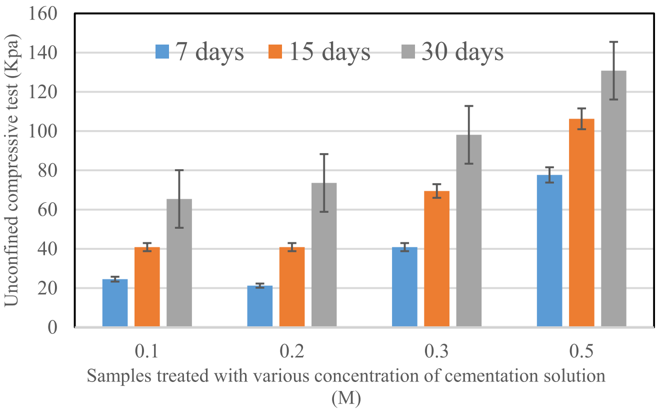

Fig. 10. The average unconfined compressive strength using 6 points of penetrometer of samples treated with various cementation solution considering time after treatment.

The results of strength properties and wind erosion potential of samples treated with 0.5 M after 30 d were the same as those reported by Daglia et al., (2021 for the sample treated with cementation solution of 1 M and 2 M with the average surface strength of 117.6 and 196.13 kPa respectively, after 20 d. It is worthy to mention that although the thickness of samples between the studies is different, the results of wind erosion protection proved that a higher cementation solution than 0.3 M does not essential and even may cause an environmental disturbance. Meng et al., (Meng, 2021) also reported the total protection toward wind erosion potential with 12.5 mm thickness with 0.57 % calcite, while the samples were treated with 0.2 M and 4 L/m2. These results also confirmed the low concentration of cementation solution for wind erosion mitigation.

Continuously, the relationship between strength properties and calcite content of all MICP treated samples was investigated and shown in Fig. 11. Interestingly, calcite content precipitation depending on the cementation solution of 0.1, 0.2, 0.3 and 0.5 M are 0.01, 0.2, 0.4 and 0.7 %, respectively. Therefore, It is concluded that one treatment of 0.3 M cementation solution through the spraying method, producing 0.4 % or more carbonate, can shape a crust to limit wind erosion and sand movements after 30 days. It was previously demonstrated that one treatment of 1.5 M cementation solution through the spraying method, produced 1.39 % carbonate (Naeimi, 2014), while Shahin et al. (2020) reported that two treatments of 1 M cementation solution, produced 1.52 % or more carbonate. Additionally, in the same case of almost 11–12 mm biocrust, the calcite content in the present study was 0.5 %, while Meng et al. (Meng, 2021) stated 0.57 %.

4.4. *Microscale identification analysis*

The microscale identification of MICP treated sand samples, including the coating of sand grains, and chemical characterization of precipitated materials was obtained from SEM and EDX analysis, as shown in Figs. 12 and 13. The precipitated calcite crystals on the surface of sand were shown in Fig. 12, along with the untreated parts of sand grains. SEM analysis was performed at 0.5 cm depth with the magnification of 100 and 200 μm.

Additionally, the chemical composition in micro-scale was analyzed using EDX analysis, Fig. 13 demonstrated the two spectrums and the peaks of Ca. Therefore, the microstructure also confirms the idea of calcite presence through the soil matrix. The XRD pattern of the sample verifies the presence of calcite crystal phase. Note that, in Spectrum 272 the O and Si has the highest peaks while in the the spectrum the O and Ca showed the highest peak. Two salient peaks of Ca at 30 and 16 wt% in the two spectrums of 274 and 272 of the sample, respectively, also indicate that the precipitation rate of calcite is different in various parts of the surface. Hence, the overall justification through the wind tunnel studies can be the more scientific and valuable for effectiveness of the method.

4.5. *Seed germination analysis*

On the basis of the before-mentioned information, this part aims at monitoring the germination emergence and survival of *H. persicum* under MICP treated conditions. Observation as presented in Fig. 14, shows that the germination of 73, 60, and 33 % in the presence of biocrust with 0.1, 0.2, and 0.3 M cementation solution, respectively. While the germination of control samples without any treatment was 87 % and there were no germination in samples treated with 0.5 M.

Moreover, the results showed that in comparison to the control samples, the reduction in the germination rate of MICP treated samples with 0.1, 0.2 and 0.3 M cementation solution was 8, 23 and 62 %, respectively. This can be explained by the effect of thicker biocrust and the excced of urea and calcium which leads to the burning of seeds. Note that the H0 was defined as the negative impact of MICP treated samples on the seed germination.

As shown in Table 2, for MICP treated samples with 0.1 and 0.2 M, since the p-value $> \alpha$, H0 cannot be rejected. The before treatment average is considered to be equal to the after treatment average. In other words, the difference between the averages of before and after is not big enough to be statistically significant. A non-significance result cannot prove that H0 is correct, only that the null assumption cannot be rejected. However, for MICP treated sample with 0.3 M, since the p-value $< \alpha$, H_0 is rejected and the before treatment average is considered to be not equal to the after treatment average.

In other words, the difference between the averages of before and after is big enough to be statistically significant.

Continueseley, the t-Test: Paired Two Sample for Means of biotreaated samples with control as presented in Table 2 showed that there is meaningful effect of 0.3 M biocrust on the germination of seeds. Note that in the 95 % region of acceptance the test statistic T equals 1, 1.871, and 4, for samples treated with 0.1, 0.2 and 0.3 M respectively. The observed effect size is also small for both non significant treatments. This indicates that the magnitude of the difference between the average of the differences and the expected average of the differences is small.

Moreover, the wind erosion potential of germinated samples treated with 0.1 and 0.2 M cementation solution also carried out using wind tunnel. The results in Fig. 15, suggested that the establishment of *H. persicum* on the surface of MICP treated samples did not make the cracks to be extended or the wind erosion potential increases. Hence, the amount of TDV was moved to 15.8 and 22.09 m/s in MICP treated samples with 0.1 and 0.2 M cementation solution, respectively. This can be explained due to the penetration of root system of the *H. persicum* in to the sand that makes the soil cohesive.

5. Conclusion

Controlling wind erosion in natural and anthropogenic environments is important for protecting soil, air, and human health, as well as reducing economic losses. In this study, the applicability of an environmentally friendly MICP based sand fixing method was investigated with the purpose to mitigate wind erosion of dunes. The following conclusions can be drawn from this study:

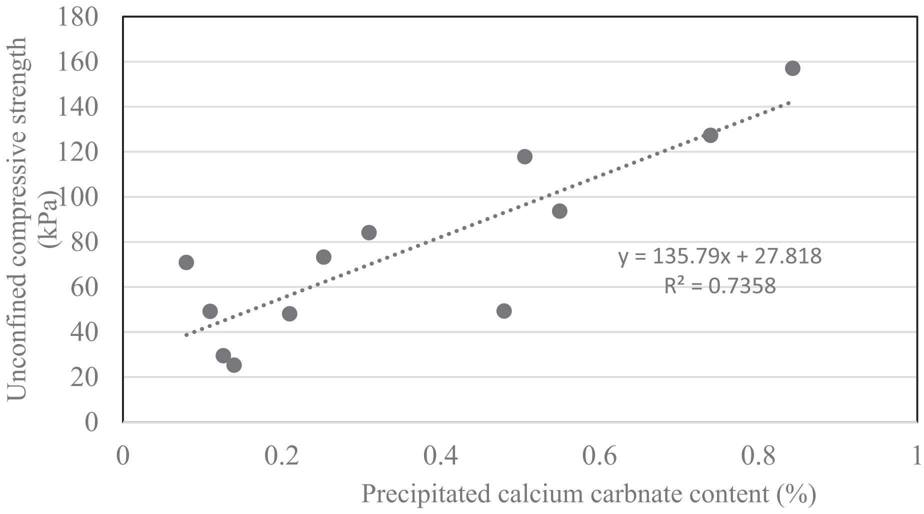

Fig. 11. Relationship between unconfined compressive strength and precipitated calcite.

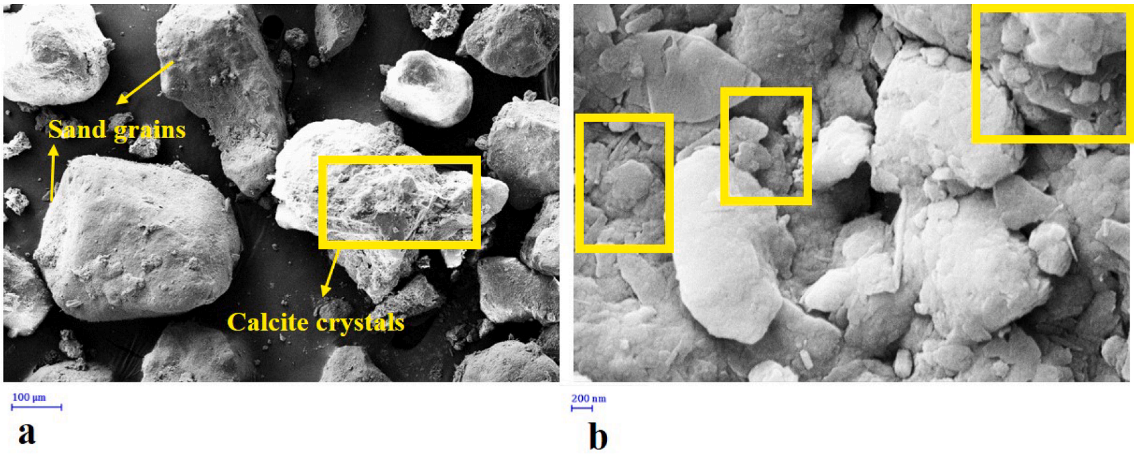

Fig. 12. Microscale analysis using SEM images: (a and b) Sand grains and the formation of calcite crystal after MICP treatment.

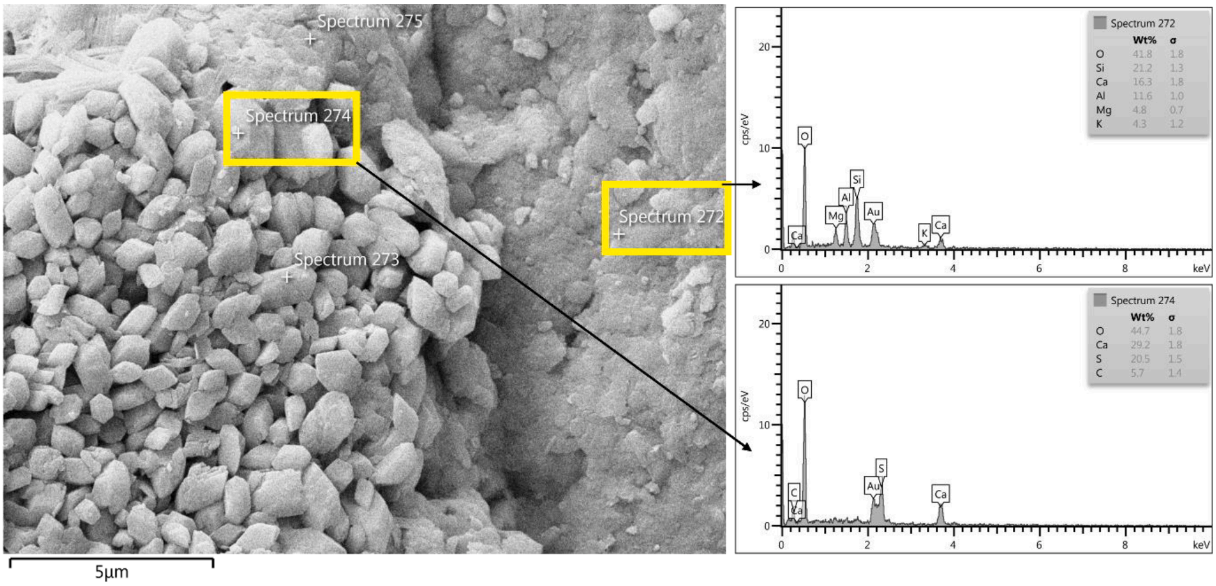

Fig. 13. Microscale chemical characterization using EDX analysis: for untreated and MICP treated.

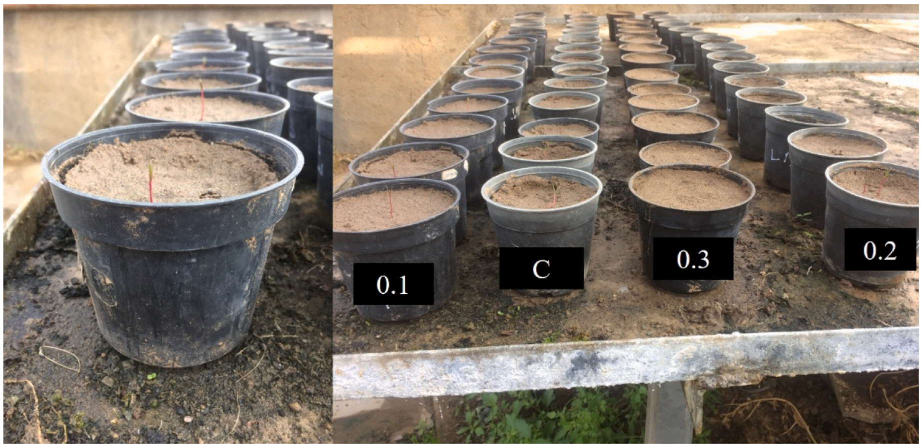

Fig. 14. Germination of MICP treated samples with 0.1 and 0.2 M cementation solution as well as control.

1) The spray method for MICP treatment with 0.1–0.5 M cementation solutions enhanced the cohesiveness of sand due to the formation of biocrust of calcium carbonate on top of sand and the ability of dunes against wind erosion. The biocrust thickness formed ranged from 0.5 to 22 mm with an average calcium carbonate content of 0.1 %–0.8 %.

Table 2
t-Test: Paired Two Sample for Means of biotreated samples with control.

Treatment			
Statistics	0.1	0.2	0.3
Mean	0.867	0.867	0.867
Variance	0.124	0.124	0.124
Observations	15.000	15.000	15.000
Pearson Correlation	0.784	0.555	0.277
p-value	0.3343	0.082	0.001
Effect size	0.26	0.48	1.03
Hypothesized Mean Difference	0.000	0.000	0.000
df	14	14	14
t Stat	1.000	1.871	4.000
P(T<=t) one-tail	0.167	0.041	0.001
t Critical one-tail	1.761	1.761	1.761
P(T<=t) two-tail	0.334	0.082	0.001
t Critical two-tail	2.145	2.145	2.145

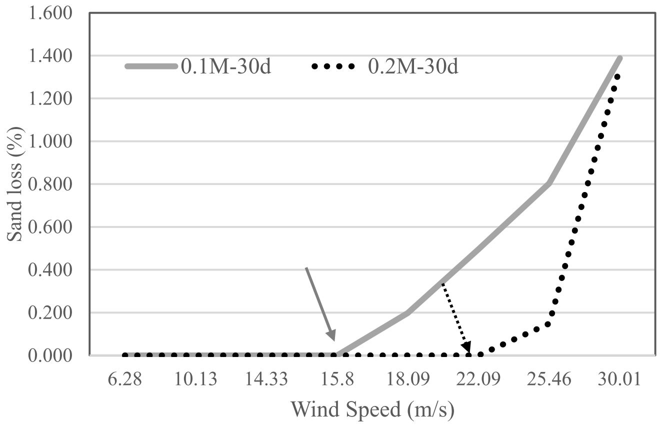

Fig. 15. Sand loss (%) in MICP treated samples with various cementation solution 30 days after treatment and germination of *H. persicum*. The plain and dash arrow shows the TDV in samples treated with 0.1and 0.2 M, respectively.

The test data showed this was effective for sand fixation after 30 days against a wind speed of 30 m/s for 5 mins.

2) The results of TDV for untreated and MICP treated sand suggested a significant dependence of curing time due to surface soil moisture on sand loss. Using a mimimum of 0.1 M cementation solution created 0.5–2 mm of biocrust after 30 days which had a 1.5 % sand losses when subjected to a wind speed 5 times more than the TDV. By increasing the calcium carbonate content by a factor of 4 would cut down the sand loss by 10 times.
3) The results of biocrust formation and wind tunnel tests, revealed for the very first time that the use of crack analysis as a rule for the selection of soil stabilizers as suggested by other studies was not scientifically approved. On the other hand, the minimum strength of 200 kPa as stated in some environmental regulations for controlling wind erosion might not be applicable for the proposed biocrust method. It is not surprising that this novel idea took time to become accepted. Hence, this study also suggests a review on the dunes stabilizers regulation when new methods are evolving.
4) The results of the novel idea of germination of *H. persicum* demonstrated that the contemporaneous of MICP treatment with native plants positively affect the TDV movements. Hence, it is suggested that biocrust with 5 mm can be applied even in dunes which mean to go under plantation.
5) The biocrust formation with 0.2 M biocement solution method could meet both geotechnical and geoenvironmental requirements. The results showed a maximum unconfined compressive strength of 100 kPa, below zero% wind erosion after 30 days under a wind speed of 20 m/s, and positive germination.
6) It is worth mentioning that the controlled laboratory experiment of this study can be extrapolated to field application showing that the spray method for MICP treatment is effective for the formation of calcium carbonate crust in the presence of vegetation cover in desert soil media to mitigate wind erosion along with the previous studies such as Naeimi and Chu (Naeimi and Chu, 2017) showed that higher temperature did not affect the MICP application in desert regions.

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.

Acknowledgement

This paper was extracted from the project entitled “Studying the Feasibility of using Modern Technologies based on Geopolymer in Dust Control of Critical Foci.“ with the number of “2-09-09-085-000731“ funded by Research Institute of Forests and Rangelands (RIFR). The authors express the gratitute to the former head of the RIFR, Dr Adel Jalili, for his devotable support. Additionally, the paper was completed with the contribution of Nanyang Technological University, Singapore, on the data analysis and paper writing.

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