International Journal of Environmental Science and Technology (2022) 19:2107–2118
https://doi.org/10.1007/s13762-021-03207-3

ORIGINAL PAPER

An experimental investigation of bacteria-producing calcareous cement in wind erosion prevention

Sh. S. Nasir[1] · A. Mohammadi Torkashvand[1] · N. Khakipour[2]

Received: 24 July 2020 / Revised: 8 November 2020 / Accepted: 13 February 2021 / Published online: 11 April 2021

Abstract

Soil stabilization is essential in different fields, such as the environment, to prevent wind erosion and dust. Microbial-induced carbonate precipitation (MICP) is a soil healing method in which bacteria with $CaCO_3$ precipitation among soil particles increase the soil erosion resistance against wind erosion. In this study, by culturing a bacterium species with the scientific name of "*Sporosarcina pasteurii*" in the laboratory and preparing the solution with three levels of urea and calcium chloride (concentrations of 0.1, 0.2, and 0.4 M) as a nutrient, the status of $CaCO_3$ precipitation was investigated. The erosion of the cemented samples was simulated at a speed of 10–20 km h^{-1} at the height of 10 cm from the tunnel bottom using a wind tunnel apparatus. The results showed that the highest $CaCO_3$ precipitation occurred in treatments of 0.1 M calcium chloride with 0.2 M and 0.4 M urea. At both wind speeds, MICP treatments significantly reduced soil erosion as compared with the control samples. The FTIR test confirmed the $CaCO_3$ precipitations. Further, the study of $CaCO_3$ precipitation using XRD and SEM analysis showed that it is more in the form of vitriol crystals, binding together loose soil particles and increasing their resistance to the shear stress of wind.

Keywords Calcium carbonate · FTIR · MICP · Stabilization · *Sporosarcina pasteurii* · XRD

Introduction

Two-thirds of Iran's area has in dry and semidry climates with over 45 million ha (hectares) of deserts (Ahmadi et al. 2004). Iran has faced a growing drought crisis and increased aerosol in the last two decades, mainly due to human interference in nature (Shokouhi Nia and Rezai Kikhaei 2018). Building excessive dams, grazing exceedingly, drilling unauthorized wells, cultivating and exporting products with high water demand, consuming water and draining underground aquifers excessively, drying wetlands and rivers, besides using plastic materials, are the factors leading to create the aerosol centers in Iran (Barzegar Bafravi et al. 2019).

The aerosol phenomenon has affected Iran, especially the western, southwestern, and central regions (Shahkoui and Rahmani 2018). It has many implications for human health (Chahar Azar et al. 2019), quality of life (Ahani et al. 2019), climate (Moradi and Aprajunqani 2017), and agriculture (Sarani and Rahdari 2019). Thus far, this phenomenon, despite the efforts of the authorities, has not been fully stopped, and it can be observed in many areas, especially the western part of the country (Alipour et al. 2019). Therefore, addressing the aerosol origin is a top priority and on the environmental–organizational agenda.

Research has tended to stabilize prone soils, resisting high-speed wind and preventing the aerosol formation (Ayaran and Kamali 2018). There are many methods to prevent entering dust particles, all of which are done to stabilize the soil. The most common of them is the soil stabilization using the oil, mineral, polymer mulches (Robichaud et al. 2017; Katebi et al. 2018; Kader et al. 2017; Azoogh et al. 2018), and biological mulches of biopolymer and plant (Chen et al. 2018, 2019; Zhang et al. 2019a; Liu et al. 2019; Wieder and Shoop 2018).

A key factor in controlling wind erosion is increasing the soil surface layer resistance to shear stress. Therefore, many

Editorial responsibility: Samareh Mirkia.

✉ A. Mohammadi Torkashvand
m.torkashvand54@yahoo.com

[1] Department of Soil Science, Science and Research Branch, Islamic Azad University, Tehran, Iran

[2] Department of Soil Science, Savadkooh Branch, Islamic Azad University, Savadkooh, Iran

soil erosion control methods are currently based on soil surface stabilization. In this respect, the formation of a physical crust can greatly reduce wind erosion. The biological process of soil remediation, as a soil stabilization technique with natural concrete, has great potential in geotechnical engineering, such as the slope stabilization and the increase in sand resistance (Jiang and Soga 2019; Zomorodian et al. 2019).

Microbial stabilization of $CaCO_3$ (MICP) is a new technique for soil remediation that involves ureolytic bacteria, such as *Sporosarcina pasteurii,* to hydrolyze urea in order to form $CaCO_3$ deposits, causing to fill soil pores (Rahim et al. 2015; Jiang et al. 2016). Urea hydrolysis is a microbial process extremely vital in biotechnological applications (Hammes and Verstraete 2002). MICP is an effective and environmentally friendly technology often used to solve various environmental problems, including soil instability and concrete crack (Anbu et al. 2016). During the MICP process, the ureolytic bacteria convert the urea (nonconductive material) molecule to two ions of ammonium (NH_4^+) and carbonate (CO_3^{2-}) (Anbu et al. 2016; Cuzman et al. 2015), subsequently leading to produce $CaCO_3$ minerals ($CaCO_3$) (Jiang et al. 2016). MICP is introduced as a highly desirable method due to its natural accessibility, efficiency, and stability (Al-Thawadi Salwa 2008; Li et al. 2018; Grabiec et al. 2017; Sharaky et al. 2018; Jiang and Soga 2019).

Many studies have shown that the microbial calcite stabilization method plays a vital role in increasing shear strength and decreasing the permeability of soil (Eryürük et al. 2015; Tayebani and Mostofinejad 2019), improving the soil biology (Warren et al. 2010), purifying the wastewater (Hammes et al. 2003), remedying crack and healing concrete resistance (Wu et al. 2019; Tayebani and Mostofinejad 2019; Jongvivatsakul et al. 2019; Ruan et al. 2019), extracting oil (Whitman et al. 1998), strength and hardness of sandy soils (Sharaky et al. 2018), solidifying the soil (Montoya 2012), dust control (Achal et al. 2011), stabilizing the heavy metal (Jiang et al. 2019; Zhang et al. 2019b; Chen and Achal 2019).

Sharaky et al. (2018) used *S. pasteurii* bacteria to enhance the stabilization of loose soil in the large irrigation canal walls of Egypt; he found these bacteria inoculation with a stabilizing solution to be effective in stabilizing the border slopes of these canals. Molares et al. (2019) investigated the replacement of chemical stabilizers with natural cement from microbial $CaCO_3$ precipitation; they showed that the bacterial effect on clay soils increased the $CaCO_3$ content, bulk density, and plasticity properties of the soil. Li et al. (2018) examined the desert sand stabilization based on the microbial precipitation rate of generated calcium carbonate. Their results showed that the addition of bacterial and cementing solutions resulted in $CaCO_3$ precipitation in sand samples. As the concentration of the cementing solution increased, the amount of $CaCO_3$ increased, thus increasing density. $CaCO_3$ reduced the pores between the sand particles and the permeability.

Grabiec et al. (2017) found that the amount of bio-$CaCO_3$ generated by *S. pasteurii* significantly affected the geotechnical properties of the soil, increasing its shear strength. This study aimed to evaluate the soil stabilization through the biological precipitation of $CaCO_3$ between soil particles in one of the dust and aerosol hot spots of Iran's central area by *S. pasteurii*.

Materials and methods

This study was conducted in 2018–2019, and data were collected and analyzed in Razi experimental complex of Science and Research Branch, Islamic Azad University, Tehran, Iran.

Soil parameters and location

The studied soil is sampled from the Aran and Bidgol deserts of Isfahan province, one of the active sites of wind erosion in the area located in 34° 00′ N and 51° 30′ E. This city, with an area of 6051 km^2, is located in 6 km northeast of Kashan in Isfahan province. Table 1 summarizes some of the physical and chemical properties of the studied soil.

Bacteria preparation

In this study, *S. pasteurii* microorganism was used for the biological precipitation of calcium carbonate. The strain of this bacterium was lyophilized from the Iranian Fungal and Industrial Bacteria Collection Center with no. PTTC 1645 (DSM 33). This bacterium is a gram-positive endospore generator grown in alkaline media with urease activity (Li et al. 2018; Omoregie et al. 2019; Jiang et al. 2019).

Table 1 Some of the physical and chemical properties of studied soil

pH	7.54
ECe (dS m^{-1})	1.10
Sand (%)	38.5
Silt (%)	53.5
Clay (%)	8.0
Organic content (%)	0.94
Equivalent $CaCO_3$ (%)	9.8
Total nitrogen (%)	0.09

ECe saturated electrical conductivity

Preparation of the bacterial suspension

Omoregie et al. (2019) used low-cost culture media to establish microbial precipitation of calcium carbonate. A comparison of food-grade media with laboratory materials showed a significant reduction in the bacterial culture cost by 99.80%. Their findings further showed that yeast extract could be an appropriate choice for bacterial culture in the MICP process concerning cost reduction. For this purpose, yeast extract was used in the LB agar culture medium and then in nutrient broth culture medium (Table 2). Bacteria were grown at 30 °C on a rotary shaker at 130 rpm for 24 h under aerobic conditions. The pH of the culture medium was adjusted to 7.5 before being put into the autoclave with NaOH. Later, 6 g of urea was added to the composition of the culture medium using a sterile filter. Once bacteria were grown properly, the solution of the liquid medium was separated from the suspended bacteria by centrifugation at 200 rpm at 2 °C.

Urease enzyme assay

The soluble electrical conductivity method (dS m^{-1}) was used to measure the urease enzyme activity of bacteria (mM urine hydrolyzed min^{-1}). Electrical conductivity measurement is a way to determine the amount of enzymatic activity of reaction (Al-Thawadi Salwa 2008; Whiffin et al. 2007; Omoregie et al. 2019). To measure urease activity, 10 ml of the suspension of grown bacteria in liquid culture medium (including bacteria and culture medium of nutrient broth) and 100 ml of urea at various concentrations of 0.4, 0.2, and 0.1 M were mixed. Then, the electrical conductivity of the mixtures was measured at a different times of 5 min, 24 h, and 48 h at 28 ± 2 °C.

Measurement of $CaCO_3$ precipitation

In the MICP process, *S. pasteurii* plays the role of catalyst in the reaction of urea and calcium chloride, causing urea hydrolysis and $CaCO_3$ precipitation. Different solutions of urea (NH_2CONH_2) and calcium chloride ($CaCl_2$) (see Table 3) were prepared to identify their best concentrations that resulted in the highest $CaCO_3$ precipitation in the MICP process.

The growth temperature was considered to be 37 °C, according to the optimum bacteria growth temperature (Whiffin et al. 2007). Five milliliters of the bacteria

Table 2 Used culture medium and their compositions

Name of culture medium	The composition of culture medium	pH
LB agar	Peptone from casein (10 g l^{-1}), yeast extract (5 g l^{-1}), sodium chloride (10 g l^{-1}), agar–agar (15 g l^{-1})	7.5
Nutrient broth	Peptic digest of animal tissue (5 g l^{-1}), sodium chloride (5 g l^{-1}), beef extract (1.50 g l^{-1}), yeast extract (1.50 g l^{-1})	7.5

Table 3 Treatment of urea and $CaCl_2$ in $CaCO_3$ precipitation using MICP method

Treatment	Concentration of urea (M)	Concentration of $CaCl_2$ (M)	Bacteria suspension	The mount of urea and $CaCl_2$	Solution volume (cc)
1	0.1	0.1	Broth + 5 cc bacteria yeast + nutrient extract	6 g urea–14.7 g $CaCl_2$	50
2	0.1	0.2	Broth + 5 cc bacteria + nutrient yeast extract	6 g urea–29.4 g $CaCl_2$	50
3	0.1	0.4	Broth + 5 cc bacteria + nutrient yeast extract	6 g urea–58.8 g $CaCl_2$	50
4	0.2	0.1	Broth + 5 cc bacteria + nutrient yeast extract	12 g urea–14.7 g $CaCl_2$	50
5	0.2	0.2	Broth + 5 cc bacteria + nutrient yeast extract	12 g urea–29.4 g $CaCl_2$	50
6	0.2	0.4	Broth + 5 cc bacteria + nutrient yeast extract	12 g urea–58.8 g $CaCl_2$	50
7	0.4	0.1	Broth + 5 cc bacteria + nutrient yeast extract	24 g urea–14.7 g $CaCl_2$	50
8	0.4	0.2	Broth + 5 cc bacteria + nutrient yeast extract	24 g urea–29.4 g $CaCl_2$	50
9	0.4	0.4	Broth + 5 cc bacteria + nutrient yeast extract	24 g urea–58.8 g $CaCl_2$	50

suspension to 50 ml of distilled water containing a mixture of urea and calcium chloride, according to the treatments in Table 3, was added to evaluate the $CaCO_3$ precipitation produced by the bacteria at the end of the growth logarithmic phase (Arias et al. 2017). Then, erlenmeyers containing the reaction solutions were placed in the incubator without shaking for 24 h at 30 °C. After that, the sample was placed at laboratory temperature. After forming the final $CaCO_3$ precipitation, the formed precipitation was dried by removing the solution and then measured.

FTIR test

Fourier transform infrared spectroscopy (FTIR) was used to determine the type of formed precipitation by *S. pasteurii* bacteria. FTIR spectra were recorded with a Fourier transform infrared spectroscopy, and Thermo AVATAR spectrometer at a wavelength of 500–4000 cm^{-1} was used to determine the effects of MICP. The mixture in erlens was shaken at 30 °C for 24 h, and then solid precipitations were collected for analysis by FTIR. The precipitates were kept at ambient temperature to dry completely. Produced precipitations in the soluble phase were used to prepare the sample, were thoroughly crushed before testing to powder, and then impregnated with inert materials. Powder samples were transformed into potassium bromide tablets for analysis. To make the tablets, the solid sample was crushed with potassium bromide to obtain powder particles smaller than 2 µm. The powder mixture was then pressed to form the tablet.

The analysis of soil resistance

Columns of PVC with an inner diameter of 6 cm and a height of 20 cm were prepared to assay the soil strength after forming precipitation. Each column was filled with the studied soil (295 g). The used treatments in this test are presented in Table 3. Each treatment was repeated three times (nine treatments), and one treatment contained bacteria without cementing solution; totally, 30 columns were prepared. Tubes were tested to evaluate the penetration resistance index of each treatment in vertical displacement at soil surfaces. The liquid inside the column naturally moved under the gravitational force.

First, 50 ml of bacterial culture medium was added to each column; after 12 h, 50 ml of cementing solution was added, according to the treatments in Table 3. This method helps to keep the bacteria in the soil. All columns were then kept at 28 ± 2 °C for 15 days. After this time, soil samples were extracted from the columns and dried at 140 °C for 48 h to evaluate the surface soil resistance at the dry state. Resistance intensity of the treated surface soil was measured using a penetrometer. The penetrometer could read a scale of 0–700 psi (0–4.83 MPa). The soil surface resistance was measured by pressing the tip of this device to the surface layer of the columns.

SEM and XRD analysis

To determine the elemental composition and the crystalline phase of the precipitation, four samples of MICP and one control sample were selected for X-ray diffraction (XRD) analysis. The dried samples were first passed through a sieve with 500 mesh and then transferred to a 50 cc Falcon tube. Apparatus with XRD 3003 PTS SEIFERT (Germany) was used for XRD. The XRD spectra were obtained using powdered samples from 5° to 80° with Cu anode with parameters of 40 kV and 35 mA. Scanning electron microscopy (SEM) images were examined using a CamScan MV2300 microscope (Canada) to investigate the $CaCO_3$ precipitation distribution in the specimens and ensure its presence in 1-cm pores of soil surface. The dried sample was cut from 1 cm of soil surface.

The measurement of soil erosion in the wind tunnel

First, trays with dimensions of 40×30 cm and height of 4 cm were prepared to measure the soil wind erosion, and then they were filled with the soil under study. The MICP solution was added to each tray (30 trays), equivalent to 1000 cc of bacteria suspension of *S. pasteurii* and 1000 cc of cementing solution of urea and calcium chloride. It was uniformly sprayed onto the soil using a sprayer. The prepared trays were completely dried in the open air for 15 days. The control treatment was sprayed with the same volume but without the MICP solution.

Next, an apparatus of the wind tunnel was simulated at the site, consisting of two main wind generators with rates of 10 m s^{-1} and 20 m s^{-1} and a wind flow transmission chamber. Using a canal with 2 m length and 50 cm width, the wind was transferred to the surface of the soil trays, and soil wind erosion was assessed in each tray. The tray was positioned in the middle of the chamber with a distance of 30 cm and a height of 10 cm from the generation site of flow so that the wind speed at the soil surface entry was set at 10 or 20 m s^{-1}. To measure the value of the soil wind erosion, the weight of the trays was first measured and then placed inside the wind tunnel apparatus for 20 min. Next, the weight of the trays was measured again. Tray weight loss showed a high rate of soil wind erosion.

The measurement of $CaCO_3$ pH and EC of treated soils

After measuring the soil resistance in the columns, pH and EC in extract 1:2 water and soil samples were investigated. The pH measurement was performed using the GLP-meter 22 pH ISE CRISON pH apparatus, and the EC measurement was done by the EC-meter GLP 31 + CRISON apparatus. $CaCO_3$ content was measured by titration using phenolphthalein.

Data analysis

Data were statistically analyzed by SPSS and MSTATC software packages, and data significance was evaluated at 5% level. The diagrams were plotted with EXCEL software.

Results and discussion

$CaCO_3$ precipitation in liquid medium

Experimental results showed that *S. pasteurii* bacteria produced $CaCO_3$ precipitation in the culture medium of nutrient broth and yeast extract after 28 h at 28 °C (Figs. 1, 2). The bacteria activity is indicated by the presence of $CaCO_3$ precipitations, urea usage as a food source, and conversion of calcium chloride to $CaCO_3$. Musa Zadeh Moghadampour et al. (2016) also used two culture media of YU and LB to investigate the maximum amount of $CaCO_3$ precipitation. The results showed that *S. pasteurii* bacteria had more precipitation in the medium with yeast extract. The highest $CaCO_3$ precipitation occurred in treatments of 0.1 M calcium chloride and 0.1 mM urea, calcium chloride of 0.1 mM and 0.2 mM urea, 0.4 mM urea and 0.1 calcium chloride, besides 0.4 M of calcium chloride.

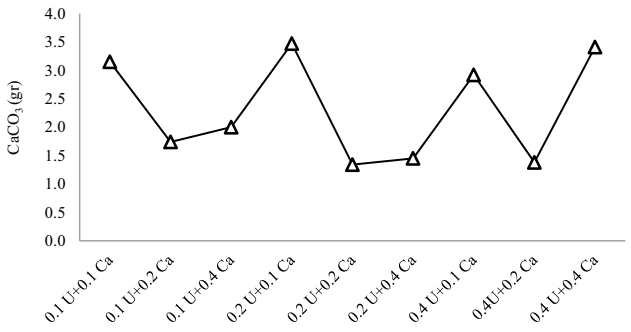

Fig. 2 Formation of $CaCO_3$ precipitation in liquid culture medium

FTIR and XRD analysis

Infrared spectroscopy (FTIR) was performed to determine the type of formed precipitations by the bacteria in the presence of calcium chloride and urea solution (Fig. 3). The FTIR test showed absorption peaks around 704.39 cm^{-1} and 859.28 cm^{-1}, indicating the calcite phase. The results of the XRD test also confirmed the presence of $CaCO_3$ crystals in the soil (Fig. 4). FTIR is a precious test used repeatedly to confirm the presence of calcium carbonate.

Achal et al. (2012) investigated the effect of *Sporosarcina ginsengisoli* bacteria on arsenic-contaminated soils, confirming the production of $CaCO_3$ by bacteria. Ha Nguyen et al. (2019) also verified the microbial $CaCO_3$ precipitations in concrete by performing FTIR analysis under the inoculation of *S. pasteurii*. $CaCO_3$ has different sizes in nature, and it consists mainly of three different types of calcite, aragonite, and vitrite crystals (Molares et al. 2019). The XRD analysis was performed to determine the type of formed precipitations between the soil pores (Fig. 4). Analysis of the MICP sample showed the highest peak at 2θ of 29.8°, indicating formed $CaCO_3$ polymorphs by bacteria. The value of precipitated crystals by bacterial cells was 100% calcite.

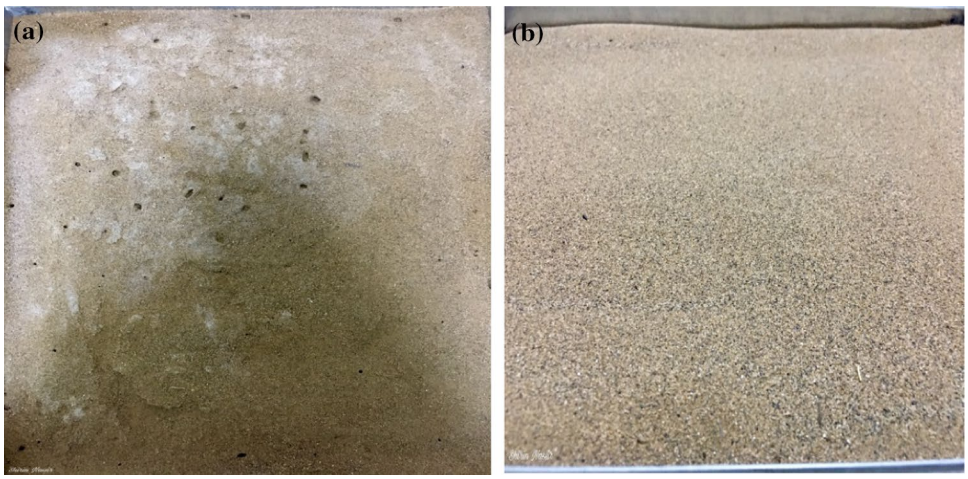

Fig. 1 Image of control sample surface (**a**) and cementing sample by MICP technique (**b**)

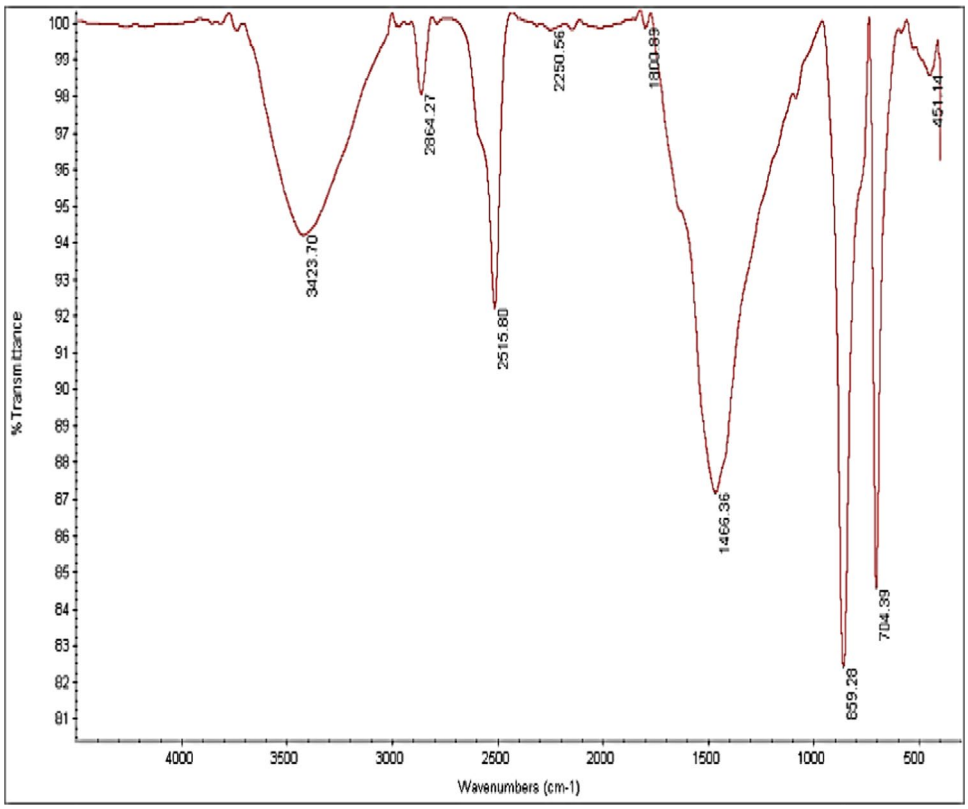

Fig. 3 FTIR test of collected precipitations from a mixture of bacteria suspension with urea–chloride calcium solution

SEM analysis

To confirm the formation of $CaCO_3$ particles by *S. pasteurii* bacteria, samples were taken from control soil and three treated columns and then images were prepared by SEM (Fig. 5). Electron microscopy images showed that the $CaCO_3$ content in the main soil sample was very low; thus, the soil particles were scattered (Fig. 5a). Examination of the soil thin sections showed that the presence of $CaCO_3$ precipitation among the soil particles caused the correlation between the soil grains, thereby increasing the soil hardness and resistance (Fig. 5b, c, d). The SEM analysis shows the formation of the observed crystal, similar to the reports by Wasim and Basit (2016) and Qiu et al. (2014), which confirm the formation of calcite with a similar crystalline structure.

Evaluation of pH and EC of treated soils

ANOVA results (Table 4) showed that the effect of treatments on soil pH and EC, $CaCO_3$ formation, and soil wind erosion (eroded soil) was significant at 1% level. pH is a key parameter in $CaCO_3$ precipitation since it determines the amount of bacterial activity in the soil. *S. pasteurii* bacterium has the highest activity at neutral pH (Hammes and Verstraete 2002); however, ambient pH enhances by increased activity and urea decomposition (Dejong et al. 2006). The general increasing trend of the pH of the treated soil samples from 7 to about 7.7 is for this reason, as shown in Fig. 6. pH on modified soils by the MICP process was tested by Omoregie et al. (2017), Henze and Randall (2019), and Ruan et al. (2019); it showed that $CaCO_3$ formation was directly related to pH, and the higher rate of $CaCO_3$ stabilization was observed at higher pH. The data analysis (Fig. 6) showed that the control soil had the lowest EC compared to the treated soil. In the treated soils, soil EC increased due to the high bacterial activity.

Precipitation of calcium carbonate

At the end of the stabilization of soil particles, samples of control and MICP treatments were used to measure the amount of formed $CaCO_3$ in the soil (Fig. 7). Results showed that the amount of $CaCO_3$ in bacteria precipitation increased by about 20% compared to the control soil. The increase of calcite crystals in the soil pores and the aggregation of soil particles explained the resistance of the samples in two tests of penetration resistance ("The measurement of penetration resistance" section) and wind tunnel. Li et al. (2018) showed that the amount of $CaCO_3$ in soil samples gradually increased using the

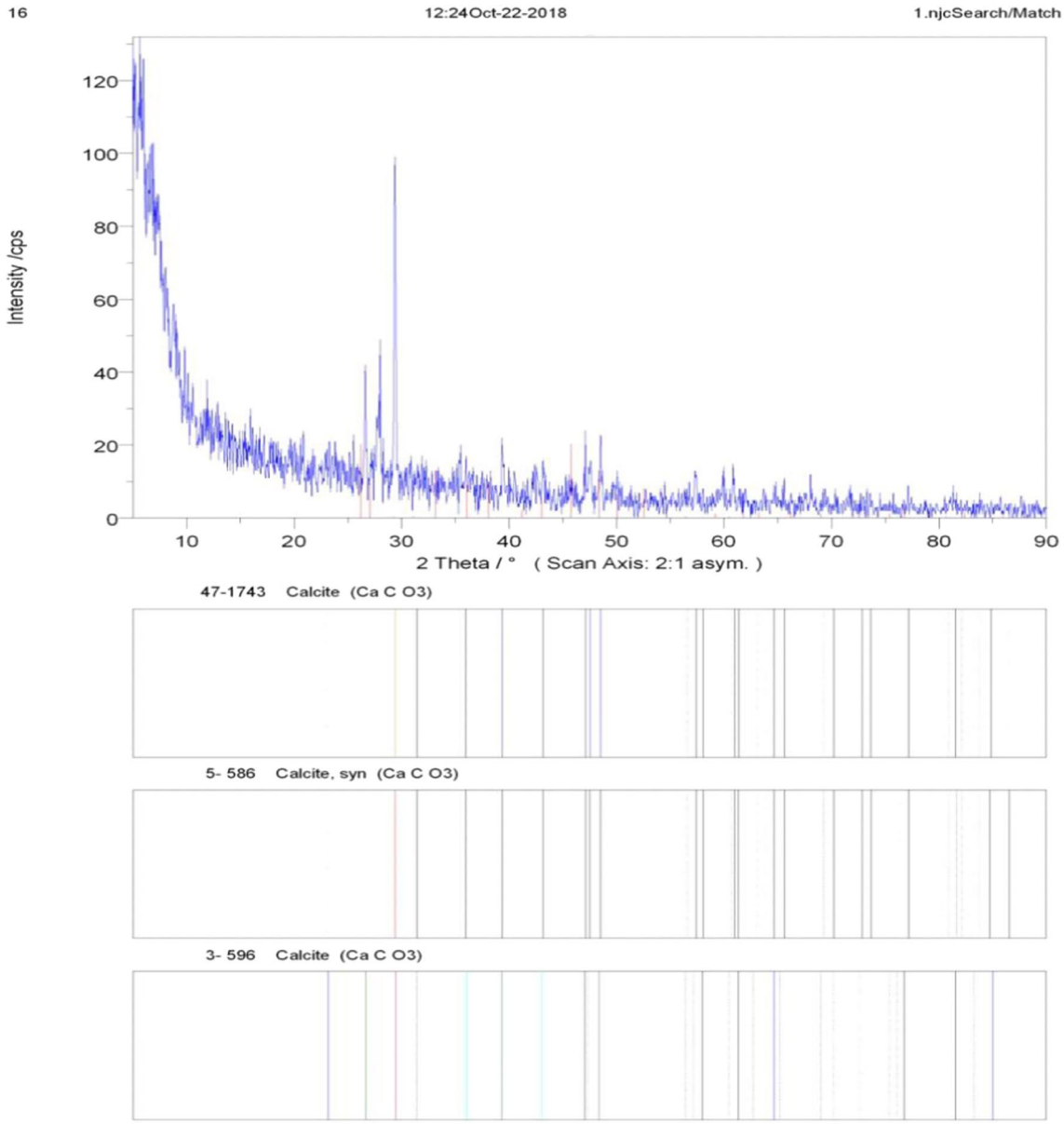

Fig. 4 XRD spectra of MICP sample

MICP process compared to the control soil. According to these results, the formation of $CaCO_3$ was the leading cause of change in other physical properties.

The measurement of penetration resistance

The MICP effect on compressibility and surface resistance was measured using a penetrometer, with values between 0 and 700 psi (0–4.83 MPa) in dry-air conditions at 1 cm of the samples' surface layer. The results of the experiment showed that all treated columns had the highest measured resistance of 700 psi. A comparison of the control sample with MICP treatments showed a fourfold increase in penetration resistance.

Many studies have been conducted on the formation of $CaCO_3$ crystals in sand columns to evaluate the degree of microbial stabilization (Dejong et al. 2010; Stabnikov et al. 2013). Studies have shown that soil microbial remediation by a mixture of sand and microorganisms increases the compressive strength of the treated specimens (Omoregie et al. 2017).

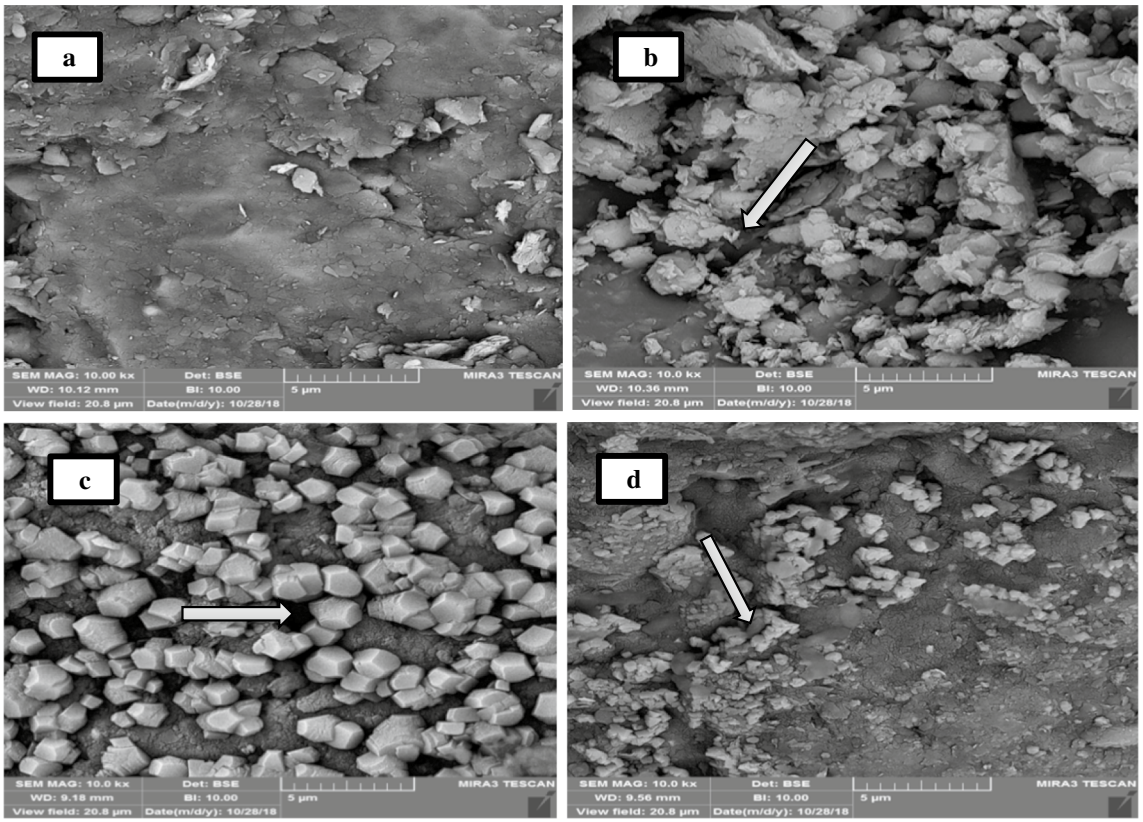

Fig. 5 SEM analysis of sandy soil before MICP treatment with magnification 5µ (**a**), SEM analysis of sandy soil with MICP treatment (0.2 urea and 0.1 $CaCl_2$) with magnification of 5 µm (**b**), SEM analysis of sandy soils with MICP treatment (0.4 urea and 0.4 $CaCl_2$) with magnification of 5µ (**c**), SEM analysis for sand refined by MICP process (0.4 urea and 0.1 $CaCl_2$) with magnification of mµ5 (**d**)

Table 4 ANOVA results of the MICP treatments effects on pH, ECe, $CaCO_3$ formation, and soil wind erosion (eroded soil)

Variations resources	Freedom degree	Mean squared					
		pH	ECe	$CaCO_3$	Eroded soil (10 m s^{-1})	Eroded soil (20 m s^{-1})	Total eroded soil
Treatment	9	3.6**	0.95**	95.8**	278**	127**	456**
Error	18	0.6	0.12	14.2	42.1	22.3	14.8
CV	–	6.5	10.1	8.2	5.4	4.6	7.2

**Significant at 1% level

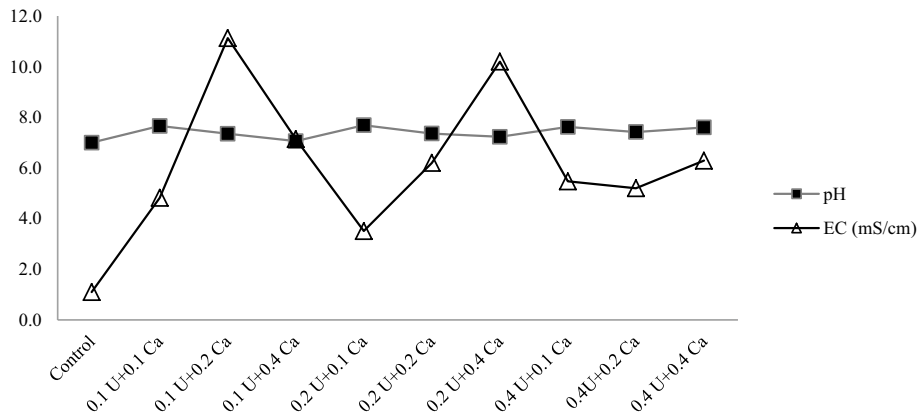

Fig. 6 pH and EC values for treated and untreated soil samples

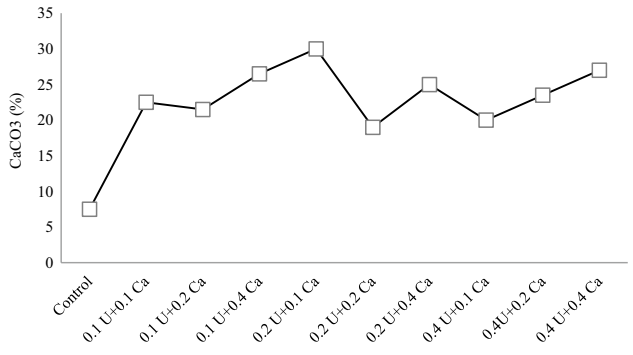

Fig. 7 $CaCO_3$ content in the treated soil samples

Wind erosion

The results of variations in the amount of eroded soil in the two samples of control and MICP treatment were investigated at two wind speeds of 10 m s^{-1} and 20 m s^{-1} (Fig. 8). The control soil tray and treated trays were tested by MICP intact after 28 days. The lost soil rate in the wind erosion test was measured by weighing the trays at the end of each experiment. The difference in the amount of erosion between biological treatments and the control soil showed a significant effect of MICP in controlling wind erosion, especially at high velocities. Maximum erosion occurred in the control soil due to the absence of bacterial activity.

The XRD analysis (Fig. 4) confirms that calcite precipitations by *S. pasteurii* bacteria in the treated columns cause pore filling; also, like a bridge, they bind the soil particle together. They are the main cause of the increase in penetration resistance of the MICP samples and, consequently, their significant resistance to wind erosion (Fig. 8). The results showed the main cause of soil resistance to be the presence of calcite crystals, which is the most stable type of $CaCO_3$ polymorph and causes the aggregation of soil particles. The XRD analysis results on sandy soil samples showed that the formed precipitations by *S. pasteurii* bacteria in the MICP process were quartz and calcite, in agreement with Dhami et al. (2017).

Based on the comparison of the SEM analysis (Fig. 5) with the wind tunnel test results (Fig. 8), it was concluded that the soil resistance was due to a significant amount of $CaCO_3$ crystals formed between the pores of the soil, causing a correlation between the porous media and its soil resistance to high wind speeds. On the other hand, the precipitation of $CaCO_3$ reduced the open pores of the soil and led to increased penetration resistance. It can be concluded that the increase in the surface layer resistance of the samples is because of the biological cement produced through the MICP process, and the cohesiveness of sand particles is the main reason for the decrease in soil loss. The experiment on soil trays confirms the results of all experiments performed in this study. According to the results of Tobler et al. (2011) and Chen et al. (2008), the bacterial activity becomes better at the higher concentration of urea and calcium chloride. According to Zomorodian et al. (2019), the MICP process can protect soil against erosion at different wind speeds. The least amount of soil erosion occurs in the treatments of 0.1 M $CaCl_2$ and 0.1 M urea, together with 0.4 M urea and 0.4 mM $CaCl_2$. As previously shown in Fig. 2, most of the $CaCO_3$ precipitation by the bacteria occurs in the abovementioned solutions, i.e., 0.1 and 0.4 M concentrations of $CaCl_2$ and urea. According to Fig. 7, the highest percentage of lime is observed in these treatments, confirming bacterial activity and $CaCO_3$ precipitation. The highest percentage of soil lime is observed in the treatment of urea 0.2 M and 0.1 M $CaCl_2$, in agreement with the results of the rate test of $CaCO_3$ precipitation (Fig. 2) and soil erosion (Fig. 8). Electron microscopy images also confirm the highest formation of $CaCO_3$ precipitate in the treatment of 0.4 M urea and $CaCl_2$. The treatment of 0.4 M urea and 0.1 M $CaCl_2$ has a large amount of $CaCO_3$ precipitation (Fig. 2); thus, it has little erosion at

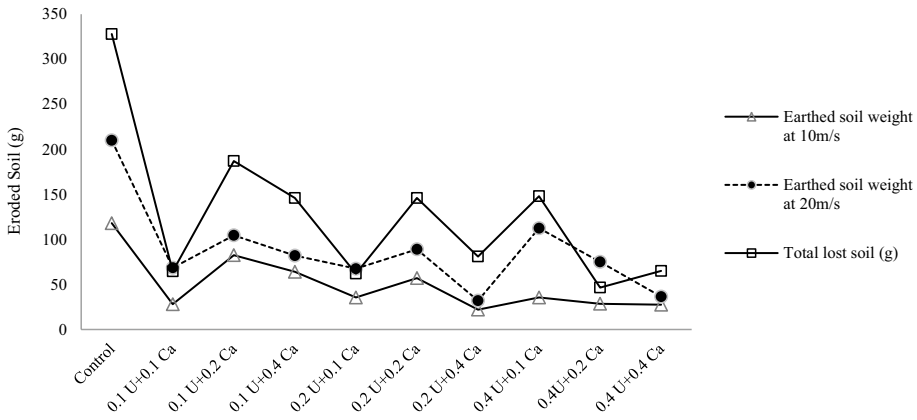

Fig. 8 Results of soil erosion supplementary test at two speeds of 10 and 20 m s^{-1} of wind

the rate of 10 m s^{-1} (Fig. 8); however, the amount of soil erosion increases at the rate of 20 m s^{-1}.

Conclusion

A main object of this study was the stabilization of erosion-prone soils through the biological precipitation of $CaCO_3$ between soil particles by *S. pasteurii*. The results have shown the highest bacterial activity at concentrations of 0.4 M urea and 0.4 M $CaCl_2$; the highest $CaCO_3$ precipitation occurs in this treatment. XRD and FTIR analyses confirm the formation of $CaCO_3$. Wind erosion is significantly reduced in MICP treatments than the control sample; however, the highest wind erosion reduction occurs in the 0.4 M urea and $CaCl_2$ treatment. The treatment of 0.1 M urea and $CaCl_2$ results in the same reduction in wind erosion as the 0.4 M urea and $CaCl_2$ treatment; economically, due to the need for less raw materials for bacterial activity and precipitation formation, the 0.1 M urea and $CaCl_2$ treatment is preferred. Results confirmed the use of MICP technique in remediation of erosion-prone areas, but field tests are recommended to validate this method further in soil stabilization and wind erosion prevention.

Acknowledgements The data were supported by Razi experimental complex of Science and Research Branch, Islamic Azad University, that is gratefully acknowledged.

References

Achal V, Mukherjee A, Reddy M (2011) Effect of calcifying bacteria on permeation properties of concrete structures. J Ind Microbiol Biotechnol 38(9):1229–1234

Achal V, Pan X, Fu Q, Zhang D (2012) Biomineralization based remediation of As(III) contaminated soil by *Sporosarcina ginsengisoli*. J Hazard Mater 201–202:178–184

Ahani E, Narouei H, Ahmadpour M (2019) Assessment of the economic, social and environmental impacts of aerosols and their damages (Zabul City Case Study). In: International dust conference on Southwest Asia, 23–25 April 2019. University of Zabol, Zabol, Iran **(in Persian)**

Ahmadi H, Khorasani NA, Karami M, Azarkar SM (2004) Estimation of wind erosion in Khorasan habitats (case study: Sarakhs area). J Environ Sci Technol 5(4):19–28

Al-Thawadi Salwa M (2008) High strength in-situ biocementation of soil by calcite precipitating locally isolated ureolytic bacteria, Ph.D. School of Biological Sciences and Biotechnology, Murdoch University

Alipour H, Jalalian A, Honarjoo N, Sarmadian F (2019) Spatial and temporal distribution of dust-bound trace metal elements around Kuhdasht watershed area in Iran. Clean Soil Air Water 19(10). https://doi.org/10.1002/clen.201900318

Anbu P, Kang CH, Shin YJ, So JS (2016) Formations of $CaCO_3$ minerals by bacteria and its multiple applications. Springerplus 5:250–262

Arias D, Cisternas LA, Rivas M (2017) Biomineralization of calcium and magnesium crystals from seawater by halotolerant bacteria isolated from Atacama Salar (Chile). Desalination 405:1–9

Ayaran A, Kamali M (2018) Investigating the role of the environment in sustainable security development (focusing on the crisis of aerosol in Khuzestan Province). In: Fourth international conference on sustainable development focused on environmental engineering, 17–9 December 2018. Center for Sustainable Development Solutions—Mehr Arvand Higher Education Institute, Tehran, Iran **(in Persian)**

Azoogh L, Khalili B, Moghadam Jafari S (2018) Interaction of petroleum mulching, vegetation restoration and dust fallout on the conditions of sand dunes in southwest of Iran. Aeolian Res 32:124–132

Barzegar Bafravi R, Dolatabadi M, Esfandiarpour N (2019) A review of factors affecting aerosol generation in Iran. In: First national aerosol conference on health-oriented approach, 4–7 February 2019. Zabol University of Medical Sciences and Health Services **(in Persian)**

Chahar Azar F, Chahar Azar Y, Javad Amiri M (2019) The role of aerosol on human health and the environment. In: International dust conference on Southwest Asia, 23–25 April 2019. University of Zabol, Zabol, Iran. **(in Persian)**

Chen X, Achal V (2019) Biostimulation of carbonate precipitation process in soil for copper immobilization. J Hazard Mater 368:705–713

Chen Y, Cheng JJ, Creamer KS (2008) Inhibition of anaerobic digestion process: a review. Bioresour Technol 99(10):4044–4064

Chen H, Zhang X, Abla M, Lü D, Yan R, Ren Q, Ren Z, Yang Y, Zhao W, Lin P, Liu B, Yang X (2018) Effects of vegetation and rainfall types on surface runoff and soil erosion on steep slopes on the Loess Plateau, China. CATENA 170:141–149

Chen J, Xiao H, Li Z, Liu C, Wang D, Wang L, Tang C (2019) Threshold effects of vegetation coverage on soil erosion control in small watersheds of the red soil hilly region in China. Ecol Eng 132:109–114

Cuzman OA, Richter K, Wittig L, Tiano P (2015) Alternative nutrient sources for biotechnological use of *Sporosarcina pasteurii*. World J Microbiol Biotechnol 31(6):897–906

Dejong JT, Fritzges MB, Nusslein K (2006) Microbially induced cementation to control sand response to undrained shear. J Geotech Geoenviron Eng 132:1381–1392

DeJong JT, Mortensen BM, Martinez BC, Nelson DC (2010) Biomediated soil improvement. Ecol Eng 36(2):197–210

Dhami NK, Alsubhi WR, Watkin E, Mukherjee A (2017) Bacterial community dynamics and biocement formation during stimulation and augmentation: implications for soil consolidation. Front Microbiol 8:1267. https://doi.org/10.3389/fmicb.2017.01267

Eryürük K, Yang S, Suzuki D, Sakaguchi I, Akatsuka T, Tsuchiya T, Katayama A (2015) Reducing hydraulic conductivity of porous media using $CaCO_3$ precipitation induced by *Sporosarcina pasteurii*. J Biosci Bioeng 119(3):331–336

Grabiec AM, Starzyk J, Stefaniak K, Wierzbicki J, Zawal D (2017) On possibility of improvement of compacted silty soils using bioprecipitation method. Constr Build Mater 138:134–140

Ha Nguyen T, Ghorbel E, Fares H, Cousture A (2019) Bacterial self-healing of concrete and durability assessment. Cem Concr Compos 104:103340. https://doi.org/10.1016/j.cemconcomp.2019.103340

Hammes F, Verstraete W (2002) Key roles of pH and calcium metabolism in microbial carbonate precipitation. Rev Environ Sci Biotechnol 1:3–7

Hammes F, Seka A, Knijf SD, Verstraete W (2003) A novel approach to calcium removal from calcium-rich industrial wastewater. Water Res 37(3):699–704

Henze J, Randall DG (2019) Microbial induced $CaCO_3$ precipitation at elevated pH values (>11) using *Sporosarcina pasteurii*. J Environ Chem Eng 6(4):5008–5013

Jiang NJ, Soga K (2019) Erosional behavior of gravel-sand mixtures stabilized by microbially induced calcite precipitation (MICP). Soils Found 59(3):699–709

Jiang N, Hideyosh Y, Koj Y, Soga K (2016) Ureolytic activities of a urease-producing bacterium and purified urease enzyme in the anoxic condition: implication for subseafloor sand production control by microbially induced carbonate precipitation (MICP). Ecol Eng 90:96–104

Jiang N, Rui Liu J, Yan Jun D, Yu Zhang B (2019) Microbial induced carbonate precipitation for immobilizing Pb contaminants: toxic effects on bacterial activity and immobilization efficiency. Sci Total Environ 672:722–731

Jongvivatsakul P, Janprasit K, Nuaklong P, Pungrasmi W, Likitlersuang S (2019) Investigation of the crack healing performance in mortar using microbially induced $CaCO_3$ precipitation (MICP) method. Constr Build Mater 212:737–744

Kader MA, Senge M, Mojid MA, Ito K (2017) Recent advances in mulching materials and methods for modifying soil environment. Soil Till Res 168:155–166

Katebi H, Fahmi A, Samadi Kafil H, Hajialilue Bonab M (2018) Stabilization of calcareous sand dunes using phosphoric acid mulching liquid. J Arid Environ 148:34–44

Li D, Tian K, Zhang H, Wub Y, Nie K, Zhang S (2018) Experimental investigation of solidifying desert aeolian sand using microbially induced calcite precipitation. Constr Build Mater 172:251–262

Liu J, Chen Z, Kanungo DK, Song Z, Bai Y, Wang Y, Li D, Qian W (2019) Topsoil reinforcement of sandy slope for preventing erosion using water-based polyurethane soil stabilizer. Eng Geol 252:125–135

Molares L, Garzon E, Romero E, Sanchez-soto PJ (2019) Microbiological induced carbonate ($CaCO_3$) precipitation using clay phyllites to replace chemical stabilizers (cement or lime). Appl Clay Sci 174:15–28

Montoya BM (2012) Bio-mediated soil improvement and the effect of cementation on the behavior, improvement, and performance of sand. University of California, Davis

Moradi G, Aprajunqani A (2019) Investigating the origin of aerosol and their impacts on air pollution. In: International dust conference on Southwest Asia, 23–25 April 2019. University of Zabol, Zabol **(in Persian)**

Musa Zadeh Moghadampour R, Tabandeh F, Kalantari F (2016) Investigation of factors affecting soil microbial improvement based on determination of unfinished soil compressive resistance. In: Third national conference on environment and natural resources, Shiraz **(in Persian)**

Omoregie AI, Khoshdelnezamiha G, Senian N, Ong DE, Nissom P (2017) Experimental optimisation of various cultural conditions on urease activity for isolated *Sporosarcina pasteurii* strains and evaluation of their biocement potentials. Ecol Eng 109:65–75

Omoregie A, Lock Hei Ngu I, Dominic Ek Leong O, Peter Morin N (2019) Low-cost cultivation of *Sporosarcina pasteurii* strain in food-grade yeast extract medium for microbially induced carbonate precipitation (MICP) application. Biocatal Agric Biotechnol 17:247–255

Qiu J, Qin Sheng Teng D, Yang E (2014) Surface treatment of recycled concrete aggregates through microbial carbonate precipitation. Constr Build Mater 57:144–150

Rahim S, Zomorodian SMA, Niazi A, O'Kelly B (2015) Improving sand with microbialinduced carbonate precipitation. Proc Inst Civ Eng Ground Improv 168(3):217–230

Robichaud PR, Jennewein J, Sharrat BS, Lewis SA, Brown RE (2017) Evaluating the effectiveness of agricultural mulches for reducing post-wildfire wind erosion. Aeolian Res 27:13–21

Ruan S, Qiu J, Weng Y, Yang Y, Yang E, Chu J, Unluer C (2019) The use of microbial induced carbonate precipitation in healing cracks within reactive magnesia cement-based blends. Cem Concr Res 115:176–188

Sarani A, Rahdari S (2019) Aerosol on agricultural performance and extension activities. In: International dust conference on Southwest Asia, 23–25 April 2019. University of Zabol, Zabol, Iran **(in Persian)**

Shahkoui A, Rahmani T (2018) Climatic survey of aerosol at Northwest of Iran. In: Second national meteorological conference of Iran, 9th May 2018. Ferdowsi University of Mashhad, Mashhad **(in Persian)**

Sharaky A, Mohamed N, Elmashad M, Shredah N (2018) Application of microbial biocementation to improve the physico-mechanical properties of sandy soil. Constr Build Mater 190:861–869

Shokouhi Nia M, Rezaei Kikhaei Kh (2018) How aerosols occur in Iran, effects and management strategies to cope with it. In: First national conference of aerosol on health-oriented approach, Zabol, Zabol University of Medical Sciences and Health Services **(in Persian)**

Stabnikov V, Jian C, Ivanov V, Li YS (2013) Halotolerant, alkaliphilic ureaseproducing bacteria from different climate zones and their application for biocementation of sand. World J Microb Biotechnol 29(8):1453–1460

Tayebani B, Mostofinejad D (2019) Self-healing bacterial mortar with improved chloride permeability and electrical resistance. Constr Build Mater 208:75–86

Tobler DJ, Cuthbert MO, Greswell RB, Riley MS, Renshaw JC, Handley-Sidhu S, Phoenix VR (2011) Comparison of rates of ureolysis between *Sporosarcina pasteurii* and an indigenous groundwater community under conditions required to precipitate large volumes of calcite. Geochim Cosmochim Acta 75(11):3290–3301

Warren LA, Maurice PA, Parmar N, Grant Ferris F (2010) Microbiolly mediated $CaCO_3$ precipitation: implications for interpreting calcite precipitation and for solid-phase capture of inorganic contaminants. Geomicrobiol J 18(1):93–115

Wasim Kh, Basit EM (2016) Crack healing in concrete using various bio influenced self-healing techniques. Constr Build Mater 102(1):349–357

Whiffin VS, van Paassen LA, Harkes MP (2007) Microbial carbonate precipitation as a soil improvement technique. Geomicrobiol J 24(5):417–423

Whitman WB, Coleman DC, Wiebe W (1998) Prokaryotes: the unseen majority. Proc Natl Acad Sci (PNAS) 95(12):6578–6583

Wieder WL, Shoop SA (2018) State of the knowledge of vegetation impact on soil strength and trafficability. J Terramech 78:1–14

Wu M, Hu X, Zhang Q, Xue D, Zhao Y (2019) Growth environment optimization for inducing bacterial mineralization and its application in concrete healing. Constr Build Mater 209:631–643

Zhang C, Zhou A, Zhang H, Zhang Q, Zhang X, Sun H, Zhao C (2019a) Soil erosion in relation to climate change and vegetation cover over the past 2000 years as inferred from the Tianchi Lake in the Chinese Loess Plateau. J Asian Earth Sci 180:103850. https://doi.org/10.1016/j.jseaes.2019.04.019

Zhang J, Kumari D, Fang C, Achal V (2019b) Combining the microbial calcite precipitation process with biochar in order to improve nickel remediation. Appl Geochem 103:68–71

Zomorodian SMA, Ghaffari H, O'Kelly BC (2019) Stabilisation of crustal sand layer using biocementation technique for wind erosion control. Aeolian Res 40:34–41