Micromorphological and Biocalcification Effects of *Sporosarcina pasteurii* and *Sporosarcina ureae* in Sandy Soil Columns

M. Sarmast¹, M. H. Farpoor¹*, M. Sarcheshmehpoor¹, and M. K. Eghbal²

ABSTRACT

Microbial calcium carbonate, by bridging sand particles, can play an important role in sand dune stability. A study was carried out on the cementation of sand grains and infilling of pore spaces by CaCO₃. Two bacterial species (*Sporosarcina pasteurii* and *Sporosarcina ureae*), three reactant concentrations (0.5, 1 and 1.5M), and six reaction times (12, 24, 48, 96, 192 and 288 hours) were tested in factorial experiment. Bacterial inocula and reactant solutions were added daily to sandy soil columns (6.5 cm height and inner diameter of 7.7 cm), while precipitation of CaCO₃ being investigated within 0-1.5, 1.5-3, 3-4.5 and 4.5-6 cm intervals. Chemical and micromorphological analyses revealed that CaCO₃ formation, inorganic C sequestration, and depth of cementation were more profound for *S. pasteurii* as compared with *S. ureae*. Both microbial CaCO₃ precipitation and inorganic C sequestration increased with increase in reaction time from 12 to 288 hours. Increase in reactant concentration also caused an increase in CaCO₃ precipitation (by 12%). Micromorphological observations showed a high degree of calcite crystals’ bridging, coating on sand particles and as well infilling of pore spaces. *S. pasteurii* is thus recommended for being used in stabilization of sand dunes; due to its significant effects on CaCO₃ deposition and as well on sand grain cementation.

Keywords: Biomineralization, Inorganic C sequestration, Sand dune fixation, Ureolytic bacteria.

INTRODUCTION

Biocalcification is the process of calcite formation resulting from metabolic activities of autotrophic and heterotrophic organisms. Using metabolic pathway of ureolytic hydrolysis through nitrogen cycle, some of the heterotrophic bacteria are of the potential of providing high concentrations of CaCO₃ in short periods of time (Castanier et al., 1999; De Muynck et al., 2010). *Bacillus, Sporosarcina, Sporolactobacillus, Clostridium* and *Desulfotomaculum* genera are among the most urease producing bacteria in soils (Ivanov and Chu, 2008).

One mole of urea is hydrolyzed intracellularly into 2 moles of ammonia and 1 mole of CO₂ [Equations (1) and (2)] through urease enzyme activity (Hammes et al., 2003). Soil pH increases as a result of this enzymatic reaction, and CaCO₃ [Equations (3) and (4)] will be precipitated from CO₃²⁻ and Ca²⁺ ions (Siddique and Chahal, 2011). Meanwhile, produced CO₂ is trapped in CaCO₃ preventing CO₂ emission into atmosphere.

\[
\text{CO(NH}_2\text{)}_2 + \text{H}_2\text{O} \rightarrow \text{NH}_2\text{COOH} + \text{NH}_3
\]  

(1)

\[
\text{NH}_2\text{COOH} + \text{H}_2\text{O} \rightarrow \text{NH}_3 + \text{CO}_2 + \text{H}_2\text{O}
\]  

(2)

\[
\text{CO}_2 + \text{Ca}^{2+} + 2\text{OH}^- \rightarrow \text{CaCO}_3 + \text{H}_2\text{O}
\]  

(3)

\[
\text{Ca}^{2+} + \text{CO}_3^{2-} + \text{H}_2\text{O} \rightarrow \text{CaCO}_3 + 2\text{H}^+
\]  

(4)

¹ Department of Soil Science, Faculty of agriculture, Shahid Bahonar University of Kerman, Kerman, Islamic Republic of Iran.

² Department of Soil Science, Faculty of Agriculture, Tarbiat Modares University, Tehran, Islamic Republic of Iran.

* Corresponding author; e-mail: farpoor@uk.ac.ir
$\text{CO}_2 + \text{H}_2\text{O} \leftrightarrow \text{H}_2\text{CO}_3 \leftrightarrow \text{HCO}_3^- + \text{H}^+ \leftrightarrow \text{CO}_3^{2-} + 2\text{H}^+$ \hfill (3)

$\text{CO}_3^{2-} + \text{Ca}^{2+} \rightarrow \text{CaCO}_3$ \hfill (4)

Landi et al. (2003) demonstrated that the soils of the prairies and of the forests have sequestered biogenic C from plant respiration and residues in the form of pedogenic carbonates and Ca is the rate-limiting factor to be precipitated with $\text{CO}_2$. Microbial activity helps inorganic sequestration of C in CaCO$_3$ form. Geological sequestration of CO$_2$ and its conversion into carbonate solid phases were studied by Dupraz et al. (2009) using Bacillus pasteurii. In a study of factors controlling urease enzyme and microbial deposition of CaCO$_3$ using Sporosarcina pasteurii previously known as Bacillus pasteurii (Yoon et al., 2001), Okwadha and Li (2010) found that CO$_2$ sequestration rate caused by ureolytic hydrolysis was directly proportional to microbial CaCO$_3$ formation.

Calcium carbonate precipitation induced by bacterial activity has extensively been employed to increase stability of structures in civil engineering. Ghosh et al. (2006) used thermophilic and anaerobic bacteria within cement-sand mortar/concrete to develop bioconcrete material. Results of the study indicated that compressive strength of concrete and cement-sand mortar increased significantly, due to the development of crystals within the pores of cement sand matrix. Effects of pure Bacillus sphaericus and a mixed culture of ureolytic bacteria on microbial CaCO$_3$ deposition and durability of mortar and concrete were studied by De Muynck et al. (2008a, b). They reported that deposited calcite on the surface of samples by bacteria decreased capillary water uptake as well as permeability towards gas. Carbonate precipitation induced by microbial activity using Bacillus pasteurii, an endospore forming soil microorganism, takes place with the highest urease activity, Sarda et al. (2009) on brick samples to increase the strength and durability.

Microbial deposition of calcium carbonate has also been employed to improve physical properties of soils and other porous media. Plastic syringe columns (60 mL) containing 100 grams sterile sand treated by Bacillus pasteurii were used by Stocks-Fischer et al. (1999) to study plugging of porous media. XRD and SEM analysis showed that calcite was precipitated in between sand particles. Using urease enzyme in glass columns (H: 30 and ID: 2.5 cm) packed with a mixture of sand and glass beads, Nemati and Voordouw (2003) created calcite cementation, which in turn caused a 98% decrease in permeability. Porosity and permeability decrease induced by Sporosarcina pasteurii in sand columns has also been reported by Cunningham et al. (2011) and Whiffin et al. (2007).

Role of microbial deposition of calcium carbonate on soil physical properties (porosity, permeability, and as well hydraulic conductivity) has been investigated by several researchers (Whiffin et al., 2007; Cunningham et al., 2011; Sarmast et al., 2011a, b). Vast areas in arid and semi-arid ecosystems are covered by sand dunes, the stabilization of which is of great importance. Besides, micromorphological observations, demonstrating microbial calcite morphology and pattern that help bridge and cement particles are lacking in literature. Despite the fact that genesis of calcium carbonate in calcareous soils of Iran is reported in the literature (Khormali and Nabioillahi, 2009; Farpoor et al., 2011; Moazallahi and Farpoor, 2012; Owliaie, 2012), however, limited information is presently available on biocalcite formation in soils and sediments in Iran. The present research was conducted to:

1. Study the levels, reaction time, and depth of secondary carbonates.
2. Compare Sporosarcina pasteurii vs. Sporosarcina ureae microbial activity on calcium carbonate formation.
3. Determine the micromorphology of bridging and cementing particles.

**MATERIALS AND METHODS**

The research was conducted in the framework of a factorial, completely randomized design experiment of 3 replicates. Effects of two bacterial species
(Sporosarcina pasteurii and Sporosarcina ureae), 3 concentrations of urea and CaCl₂ mixture (0.5, 1 and 1.5M), along with 6 time intervals (12, 24, 48, 96, 192 and 288 hours) were studied on microbial calcium carbonate formation.

### Soil Sample

Soil sample was taken from sand dunes of Jupar area in Kerman Province. Air dried soil sample was sieved through a 2 mm sieve and routine soil physicochemical properties determined. Pipette method was employed for particle size distribution analysis of the soil (Gee and Bauder, 1986). Electrical conductivity of the saturated extract (Rhoades, 1982), and pH of the saturated paste (Mclean, 1982) were determined applying Jenway EC and pH meters. Calcium carbonate equivalent (CCE) was investigated through back titration (Nelson, 1982). Gypsum content was measured through acetone method (Nelson and Sommers, 1982). No gypsum was detected during chemical analyses and through morphological observations. Table 1 shows physicochemical properties of the soil sample used in the experiment.

### Table 1. Selected physicochemical properties of the soil studied.

<table>
<thead>
<tr>
<th>Particles (Percent)</th>
<th>Texture</th>
<th>EC (dS m⁻¹)</th>
<th>pH</th>
<th>CCE ‡</th>
<th>Gypsum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very Fine</td>
<td>Coarse</td>
<td>Medium</td>
<td>Fine</td>
<td>Very Fine</td>
<td>Sandy</td>
</tr>
</tbody>
</table>

‡ Calcium Carbonate Equivalent.

### Soil Column Parameters

Plastic columns with heights of 6.5 and inner diameters of 7.7 cm were packed with 500 grams of sterile sandy soil to study the depth of bacterial activity. The daily flows including inoculum, fixation flow of 50 mM CaCl₂ and cementation flow (urea + CaCl₂) were added uniformly and continuously to the columns. The sandy soil columns were incubated at 28±2°C. Flow rates were adjusted according to the hydraulic conductivity of the sandy soil (10⁻²⁻¹⁰⁻³ cm sec⁻¹).

### Microorganisms and Growth Conditions

Sporosarcina pasteurii (PTCCi 1645; previously known as Bacillus pasteurii; Yoon et al., 2001) and Sporosarcina ureae (PTCCi 1642) were obtained from Iran Research Organization of Science and Technology. Both species are gram positive, endospore forming, of the potential of being grown in alkaline environments, and bear urease activity. Bacterial inoculums, using appropriate medium cultures (Table 2), were prepared at 30°C, being shaken for 24 hours and at 140 rpm. The pH of the media was

### Table 2. Composition of culture media.

<table>
<thead>
<tr>
<th>Bacteria</th>
<th>Culture</th>
<th>Composition</th>
<th>Content (g L⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S. pasteurii</td>
<td>Tryptic Soy Broth</td>
<td>Peptone from casein</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Peptone from soymeal</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>NaCl</td>
<td>5</td>
</tr>
<tr>
<td>S. ureae</td>
<td>Nutrient Broth</td>
<td>Peptone</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Meat extract</td>
<td>3</td>
</tr>
</tbody>
</table>
adjusted to 8 using 1M KOH prior to being autoclaved with no urea addition. Filter sterilized urea was added following autoclaving. Estimation of bacterial density was performed through second tube (6×10^8 cell mL^-1) of McFarland Barium Sulfate Standard test tubes (Cappuccino and Sherman, 1987).

Experimental Treatments

Inoculum solution (36 m L^-1) was added to the sandy soil columns by use of dropper and then immediately, followed by addition of 142 ml of 50 mM CaCl\(_2\) as fixation fluid. Following the fixation fluid being fully added, the cementation fluid a mixture of 72 ml of (0.5, 1 and 1.5M equimolar of CaCl\(_2\) and 72 mL of urea) was flushed through (Whiffin et al., 2007). The fixation and cementation fluids were made to pass through the sandy soil columns under a constant head. Time intervals of 12, 24, 48, 96, 192 and 288 hours were applied to different columns. Finally, and at due time for each treatment, samples were removed from incubator, and addition of daily flows stopped to end bacterial activity with the measurements being carried out immediately for the replicates. Selection of treatments was based on Whiffin (2004) followed by changes applied according to pre-experiments performed prior to the ongoing research.

Measurements and Analyses

To remove the soil samples, the columns’ covering were cut off first. Calcium carbonate equivalent was determined at 4 depths separated by a micrometer (Vernier Caliper). The thickness of the cemented layer was also determined, making use of micrometer. Since CCE in *Sporosarcina ureae* treated samples showed no significant differences with depth, concentration, and time factors, micromorphological observations were conducted only on the samples treated by *Sporosarcina pasteurii*. Two depths (0-3 and 3-6 cm) were selected for thin section preparations (horizontal cuttings) using guidelines described in Murphy (1986). An Olympus, BH\(_2\) petrographic microscope was used for thin section descriptions (Stoops, 2003) in plain (PPL) and cross Polarized (XPL) lights and then photographed by a digital Sony camera.

The ratio proposed by Okwadha and Li (2010) was employed to evaluate the sequestrated CO\(_2\). Urea hydrolysis and microbial deposition of CaCO\(_3\) are stoichiometrical reactions indicating why the level of sequestrated CO\(_2\) is a direct proportion of the level of microbial CaCO\(_3\) precipitation. The concentration of CO\(_2\) is therefore calculated using the following simple ratio: 44/100= x/y, where x is the level of sequestrated CO\(_2\) and y the amount of precipitated CaCO\(_3\) (Okwadha and Li, 2010).

MSTAT-C software was employed for ANOVA analysis, and Duncan test (P<0.05) for a mean comparison of the data.

RESULTS AND DISCUSSION

Microbial CaCO\(_3\) Formation and CO\(_2\) Sequestration

The results obtained indicated that bacterial species, reactant concentration, reaction time, depth intervals as well as the mutual effects of these factors significantly influenced the formation of calcium carbonate (P< 0.01). Mean calcium carbonate formation were recorded 12.2 and 9.2% for *S. pasteurii* and *S. ureae*, respectively. The difference in CaCO\(_3\) precipitation between the two bacterial species could be attributed to different capabilities of these species to provide varied types of urease enzymes (McCoy et al., 1992). Comparing different strains of bacteria, Hammes et al. (2003) also reported that the level of urease enzyme was different among various strains.
Microbial Calcium Carbonate Formation in Soils

 Calcium carbonate precipitation significantly increased for \textit{S. pasteurii} as reactant concentration increased, but no statistically significant difference was observed for \textit{S. ureae}. Mean calcium carbonate contents were 11.0, 12.3, and 13.4\%, for reactant concentrations of 0.5, 1.0 and 1.5M, in \textit{S. pasteurii} columns vs. 9.1, 9.3, and 9.3\% for \textit{S. ureae} (Figure 1-a). Nemati and Voordouw (2003), and also Okwadha and Li (2010) have reported that reactant concentration increase microbial calcium carbonate formation. On the other hand, Hammes \textit{et al}. (2003) reported that due to the significant effect of calcium ions on urease enzyme activity, calcium carbonate precipitation by \textit{S. pasteurii} increases as a result of increased reactant concentrations. They speculated that calcium ions could better facilitate trans-membrane transport or improve the intracellular signaling process. Tobler \textit{et al}. (2011) also mentioned that \textit{S. pasteurii} is capable of tolerating high concentrations of Ca\textsuperscript{2+}. Whiffin (2004) reported that \textit{S. pasteurii} gains the necessary energy for calcium metabolism from the ATP produced during urea hydrolysis. No data for such mechanisms have been reported for \textit{S. ureae}.

 Lack of significant differences among 12, 24, and 48 hour treatments in both \textit{S. pasteurii} and \textit{S. ureae} species (Figure 1-b) might be due to inadequate microbial fixation time. The significant differences among 96, 192, and 288 hour treatments observed for \textit{S. pasteurii} might likely be due

<table>
<thead>
<tr>
<th>Reactant concentration (M)</th>
<th>CCE (%)</th>
<th>\textit{S. pasteurii}</th>
<th>\textit{S. ureae}</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>11.0</td>
<td>A</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>12.3</td>
<td>B</td>
<td></td>
</tr>
<tr>
<td>1.5</td>
<td>13.4</td>
<td>C</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Reaction time (hr)</th>
<th>CCE (%)</th>
<th>\textit{S. pasteurii}</th>
<th>\textit{S. ureae}</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>9.1</td>
<td>D</td>
<td></td>
</tr>
<tr>
<td>24</td>
<td>9.3</td>
<td>EDF</td>
<td></td>
</tr>
<tr>
<td>48</td>
<td>9.3</td>
<td>B</td>
<td></td>
</tr>
<tr>
<td>96</td>
<td></td>
<td>DEF</td>
<td></td>
</tr>
<tr>
<td>192</td>
<td></td>
<td>C</td>
<td></td>
</tr>
<tr>
<td>288</td>
<td></td>
<td>D</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Depth of columns (cm)</th>
<th>CCE (%)</th>
<th>\textit{S. pasteurii}</th>
<th>\textit{S. ureae}</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-1.5</td>
<td>14.2</td>
<td>A</td>
<td></td>
</tr>
<tr>
<td>1.5-3</td>
<td>14.3</td>
<td>D</td>
<td></td>
</tr>
<tr>
<td>3.5-6</td>
<td>14.4</td>
<td>B</td>
<td></td>
</tr>
<tr>
<td>4.5-6</td>
<td></td>
<td>C</td>
<td></td>
</tr>
</tbody>
</table>

\textbf{Figure 1.} Effect of reactant concentration (a), reaction time (b), depth (c) and bacterial species on Calcium Carbonate Equivalent (CCE).
to daily addition of inoculums and reactants, as also reported by Whiffin (2004). Low differences among time interval treatments were recorded for S. ureae, which might be attributed to less urease activity of this bacterial species. McCoy et al. (1992) reported that although S. ureae and S. pasteurii are closely related, the kind and activity of urease enzyme in the two species are different.

Calcium carbonate content in the top 0-1.5 cm was significantly higher than that in the 4.5-6 cm for S. pasteurii treated columns (15.6% as compared with 10.2%), which shows a significant decreasing trend of calcium carbonate content with depth (Figure 1-c). The change in calcium carbonate precipitation with depth for S. ureae was not significant (from 9.3 to 9.1%). Whiffin et al. (2007) and Achal et al. (2009a, b) also found similar results for S. pasteurii in sand columns. Different amounts of calcium carbonate precipitates in the four depths of soil columns by S. pasteurii may have also been caused by limitation in availability of nutrients, reactants and oxygen flow due to higher activity and adsorption of bacteria in the surface layer of the soil, thus sealing the upper pore spaces (Day et al., 2003).

Besides, facultatively anaerobic S. pasteurii growth is normally higher in the presence of oxygen, explaining higher microbial formation of calcium carbonate in the surface layers (Day et al., 2003; Achal et al., 2009a, b).

Carbon dioxide consumption also showed an increasing trend with reaction time, reactant concentration, and depth reduction in S. pasteurii. The close relationship between sequestrated CO₂ and precipitated microbial calcium carbonate was also observed by Okwadha and Li (2010).

Micromorphological Studies

Micromorphological observation of samples treated with S. ureae showed no visible calcium carbonate cementation and induration. This supports the earlier results of no significant relationship among different treatments for S. ureae. Therefore, a complete detailed micromorphological analysis for S. ureae was not performed in this study. Figure 2-a shows a thin section of the blank sample (sandy soil with no treatments). Plagioclase, pyroxene, quartz, biotite, igneous microlites, and opaque particles were observed in the blank sample.

Figure 2. Thin sections of blank sample at 0-3 cm depth (a) and sample treated by S. pasteurii (b) in 288 hours, 1.5M reactant concentration and 0-3 cm depth (both samples in XPL).
Although chemical analysis showed that there is about 8.8% calcium carbonate equivalent in this sample (Table 1), but the calcium carbonate is in a disseminated form based on micromorphological observations with no secondary calcite crystals being found.

Calcite crystals bridging sand particles were observed in thin sections of the S. pasteurii treated samples (Figure 2-b). Although micromorphological observations are qualitative and no quantification technique was used throughout the present study, however, the thin sections studied clearly showed the difference in relative amounts of calcite crystals among treatments.

Thin sections from 0-3 cm depth of columns showed more calcite crystals as compared with the 3-6 cm depth for all the reactant concentrations (Figure 3). The decreasing trend of microbial calcium

![Figure 3](image)

**Figure 3.** Thin sections (XPL) of 192 hour treatment for *S. pasteurii* in 0.5, 1.0 and 1.5M reactant concentrations showing the effect of column depth (left picture 0-3 cm and right pictures 3-6 cm).
carbonate cementation by *S. pasteurii* with depth was also reported by Day *et al.* (2003) using an XRD technique. They showed that maximum microbial calcium carbonate formation was in the surface layer and no calcite crystal formed below 3.8 cm depth. Bang *et al.* (2001) also came to the conclusion that microbial calcium carbonate was more capable of surface crack remediation than the subsurface cracks. This observation also supports the data from the chemical analysis. Since the growth and ureolytic hydrolysis of *S. pasteurii* is sensitive to O\(_2\) concentration in the soil environment (Achal *et al.*, 2009a, b), a decreasing trend of calcite formation and increase in porosity with depth is not surprising.

Calcite coating, infilling, and bridging were among the pedofeatures observed in thin sections of the samples treated. Verrecchia and Verrecchia (1994) have also reported biocalcite morphology, crystal habits, and microfabrics formed by calcifying bacteria. Figure 4 shows the effect of reactant concentrations on calcite crystals formed by *S. pasteurii* for the 288 hour treatment. The thin section images from 0-3 cm layer of columns treated with 1.5M reactant concentration showed a continuous cementation of CaCO\(_3\) infillings as compared with only bridging and coating morphology of calcite in columns treated with 1M reactant concentration. Isolated calcite micro spars were the dominant crystals observed in thin sections treated with the 0.5M cementation. Pore spaces are also reduced increasingly with the increase of reactant concentration (Figure 4).

No significant difference was observed in calcium carbonate equivalent in the samples treated for 12, 24, and 48 hours. This is supported with the fact that no cementation was observed in the same treatments. Thin sections from the 0-3 cm depth treated for 96, 192 and 288 hours by 1.5 M reactant, however, showed an increasing trend of microbial calcite formation with time. The highest level of microbial calcium carbonate formation and the least porosity were observed in the thin section treated with 1.5M concentration for 288 hours. Coating and bridging of calcite were dominant in the 192 hour sample, but only weak coatings and bridging of CaCO\(_3\) were found in the 96 hour sample (Figure 5).

**Cemented Layer Thickness**

The thickness of the top cemented layer was statistically significantly (P< 0.01) affected by bacterial, reactant concentration, and reaction time. The cemented layer created by *S. pasteurii* had a mean thickness of 16 mm which was significantly thicker than the cemented layer created by *S. ureae* (7mm). Whiffin (2004) reported that the activity of urease enzyme and composition of media culture are among the factors controlling the cementation layer.

A mean comparison of data showed that increase in reactant concentration and reaction time tend to increase cementation depth in *S. pasteurii*, but no statistically significant difference was observed for *S. ureae* (Figure 6). High activity of urease enzyme in *S. pasteurii* is extensively reported in the literature (Stocks-Fischer *et al.*, 1999; Whiffin, 2004; Sarda *et al.*, 2009). Although urease enzyme was not determined in the present research, but it is possible that higher activity of this enzyme could be the reason for the greater cementation depth observed in the *S. pasteurii* treated columns, also supported by data from chemical analysis.

Time intervals of 288 and 192 hour showed the greatest cementation depths of 20.9 and 18.8 mm, respectively. This difference was not statistically significant; however, treatments of 12, 24, 48 and 96 hour had significantly lower cementation depths (Table 3). Mean cemented layer thickness (Table 3) varied from 8.4 mm (0.5 M reactant concentration) to 13.1 mm (1.5 M reactant concentration). An increasing cementation depth with reactant concentration was also supported by CCE,
Figure 4. Thin sections (XPL) of 0-3 cm depth for 288 hour time treatment of *S. pasteurii* showing the effect of reactant concentrations (0.5, 1.0, and 1.5M).

Figure 5. Thin sections (XPL) of 0-3 cm depth, 1.5M reactant concentration for *S. pasteurii* showing the effect of time (96, 192, and 288 hours).
Figure 6. Effects of reactant concentration (a) and reaction time (b) on thickness of CaCO$_3$ layer in two bacteria species.

Table 3. Mean comparison data of time and concentration on thickness of cemented layer (mm). $^a$

<table>
<thead>
<tr>
<th>Concentration (M)</th>
<th>0.5</th>
<th>1</th>
<th>1.5</th>
<th>12</th>
<th>24</th>
<th>48</th>
<th>96</th>
<th>192</th>
<th>288</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time treatment (hr)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>4.8d</td>
<td>5.1d</td>
<td>4.6d</td>
<td>7.8d</td>
<td>13.8c</td>
<td>14.5c</td>
<td>8.4B</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>24</td>
<td>3.8d</td>
<td>3.8d</td>
<td>7d</td>
<td>13.6c</td>
<td>18bc</td>
<td>25.8a</td>
<td>12A</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>48</td>
<td>5d</td>
<td>4.6d</td>
<td>6.0d</td>
<td>15.8c</td>
<td>24.6a</td>
<td>22.3ab</td>
<td>13.1A</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>96</td>
<td>4.5C</td>
<td>4.5C</td>
<td>6C</td>
<td>12.4B</td>
<td>18.8A</td>
<td>20.9A</td>
<td>Mean</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$^a$ Same letter within each column indicates no significant difference among treatments (P < 0.05).

CO$_2$ sequestration and micromorphological studies, as discussed earlier.

**CONCLUSIONS**

In this investigation bacterial species, reactant concentration, reaction time, and depth were among the factors affecting calcium carbonate formation. In $S$. pasteurii treated columns, mean calcium carbonate precipitation increased significantly toward the upper layers with increasing reactant concentration through time. No significant calcite precipitation was observed for $S$. ureae. CO$_2$ sequestration and depth of cementation layer of calcium carbonate showed a similar trend with the calcium carbonate equivalent.

Micromorphological observations of thin sections from different layers of treated columns with $S$. pasteurii also supported the chemical data. Microbial calcium carbonate showed bridging, coating, and / or infillings of sand particles in thin sections, causing reduction in soil porosity. The cementation
induced by microbial calcium carbonate formation technique could likely be used in arid and semi-arid areas to stabilize sand dunes.

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بر روی میکروورمولوژی Sporosarcina ureae و Sporosarcina pasteurii
و تشكیل آهک زیستی در ستون‌های خاک شیت

م. سرمست، م. ه. فریبرز، م. سرچشم‌شور و م. ک. اقبال

چکیده

کربنات کلسیم میکرووری با ایجاد پل در بین ذرات شیت، نقش مهمی در پایداری ته شیت ایفا می‌نماید. مطالعه‌ای روزی سیمانی شدن ذرات شیت و پرشده‌گی منافذ توسط CaCO₃ انجام دادم. آزمایش به صورت فاکتوریال با فاکتورهای درگیر میکروب باکتری (Sporosarcina pasteurii) و Sporosarcina ureae به فاکتورهای 1/5 و 1/10 مولار و شیت زمان واکنش (۱۲, ۲۴, ۴۸, ۷۲ و ۸۸ ساعت) انجام شد. مایه تلفیق باکتری‌ها و محلول‌های واکنشگر روزانه به ستون‌های خاک شیت (ارتفاع ۶/۵ و قطر داخلی ۶/۷ سانتی‌متر) اضافه شدند و رسوب CaCO₃ در فواصل C، C نشان دادند که با ترکیب Sporosarcina pasteurii در تشکیل شیمیایی و CaCO₃، CaCO₃، CaCO₃، CaCO₃ غیرآلی و عمق سیمانی شدن پیشرفت از گونه S. ureae بود. با افزایش زمان واکنش از ۱۲ به ۸۸ ساعت، رسوایی میکرووری CaCO₃ و ترکیب غیرآلی افزایش یافت. افزایش غلظت واکنشگر فاکتورهای باکتری S. pasteurii در صورت پیوستن دو روش شن و پرکندگی منافذ نشان داد. با توجه به تاثیر معنادار باکتری S. pasteurii و سیمانی شدن ذرات شیت، استفاده از این باکتری جهت تثبیت ته‌های شیت توصیه می‌گردد.