Surface Soil Stabilization by Microbial Induced Calcite Precipitation

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Microbe and Soil Cementation

Bioinspiration

Termite Mound
https://static01.nyt.com/images/2015/03/03/science/03JPTERMITEs

Microcoleus in the Sonoran desert
https://askabiologist.asu.edu/explore/desert-microbes

Closer look of a sandy crust
https://geochange.er.usgs.gov/sw/impacts/biology/crypto/

Stromatolites
http://stromatolites.weebly.com/morphology.html
Microbe and Soil Cementation

Bioinspiration: MICP

Bacteria Cell: *Sporosarcina pasteurii*

- \( \text{NH}_2\text{−CO−NH}_2 + \text{H}_2\text{O} \rightarrow 2\text{NH}_3 + \text{CO}_2 \)

- \( 2\text{NH}_3 + 2\text{H}_2\text{O} \rightarrow 2\text{NH}_4^+ + 2\text{OH}^- \)

- \( \text{CO}_2 + \text{OH}^- \rightarrow \text{HCO}_3^- \)

- \( \text{Ca}^{2+} + \text{HCO}_3^- + \text{OH}^- \rightarrow \text{CaCO}_3 + \text{H}_2\text{O} \)

Net Urea Hydrolysis Reaction: \( \text{NH}_2\text{−CO−NH}_2 + 3\text{H}_2\text{O} \rightarrow 2\text{NH}_4^+ + \text{HCO}_3^- + \text{OH}^- \)

Net pH increase: \([\text{OH}^-]\) generated from \(\text{NH}_4^+\) production >> \([\text{Ca}^{2+}]\)

(Montoya 2012)
Microbe and Soil Cementation

Existing Treatment Schemes

Multiple Phase Injection

- Most studied
- Similar to existing grouting techniques
- Special Equipment
- Multiple step, tedious
- Hard to control
- Extraction wells needed for field applications
- Low efficiency due to waste of materials

Immersing

- Uniform treatment
- One step method
- Low efficiency due to waste of materials
- Limited to laboratory studies

Microbe and Soil Cementation
MICP for surface erosion control

 Desired features:

- Can be applied from the surface
- Create a crust with a controllable thickness
- Both strong and tough
Microbe and Soil Cementation
MICP for surface erosion control

Infiltration problem:

Richard’s equation
\[
\frac{\partial}{\partial t} = \frac{\partial}{\partial z} \left[ K \left( \frac{\partial}{\partial z} + 1 \right) \right]
\]

Green-Ampt equation
\[
L(t) = K(t) t + \ln \left( 1 + \frac{L(t)}{y} \right)
\]
\[
L(t) = K(t) t
\]

Infiltration depth and time can be controlled by tuning the permeability of the solution in the porous soil.

Permeability
\[
K = C_s \left( \frac{\gamma_p}{S_0^2} \left( \frac{e^3}{1+e} \right) S^3 \right)
\]

Modification of the viscosity of the cementation solution might be a viable way to control the treatment depth.

Soil Properties:
- \( e \): void ratio
- \( \theta \): volumetric moisture content
- \( \psi \): wetting front suction

Fluid properties:
- \( K \): hydraulic conductivity
- \( \gamma_p \): unit weight
- \( \mu \): viscosity
Microbe and Soil Cementation

1 Concept Proof

Sand: ASTM standard graded sand (Ottawa, IL)

Bacteria solution: Sporosarcina pasteurii (ATCC 11895), Nutrient broth;

Cementation solution: Water or Polymer additives, Urea, CaCl$_2$, NH$_4$Cl, NaHCO$_3$, Nutrient broth;

Dye: Methylene Blue
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1 Concept Proof

PVA powder
[\text{CH}_2\text{CH(OH)}_n]

Hydrogel

Stirrer

Heater

Bacteria

Cementation

Hydrogel
Microbe and Soil Cementation

1 Concept Proof

Hydrogel: Slow, uniform infiltration

Water: Fast, non-uniform infiltration
Microbe and Soil Cementation

1 Concept Proof

<table>
<thead>
<tr>
<th>Observed</th>
<th>Estimated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogel</td>
<td>Water</td>
</tr>
<tr>
<td>Infiltration time (s)</td>
<td>&gt;2400</td>
</tr>
<tr>
<td>Infiltration depth (cm)</td>
<td>≅5</td>
</tr>
</tbody>
</table>

Sample after Soaking and Rinsing

Hydrogel

Water
Optimization

Summary of the recipes for tests in plastic molds

<table>
<thead>
<tr>
<th>Group number</th>
<th>Specimen number</th>
<th>Formula</th>
<th>[CaCl$_2$] (M)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1-6</td>
<td>Hydrogel cementation solution + Bacteria</td>
<td>0.5</td>
</tr>
<tr>
<td>2</td>
<td>7-12</td>
<td>Hydrogel cementation solution + Bacteria</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>13-18</td>
<td>Hydrogel cementation solution + Bacteria</td>
<td>1.5</td>
</tr>
<tr>
<td>4</td>
<td>19-24</td>
<td>Dyed Hydrogel cementation solution + Bacteria</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>25-30</td>
<td>Hydrogel cementation solution only</td>
<td>1</td>
</tr>
</tbody>
</table>

Pre-treatment | Post-treatment | Soaking-w/o bacteria | Soaking-w/bacteria |
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1 Concept Proof_XRD

Water

Hydrogel
Microbe and Soil Cementation

Optimization

CaCO₃ content

Reaction efficiency
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Optimization

Unconfined compression test
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Optimization

Unconfined compression test

Water

Hydrogel

Peak strength (kPa)

Concentration of CaCl₂ (M)
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Laboratory validation

Hydrogel-based MICP around a bridge pier model
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3 Laboratory validation

Flume erosion test result: bridge scour
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SUMMARY
✓ Surface treatment of loose sand can be achieved via a hydrogel-based MICP
✓ Hydrogel significantly affects the precipitated CaCO₃
  ✓ Crystal Polymorph
  ✓ Morphology
  ✓ Crystal Size
✓ Hydrogel-based MICP significantly decreases erodibility of loose sand

CURRENT/FUTURE WORK
☐ Fundamental mechanism
☐ Tunable design
☐ O/I hybrids
☐ Scaling up, QA/QC
# Microbe and Soil Cementation

**Extraterritorial in situ resource utilization**

- Bio-brick factory?
- Surface soil stabilization for dust control?
- Soil stabilization for underground habitat?
- 3D printing?

<table>
<thead>
<tr>
<th></th>
<th>Martian soil</th>
<th>Lunar soil</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Formula</strong></td>
<td><strong>Composition (wt %)</strong></td>
<td><strong>Composition (wt %)</strong></td>
</tr>
<tr>
<td>SiO₂</td>
<td>45~50%</td>
<td>SiO₂</td>
</tr>
<tr>
<td>FeO, Fe₂O₃</td>
<td>~17%</td>
<td>Al₂O₃</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>~9%</td>
<td>CaO</td>
</tr>
<tr>
<td>MgO</td>
<td>~8%</td>
<td>FeO</td>
</tr>
<tr>
<td>CaO</td>
<td>~7%</td>
<td>MgO</td>
</tr>
<tr>
<td>SO₃</td>
<td>~5%</td>
<td>TiO₂</td>
</tr>
<tr>
<td>Na₂O</td>
<td>~3%</td>
<td>Na₂O</td>
</tr>
<tr>
<td>TiO₂</td>
<td>~2%</td>
<td></td>
</tr>
</tbody>
</table>

- Soil compositions and particle size distributions are suitable
- Calcium rich regolith
- CO₂ rich in Martian atmosphere
- Human waste (urine) can be reutilized
- Bacteria duplicate fast
- Survivability in ambient environment (Temperature, radiation)?
- Biocontamination?
Thank you!