Ceramic Material Processing Towards Future Space Habitat---Microstructure and Properties of field-assisted sintering of lunar soil simulant (JSC-1)

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Introduction of lunar habitat

- Goal: long duration human presence on the surface of the Moon
- Reduce mass of essentials from Earth by *in situ* resources utilization
  - Extraction of oxygen for propellant and human sustenance
  - Extraction of metals and other pure materials (e.g. Si) for solar cells (power generation)
  - Construction of habitats and structures for habitation
Complexities of the conditions on the moon

- Lunar exosphere – “hard vacuum”
  - 14 times less molecules/cm³ than Earth atmosphere
  - Gases: Ar, He, O₂, CH₄, N₂, CO, CO₂
- 17% gravity of Earth
- Temperature range from -173°C to 127°C depending on the sun

Lunar Resource Book.
Lunar regolith simulant JSC-1 to approximate lunar soil

- Lunar soil: NaAlSi$_3$O$_4$, CaAl$_2$Si$_2$O$_8$, (MgFe)$_2$SiO$_4$...
- Simulant developed by NASA and Johnson Space Center

<table>
<thead>
<tr>
<th>Oxide</th>
<th>Lunar soil</th>
<th>Simulant powder</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Concentration (wt.%)</td>
<td></td>
</tr>
<tr>
<td>SiO$_2$</td>
<td>47.3</td>
<td>47.71 ± 0.10</td>
</tr>
<tr>
<td>Al$_2$O$_3$</td>
<td>17.8</td>
<td>15.02 ± 0.04</td>
</tr>
<tr>
<td>CaO</td>
<td>11.4</td>
<td>10.42 ± 0.03</td>
</tr>
<tr>
<td>MgO</td>
<td>9.6</td>
<td>9.01 ± 0.09</td>
</tr>
<tr>
<td>FeO</td>
<td>10.5</td>
<td>7.35 ± 0.05</td>
</tr>
<tr>
<td>Fe$_2$O$_3$</td>
<td>0.0</td>
<td>3.44 ± 0.03</td>
</tr>
<tr>
<td>Na$_2$O</td>
<td>0.7</td>
<td>2.70 ± 0.03</td>
</tr>
<tr>
<td>TiO$_2$</td>
<td>1.6</td>
<td>1.59 ± 0.01</td>
</tr>
</tbody>
</table>
Previous reports on *in situ* resource utilization using lunar simulant soil

Sintering of micro-trusses created by extrusion-3D-printing of lunar regolith inks

Glass fibers and hollow glass microspheres produced by melting the simulant at 1450°C in air

Allen et al., 1992, high T sintering
Indyk, et al., 2017, high T sintering
Altemire et al., 1993, cold press
Taylor et al., 2005, microwave sintering
Why field-assisted sintering?

- Also known as spark plasma sintering (SPS)
- Joule heating of graphite die by an applied field
- Significant reduction in sintering temperature and time compared to conventional sintering

Proposed steps to process lunar soil

Densification of powder compacts at low temperatures

- Densification occurs between 550 to 600°C

Phase analysis and final properties of the bulk specimens after SPS

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>2.85 g/cm³</td>
</tr>
<tr>
<td>Hardness</td>
<td>6.01 ± 0.66 GPa</td>
</tr>
</tbody>
</table>

Much higher compressive hardness and full density compared to prior reports.

Microstructure of the bulk specimens after SPS of lunar soil simulant

Summary

• Ceramic sintering experiment was conducted using lunar simulants.

• The bulk structures sintered by field-assisted sintering under moderate temperatures are of full density, without obvious porosity.

• Such dense sintered ceramic structures present great opportunities for constructing ceramic structures for future human space habitats.

• Much work is very much needed to further reduce the sintering temperature, optimize/simplify powder processing, evaluate structural integrity under lunar surface conditions, and conduct sintering experiments using actual lunar soils and lunar surface conditions.