Fabrication of Construction Materials from Lunar and Martian Regolith Using Thermite Reactions with Magnesium

Sergio Cordova, Armando Delgado, and Evgeny Shafirovich

Department of Mechanical Engineering
The University of Texas at El Paso
El Paso, Texas, USA
In-Situ Production of Construction Materials from Lunar and Martian Regolith

• In future lunar and Mars missions, construction materials will be needed for landing/launching pads, radiation shielding, and other structures.

• Fabrication methods:
  • Lunar concrete
    – Water or sulfur recovered from regolith
    – Thermoplastic brought from Earth
  • Microwave heating of regolith
    – Needs lots of energy
  • Energetic additives enabling a self-sustained combustion
    – Low energy needed
Self-Propagating High-Temperature Synthesis (SHS)

• Upon ignition of a mixture, exothermic reactions cause a self-sustained propagation of the combustion wave.

• Advantages:
  – Low energy for ignition
  – High temperatures generated by the reaction heat release

• Used for synthesis of many ceramic materials.
Combustion in Regolith-based Mixtures

<table>
<thead>
<tr>
<th>Research Team</th>
<th>Energetic Additive</th>
<th>Additive Content (wt%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Martirosyan and Luss (2006)</td>
<td>Ti + B</td>
<td>&gt;40</td>
</tr>
<tr>
<td>Corrias et al. (2012)</td>
<td>FeTiO₃ + Al</td>
<td>&gt;70</td>
</tr>
<tr>
<td>Faierson et al. (2010)</td>
<td>Al</td>
<td>&gt;37</td>
</tr>
</tbody>
</table>

- JSC-1A/Al mixture
- Large external energy is supplied by a long heating wire embedded in the mixture
- No self-sustained combustion

Faierson et al., PISCES and JUSTSAP Conference, 2008.
Prior Research of Our Team

- Combustion of mixtures of JSC-1A lunar regolith simulant with magnesium
- Magnesium is easier to ignite than aluminum
- Thermodynamic calculations of the adiabatic flame temperatures and combustion products.
  - For Mg, the temperatures are higher than for Al.
  - Maximum adiabatic temperature: 1417 °C at 26 wt% Mg (equal to the melting point of Si)

Combustion at 26 wt% Mg
Prior Research of Our Team (contd.)

- Preheating (100°C) decreased content to **8 wt% Mg**.
- SHS compaction increased the density of the products by **66%** as compared to conventional SHS in argon.
- The compressive strength for SHS compaction products is about **10 MPa** – twice stronger than common bricks (5 MPa).

Present Research: Objectives

• Study combustion of Martian regolith simulants with Mg and compare it with combustion of JSC-1A lunar regolith simulant with Mg.
  – Martian regolith simulants: JSC-Mars-1A and Mojave Mars

• Clarify the mechanisms of reactions that occur during combustion of the lunar and Martian regolith simulants with Mg.
Regolith Simulant Compositions

Mineral composition is known only for JSC-1A. Simple oxide compositions are shown here:

<table>
<thead>
<tr>
<th>Compound</th>
<th>Concentration, wt%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>JSC-1A</td>
</tr>
<tr>
<td>SiO₂</td>
<td>45.7</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>16.2</td>
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<tr>
<td>Fe₂O₃</td>
<td>12.4</td>
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<tr>
<td>CaO</td>
<td>10</td>
</tr>
<tr>
<td>MgO</td>
<td>8.7</td>
</tr>
<tr>
<td>Na₂O</td>
<td>3.2</td>
</tr>
<tr>
<td>TiO₂</td>
<td>1.9</td>
</tr>
</tbody>
</table>

Main potential reactions:

\[
\text{SiO}_2 + 2 \text{ Mg} \rightarrow 2\text{MgO} + \text{ Si} \\
\text{Fe}_2\text{O}_3 + 3\text{Mg} \rightarrow 3\text{MgO} + 2\text{Fe}
\]
Thermodynamic Calculations for Combustion of Regolith Simulants with Mg

![Graph showing adiabatic flame temperature vs Mg concentration for different samples.](image-url)
Sample Preparation

- Regolith is milled in a planetary ball mill (1100 rpm, 40 min).
- Regolith is mixed with Mg (10, 20, 30.., wt%).
- The mixtures are compacted into pellets.
  - Mass: 5 g
  - Diameter: 1.3 cm
  - Force: 2 metric tons
- Channel drilled for thermocouple.
Experimental Setup
Mars Regolith/Mg Combustion

JSC-Mars-1A/Mg pellet (30 wt% Mg)  Mojave Mars/Mg pellet (30 wt% Mg)
Conclusions from Combustion Experiments

• JSC-Mars-1A combustion was much more vigorous than for Mojave Mars.
  – Relatively fast, steady propagation of combustion and a uniform structure of the product
• Different combustion behaviors may be related to different $\text{SiO}_2/\text{Fe}_2\text{O}_3$ ratios.
• To clarify reaction mechanisms in regolith/Mg mixtures, thermoanalytical experiments should be conducted.
Thermoanalytical Experiments

- To investigate reaction mechanisms of regolith/Mg mixtures.
  - Differential scanning calorimeter (Netzsch DSC 404 F1 Pegasus)
- Examined mixtures:

  **Regolith Simulant Mixtures**
  - 26 wt% Mg / 74 wt% JSC-Mars-1A
  - 26 wt% Mg / 74 wt% JSC-1A
  - 26 wt% Mg / 74 wt% Mojave Mars

  **Simple Oxide Mixtures**
  - Mg / SiO$_2$-Fe$_2$O$_3$ (SiO$_2$-Fe$_2$O$_3$ ratio: 0.5)
  - Mg / SiO$_2$-Fe$_2$O$_3$ (SiO$_2$-Fe$_2$O$_3$ ratio: 1)
  - Mg / SiO$_2$-Fe$_2$O$_3$ (SiO$_2$-Fe$_2$O$_3$ ratio: 2)

Comparable composition with simple oxides
DSC peaks correlate with $\text{SiO}_2$-$\text{Fe}_2\text{O}_3$ ratio: Increase in this ratio decreases the temperature of the peak.
DSC of Mg-Fe$_2$O$_3$-SiO$_2$ Thermites

Temperature order of the peaks correlates with SiO$_2$-Fe$_2$O$_3$ ratio. This explains the different peak temperatures of the three simulants.
Conclusions from Thermoanalytical Experiments

• Iron oxide plays a primary role in combustion of iron-rich JSC-Mars-1A simulant with Mg.
  – The iron-rich regolith exhibits higher temperatures and more vigorous combustion owing to the higher exothermicity of Mg–Fe$_2$O$_3$ reaction.

• The effect of silica is significant in combustion of iron-lean JSC-1A and Mojave Mars simulants
  – It is easier to ignite the iron-lean regolith simulants because Mg–SiO$_2$ reaction occurs at a lower temperature.
Summary

• Combustion-based methods for the fabrication of construction materials from lunar and Martian regolith have an advantage of low energy consumption.
• Mixtures of lunar and Martian regolith simulants with Mg exhibit a self-sustained combustion, leading to formation of ceramic materials.
• The reaction mechanisms in these mixtures involve thermite reactions of Mg with silica and iron oxide.
  – Iron oxide ensures intensive combustion.
  – Silica facilitates the ignition.
Acknowledgements

- The NASA Office of Education for support of this research
- The Solar System Exploration Research Virtual Institute (SSERVI) for support of my travel here

Thank you!
BACK-UP SLIDES
Spin Combustion

- Two counter-propagating hot spots
Reasonable agreement between experimental values and calculated adiabatic flame temperatures
XRD of Combustion Products

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<th>Peak</th>
<th>Phases</th>
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<tr>
<td>1</td>
<td>Ca$_2$MgSi$_2$O$_7$, CaMgSiO$_4$, Mg$_2$Si</td>
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<tr>
<td>2</td>
<td>MgAl$_2$O$_4$, CaMgSiO$_4$, FeSi, Mg$_2$Si</td>
</tr>
<tr>
<td>3</td>
<td>MgAl$_2$O$_4$, MgO, MgO$_2$</td>
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<tr>
<td>4</td>
<td>Al$_2$O$_3$, FeSi, Fe, Mg$_2$Si</td>
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<tr>
<td>5</td>
<td>MgO</td>
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<td>MgAl$_2$O$_4$, FeSi</td>
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<td>7</td>
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<td>9</td>
<td>MgO, FeSi</td>
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<td>11</td>
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## Combustion Products from THERMO

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<tr>
<td>Mg₂SiO₄</td>
<td>S</td>
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</tr>
<tr>
<td>Ca₂SiO₄</td>
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<tr>
<td>CaMgSi₂O₆</td>
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<tr>
<td>SiO</td>
<td>G</td>
<td>-</td>
</tr>
</tbody>
</table>
DSC of JSC-1A/Mg (26 wt% Mg)

- Differential scanning calorimetry (DSC) curve
- Heating rate: 10°C/min
- DSC curve shows exothermic peak at 560°C.
XRD of Reaction Products at Different Temperatures

- To investigate reaction, analysis was stopped at 500°C, 550°C, and 590°C.
- Heating rate: 5°C/min
- The reaction is complete at a temperature between 550°C and 590°C.
- Magnesium is solid throughout reaction (\(T_{\text{melting,Mg}} = 650°C\)).
DSC of Mg-Fe$_2$O$_3$ and Mg-SiO$_2$ Thermites

Stoichiometric mixtures of

\[ \text{SiO}_2 + 2\text{Mg} \rightarrow 2\text{MgO} + \text{Si} \]
\[ \text{Fe}_2\text{O}_3 + 3\text{Mg} \rightarrow 3\text{MgO} + 2\text{Fe} \]

The peak temperature for Mg-Fe$_2$O$_3$ is higher than for Mg-SiO$_2$.