Indigenous Lunar Construction Materials

Wayne Rogers
Stein Sture

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A NASA Space Engineering Research Center at the University of Colorado
Motivation

*The utilization of local resources for the construction and operation of a lunar base can significantly reduce the costs of transporting materials and supplies from Earth.*

- Primary examples of utilization of lunar resources: radiation shielding, oxygen extraction, water production, helium-3 mining.

- **Construction materials** are excellent candidates for utilization of local resources: they are relatively simple, heavy, and available. Raw materials may be by-product of other operations such as oxygen extraction.

<table>
<thead>
<tr>
<th>Why</th>
<th>Why not</th>
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<tr>
<td>Pay-load weight savings</td>
<td>Unfamiliar technologies</td>
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<tr>
<td>Long term manned presence in space</td>
<td>Significant infrastructure</td>
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Comparison of Various Lunar Structures

- SFF
  Space Station
  Freedom Module
- HLLV
  Heavy Lift Launch Vehicle Module
- PREFAB
  Déplôyable Module
- INFLAT
  Inflatable Sphere

Transported Mass (tons)

Enclosed Pressurized Volume (m³)

CAST
Cast Regolith Structure

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Processing - material - construction - structure relationships

Regolith (volume) → Melting → Material characteristics → Construction → Structure

Power (Watts) → Cooling → Mechanical properties → Design → Structure

Equipment (crucible, crane...) → Forming → Structural members → Design → Structure

Function (habitation, pad...) → Structure

Radiation shielding properties → Strength properties → Architectural properties → Equipment requirements
Objectives

- Investigate the *feasibility* of the use of local lunar resources for construction of a lunar base structure.
- Develop a material processing method and integrate the method with design and construction of a pressurized habitation structure.
- Estimate specifications of the support equipment necessary for material processing and construction.
- Provide parameters for systems models of lunar base constructions, supply and operations.
Indigenous Lunar Construction Materials

- **Minimally processed materials**: lunar rocks, regolith mortar, compressed regolith, free flowing molten regolith, for domes, roads, and landing pads (Khalili SCIA). *Materials do not have good mechanical properties.*

- **Solar power fused regolith** for large layered slabs (Clifton). *Solar power is not sufficient to melt large quantities of regolith in reasonable lengths of time.*

- **Sintered and hot pressed regolith** for bricks, plates, columns (Simonds, NASA LSI; Meek, UT; Vaniman, LANL; Sullivan, Battelle). *Small structural components. Not suited to tensile (pressurized) loading conditions or automated construction.*

- **Concrete**: traditional steel reinforced concrete structure using columns, beams, and slabs (Lin, CTL). *Lack of water.*

- **Iron and Steel**, high quality construction materials (UA). *Complex processing methods with high energy requirements.*

- **Cast basalt**: liquified regolith cast into large slab forms (Capps and Wise, Boeing; Binder, Lockheed)
Guidelines for Material Processing Method

- Material processing method should be applicable to a variety of structural element geometries and sizes.
- Processing method should produce a material with good, consistent mechanical properties.
- Amount of material processing-specific support equipment should be minimized.
- Material processing method should be integrated with structural design and construction operations.
- Processing and construction steps should be simple in order to accommodate robotic automation.
Assumptions

- Material processing method is intended for far-term lunar base. *A certain level of infrastructure must be in place.*

- **Power source** of 100 kW is available (SP-100 nuclear reactor). *This places tight constraints on processing time and structural component size.*

- **Earth moving equipment** is available. *All scenarios include plans for regolith shielding which requires earth moving.*

- **Lunar crane** with 10 ton capacity is available. *Near-term lunar base construction is likely to require lunar crane.*
Cast Lunar Regolith

- **Raw materials:** regolith is abundant over the lunar surface. Chemical composition of regolith is very similar to terrestrial basalts.

- **Terrestrial cast basalt** processing methods are moderately well established. Cast basalt has good mechanical properties and can be formed into complex geometries.

- **Proposed cast regolith** process is a simplification of terrestrial cast basalt suited to the lunar environment. Beneficiation, grinding, homogenization steps are unnecessary. High vacuum and low gravity pose no unusual problems.

- Material processing may be integrated with oxygen production.
Examples of Cast Basalt Components
Cast Regolith Process

mining
unbeneficiated
regolith

load furnace w/crane
8 ton capacity

crane

crane

cold regolith

melt regolith
Temp 1200-1300°C
Time 24 hrs

controlled
cooling

pour into
graphite form
2 cubic m volume

remove crucible

collect volatiles

power
100 kW

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Processing Equipment

- **Furnace**: batch operation, electrical resistance, 1300°C capability, 90% efficiency, 3 ton weight, enclosed heating chamber for recovery of volatiles (hydrogen, nitrogen,...). At 100 kW, melting cycle lasts 24 hrs for 6 ton regolith capacity.

- **Ladle**: heating chamber of furnace is removable to act as a ladle for the transfer of molten regolith to casting forms.

- **Casting forms**: reinforced graphite panels, 1500°C capability, 0.5 ton weight. Reflective surfaces reduce radiative heat transfer for controlled cooling and recrystallization over a 24 hr period.
# Mechanical Properties of Cast Basalt

<table>
<thead>
<tr>
<th></th>
<th>Cast Regolith</th>
<th>Concrete</th>
<th>Cast Iron</th>
<th>Aluminum</th>
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</thead>
<tbody>
<tr>
<td>Density (g/cc)</td>
<td>2.9</td>
<td>2.4</td>
<td>7.1</td>
<td>2.8</td>
</tr>
<tr>
<td>Elastic Modulus (GPa)</td>
<td>110</td>
<td>21</td>
<td>160</td>
<td>70</td>
</tr>
<tr>
<td>Tensile Strength (MPa)</td>
<td>&gt;35</td>
<td>7</td>
<td>125</td>
<td>100*</td>
</tr>
<tr>
<td>Fracture Tough. (MPa√m)</td>
<td>2</td>
<td>2</td>
<td>15</td>
<td>25</td>
</tr>
<tr>
<td>Thermal Expan. (x10^-6/°C)</td>
<td>7.8</td>
<td>13</td>
<td>11</td>
<td>22</td>
</tr>
<tr>
<td>Melting Point (°C)</td>
<td>1200</td>
<td>-</td>
<td>1400</td>
<td>600</td>
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* yield
Material Properties and Structural Design

- **Brittle material.** Design must minimize tensile and bending stresses and stress concentrations. Compression loading is ideal but unrealistic for pressurized structure.

- **Joining** introduces stress concentrations so the minimum number of structural components should be used. The maximum size of a structural element is dictated by the capacity of the batch furnace, casting capabilities, and constructibility.

- **Net shape forming** is necessary because cutting is very difficult.

- Large factors of safety must be avoided to reduce mass of structure and time required for material processing.

- Earth-based structural elements are necessary for joining, reinforcement, and air-locks. Design should minimize these.
Future Work

- **Material processing demonstration.** Demonstrate liquification, casting characteristics, viscosity, cooling and recrystallization, environmental effects.

- **Material property evaluation:** density, elastic moduli, fracture toughness, statistical measures of strength.

- **Structural design.** Develop a point estimate of a pressurized lunar habitation structure based on cast regolith.

- **Construction methods.** Establish integrated material processing and construction steps. Investigate potential for robotic automation.

- **Scale structural testing.** Validate design models and demonstrate structural reliability of point design.