Additive Construction with Mobile Emplacement:
Multifaceted Planetary Construction Materials Development

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ACME: Background

• Additive Construction
  • “The process of joining materials to create constructions from 3D model data” (Labonnote et al., 2016)
    • brick stacking, powder bed printing, and liquid/slurry/paste extrusion
    • 3D models allow fabrication of multiple types of structures – roads, berms, habitats, garages, hangars, etc. – with a single device

• Original work at Marshall Space Flight Center (MSFC) 2004-2007
  • Contour Crafting, goal of using resources found in-situ on planetary surfaces
ACME: Background

• Interest from the United States Army Corps of Engineers (USACE) since 2014
  • Use locally available cement/concrete

• Work captured, co-funded by USACE and NASA/STMD/GCDP* (2015-2017)
  • Additive Construction with Mobile Emplacement (ACME)
  • Delivery of Additive Construction of Expeditionary Structures (ACES) system
  • Materials work

• Paste type preferred
  • Little to no construction waste
  • No mortar and adhesive used between bricks
  • No formwork
  • Single feedstock delivery and emplacement system
  • Scalable

*National Aeronautics and Space Administration / Space Technology Mission Directorate / Game Changing Development Program
ACME: Background – MSFC ACME-2

- Gantry Mobility System
- Mixer
- Pump
- Accumulator (allows pump to stay on when nozzle closes for doors/windows)
- Hose
- Nozzle

Image credit: NASA
ACME: Material Constraints

- Must be compatible with additive construction technologies
  - Capable of being extruded, stacked, or emplaced layer by layer – predictably
    - Avoid warping and shrinkage during cooling/curing
  - Capable of being removed for system cleaning easily (or avoid cleaning by using a material such as thermoplastics)
  - Capable of being pumped or moved through the system without easily damaging, clogging, or abrading system components
    - Vibration
  - Capable of mixing adequately and predictably
    - Accurate dispensing and mixing ratios
  - Capable of pressurization if pumped
  - Consistency of a mix-specific viscosity
ACME: Material Constraints

- Must be composed of in-situ resources (reduce/eliminate cost of launching construction material)
  - Resources are site-specific, must know what materials are available (and have adequate simulants)
  - **LARGE** quantity of (processed) feedstock is needed

![Diagram of a rectangular structure with dimensions 2.5m x 20m x 20m, adding 0.2m wall thickness, resulting in 40m³ construction material (not including foundation or roof).]
ACME: Material Constraints

- Must be composed of in-situ resources
  - Minimize the use of water
  - Minimize the potential for deleterious chemical reactions
    - Geology varies on small scales
    - Mechanical binder for regolith grains is preferred (does not have to be a “precise mix”)
- Minimize the energy needed to mine the material
  - Use loose surface regolith when possible
- The original composition dictates:
  - Viscosity at given temperatures
  - Extrudability / workability of the mixture
  - Initial compressive strength, support subsequent layers
  - Initial set time
  - Layer adhesion
  - Resistance to aging (degradation over time)
ACME: Material Constraints

- Must be compatible with (extreme) planetary surface environments
  - Deposition
    - Gravity
    - Pressure at the surface
  - Deposition and Aging
    - Temperature swings
      - Thermal expansion
  - Aging
    - Radiation (galactic cosmic rays, solar particle events)
    - Solar wind
    - Micrometeorite bombardment
ACME: Material Constraints

• Ability to provide necessary structural integrity
  • Strength of the material (all aspects)
  • Define accurate construction tolerances for thermal expansion and vapor loss
• Layer adhesion
• Durability in the environment
• Compatibility with human activities – must not be flammable, decompose, or become toxic when exposed to H₂O, O₂, or CO₂ (unless lined)
ACME: Methodology

• Multiple materials are under study as planetary construction materials by multiple groups

• ACME materials research
  • Kennedy Space Center – focus on minimally processed regolith
    • Sintering
    • Polymer/regolith simulant mixtures (polymer to be created from the CO₂-rich atmosphere of Mars)
  • Marshall Space Flight Center - focus on cementitious materials similar to USACE
    • Planetary regolith simulant as aggregate
    • Binders such as Ordinary Portland Cement, MgO-based cements, and sodium silicate
    • Previous work with sulfur, polyethylene, and sintering
ACME: Methodology - MSFC

- **Standard mixture**
  - Ordinary Portland Cement (OPC)
  - Water
  - Navitas (rheology control)
  - Stucco mix (includes sand)

- **Simulant mixture**
  - OPC
  - Water
  - Navitas
  - Simulant (JSC Mars-1A)
  - Stucco mix (includes sand)

All aggregate used was less than 64mm in size.
Mixes captured above were used for printing.
Other mixtures were compression tested.

JSC Mars-1A, 5mm and less in size
Image credit: NASA
ACME: Methodology - MSFC

• Standard mixture defined viscosity for the ACME-2 additive construction system (between 5 and 20 Pa*s for OPC-based material)
  • Pump-able mixture
  • Retain cohesiveness
  • Smooth extruded bead

• MgO-based binder also investigated but not utilized in the ACME-2 system
  • Required constant vibration not possible in the ACME-2 feedstock delivery system
  • QUICK set-up time
ACME: Results to Date - MSFC

• Three samples were cast into 15.24cm x 15.24cm x 2.54cm molds, one was 3D printed with Mars simulant aggregate. Martian simulant JSC Mars-1A, stucco mix, OPC, Navitas, and water sample fractured during shipping to JSC prior to testing.

Martian simulant JSC Mars-1A, MgO-based cement, boric acid (set retardant) and water – sample fractured during shipping to JSC prior to testing.

Sample delaminated during shipping to JSC on a boundary between prints made on different days.

Lunar simulant JSC-1A, stucco mix, OPC, Navitas, and water.

Image credits: NASA
Hypervelocity impact tests were internally funded and performed at the White Sands Test Facility in Las Cruces, NM.

- 2.0mm Al 2017-T4 (density 2.796g/cm³) impactor, 0.17-caliber light gas gun, 0° impact angle, 1Torr N₂ in chamber during test.

- 7.0±0.2km/s velocity (approximate mean expected velocity of micrometeorites at the surface of Mars, and higher than expected velocity for bullets on Earth).

- Kinetic energy is equivalent to a micrometeorite with a density of 1g/cm³ and a diameter of 0.1mm traveling at a velocity of 10.36km/s, as well as a 9x17mm Browning Short bullet.
ACME: Results to Date - MSFC

- Image scales are comparable

Martian simulant JSC Mars-1A, stucco mix, OPC, Navitas, and water

Lunar simulant JSC-1A, stucco mix, OPC, Navitas, and water

Martian simulant JSC Mars-1A, MgO-based cement, boric acid (set retardant) and water
• Hypervelocity Impact Testing conclusions (Ordonez et al., 2017)
  • MgO-based cement, in this formulation, is not as resistant to impact as OPC
  • The projectile did not penetrate as deeply into the JSC-1A simulant-based mortar (compared to the JSC Mars-1A simulant-based mortar)
    • Smaller grain size of JSC-1A simulant
    • Makeup of JSC-1A simulant (grains not as porous as JSC Mars-1A simulant, crushed basalt versus weathered ash)
    • More deleterious reactions in the JSC Mars-1A mortar?
  • Layer adhesion issue
Grain size analysis/OPC binder - compression testing
- Standard 5.08cm cubes, 7 and 28 days
  - Initial strength related to tricalcium silicate formation
  - Ultimate strength related to dicalcium silicate formation

<table>
<thead>
<tr>
<th>Size Fraction (µm)</th>
<th>JSC Mars-1A (kPa)</th>
<th>JSC-1A (kPa)</th>
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- Tensile properties not measured but expected to be ~10% of compression results
ACME: Results to Date - MSFC

• One more thing...

Image credit: NASA
ACME: Next Steps

- Investigate and characterize more binders
  - Target specific proposed landing sites, generate (as accurately as possible) simulants, and mature binder fabrication and emplacement technologies
  - Test them in replicated environments
    - Thermal cycling, vacuum curing, etc.

- Establish building codes for planetary structures, and standards for additively constructed materials

- Set up an artificial neural network to help optimize these multifaceted, multifunctional materials
  - Balance between the site-specific regolith composition, extreme environments, emplacement via additive technologies, and characteristics of the final structure
ACME: Next Steps

• Optimization through trade studies / artificial neural network
  • Grain size
  • Compressive strength (including regolith load)
  • Tensile strength
  • Thermal conductivity
  • Radiation protection (materials and/or regolith shell)
  • Need for a skin/liner (pressurized?)
  • Cost to produce
  • Time to produce
  • Aging
  • Ability to be repaired
  • Ability to cure in a specific planetary environment
References and Acronyms


3D – Three-dimensional

ACES – Additive Construction of Expeditionary Structures

ACME – Additive Construction with Mobile Emplacement

ESSCA – Engineering Services and Science Capability Augmentation (contract)

GCDP – Game Changing Development Program

JSC – Johnson Space Center

KSC – Kennedy Space Center

MSFC – Marshall Space Flight Center

NASA – National Aeronautics and Space Administration

OPC – Ordinary Portland Cement

STMD – Space Technology Mission Directorate

USACE – United States Army Corps of Engineers