Additive Construction with Mobile Emplacement:
Multifaceted Planetary Construction Materials Development

Dr. Jennifer Edmunson

Jacobs ESSCA/NASA MSFC

Mike Fiske – Jacobs ESSCA/NASA MSFC
Rob Mueller – NASA KSC
Dr. Hunain Alkhateb – University of Mississippi
Dr. Amin Akhnoukh – East Carolina University
Heather Morris – Jacobs ESSCA/NASA MSFC
Van Townsend – Craig Technologies/NASA KSC
John Fikes – NASA MSFC
Mallory Johnston – NASA MSFC

Image credit: NASA

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)

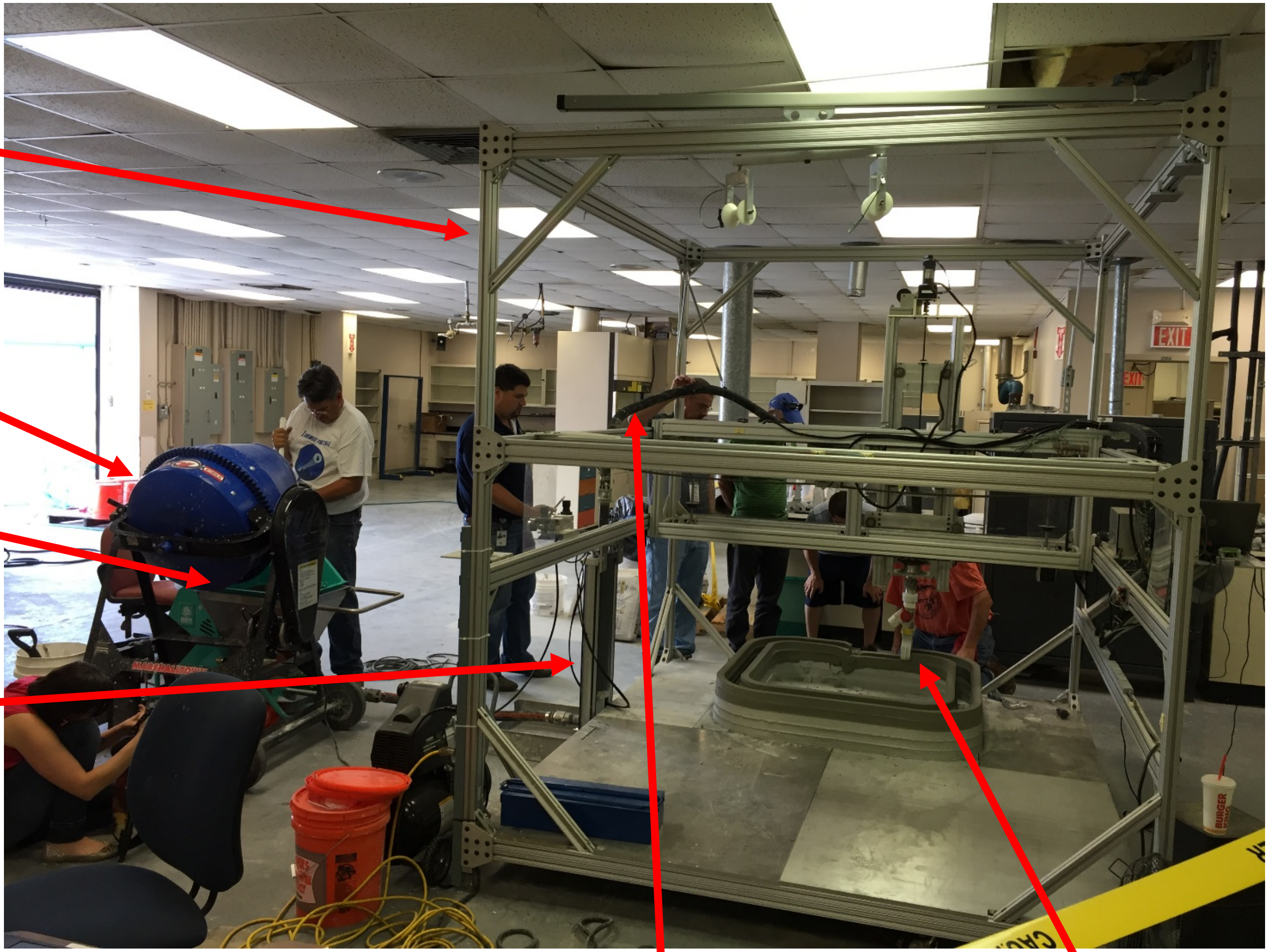


Image credit: NASA

Hose

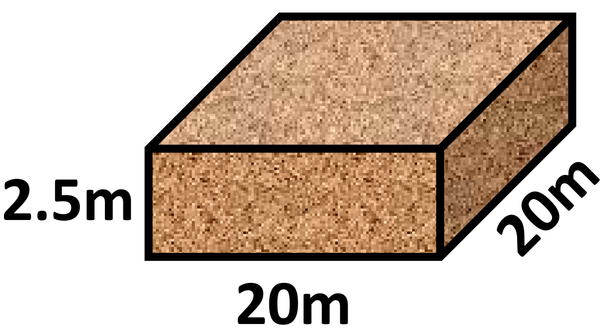
Nozzle

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



+ 0.2m wall thickness = $40m^3$ 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 H_2O, O_2, or CO_2 (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 CO_2-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)

JSC Mars-1A, 5mm and less in size

Image credit: NASA

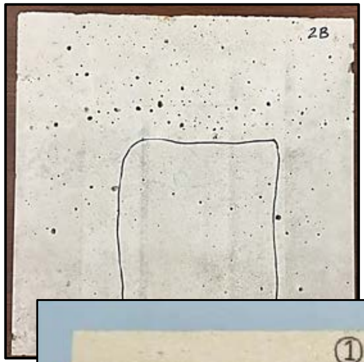
All aggregate used was less than 64mm in size.
Mixes captured above were used for printing.
Other mixtures were compression tested.

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

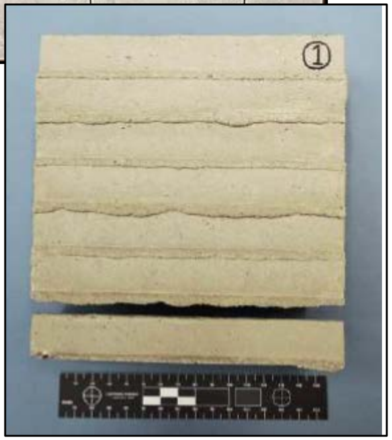
ACME: Results to Date - MSFC

- Three samples were cast into 15.24cm x 15.24cm x 2.54cm molds, one was 3D printed with Mars simulant aggregate

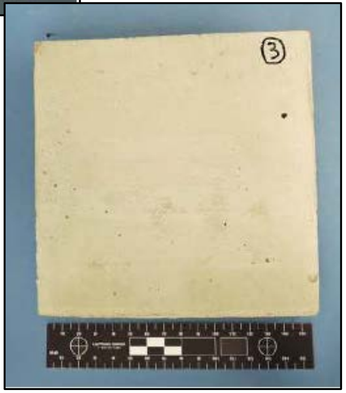


Martian simulant JSC Mars-1A, stucco mix, OPC, Navitas, and water

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

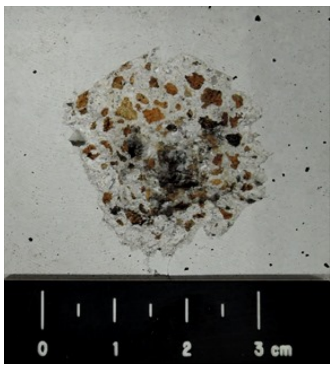
Image credits: NASA

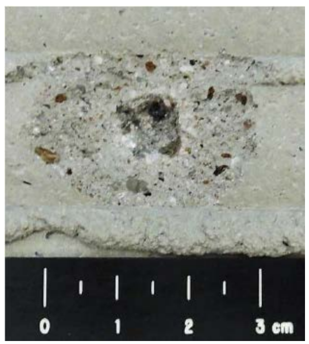
ACME: Results to Date - MSFC

- 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/cm^3) impactor, 0.17-caliber light gas gun, 0° impact angle, 1Torr N_2 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/cm^3 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

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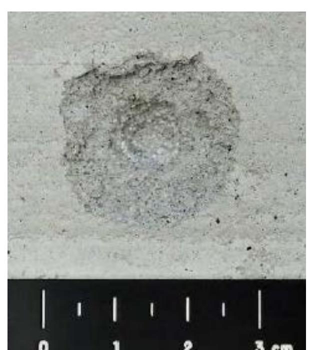

Martian simulant JSC Mars-1A, MgO-based cement, boric acid (set retardant) and water

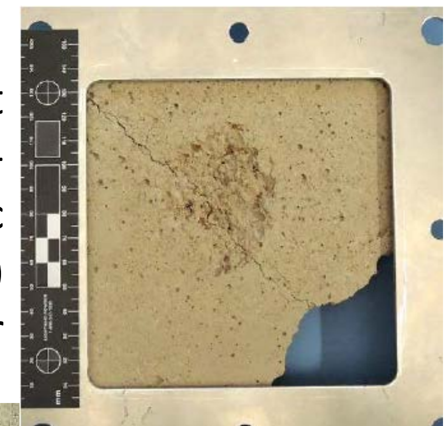
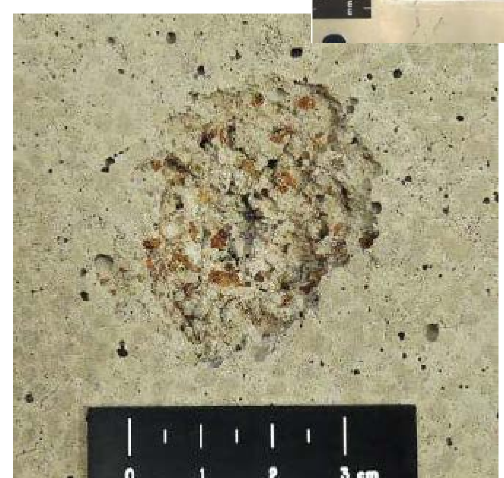

Image credits: NASA

ACME: Results to Date - MSFC

- 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

ACME: Results to Date - MSFC

- 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

Size Fraction (μm)	*JSC Mars-1A (kPa)*		*JSC-1A (kPa)*	
	7-Day	28-Day	7-Day	28-Day
4000-5000	20339	32218		
2000-3999	21146	35584		
1000-1999	22111	32675		
500-999	21335	33515	20554	28244
250-499	21949	35633	24728	34158
125-249	25628	31905	21089	26170
63-124	27802	34326	27820	37098
<63	23939	29967	29367	37140
Unsieved	22826	24383	27796	36092

- Tensile properties not measured but expected to be ~10% of compression results

ACME: Results to Date - MSFC

- One more thing...

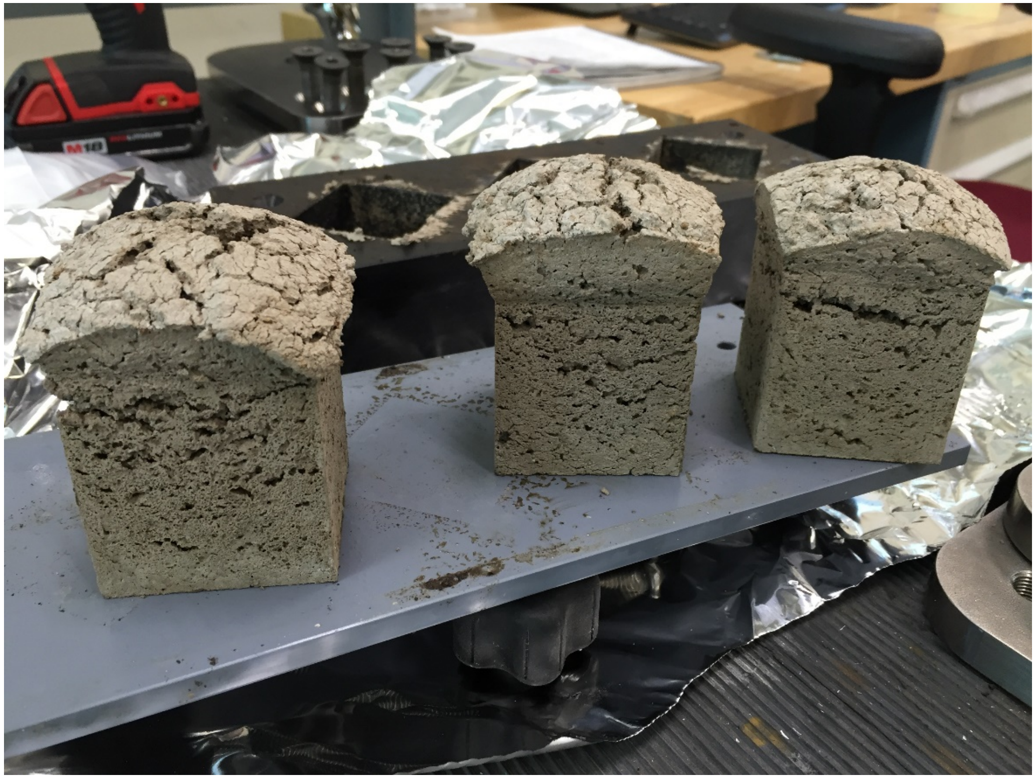

Image credit: NASA

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

https://www.bradley.edu/sites/challenge/

Image credit: NASA

References and Acronyms

Labonnote, N., Ronnquist, A., Manum, B., Ruther, P. (2016) "Additive construction: State-of-the-art, challenges and opportunities". *Automation in Construction*, 72(3), 347-366.

Ordonez, E., Edmunson, J., Fiske, M., Christiansen, E., Miller, J., Davis, B., Read, J., Johnston, M., and Fikes, J. (2017) "Hypervelocity impact testing of materials for additive construction: Applications on Earth, the Moon, and Mars". *Procedia Engineering*, 204, 390-396.

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