Additive Construction: Using In-Situ Resources on Planetary Surfaces

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and the ACME Team

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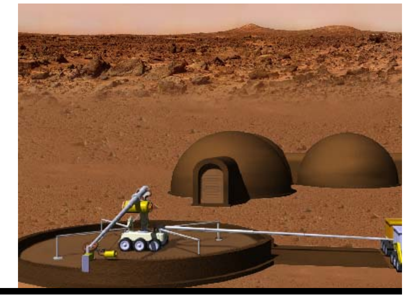
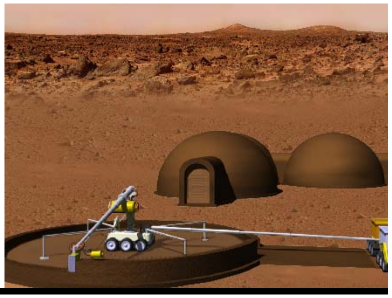
ACME Materials



- The original composition of the mix dictates:
  - Viscosity
  - Extrudability / workability
  - Initial set time
  - Initial strength to support superimposed layers
  - Temperature range acceptable for setting
  - Pressure range in which it can be printed
  - Functional temperature range for the cured material
  - Resistance to material aging in a planetary surface environment
  - How much material will need to be brought from Earth

Planetary Constraints

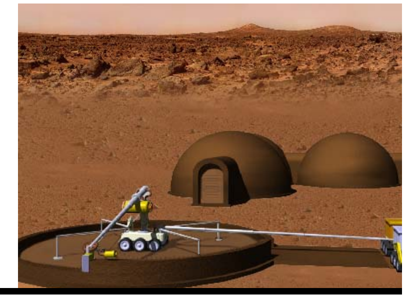


- Environment of deposition is the greatest constraint in the materials we choose for additive construction

Parameter	Mars	Moon
Gravity	1/3 that of Earth	1/6 that of Earth
Pressure at surface	3-10 Torr ($4x10^{-3}$ to $1x10^{-2}$ ATM)	$2x10^{-12}$ Torr ($3x10^{-15}$ ATM)
Surface Temperatures	-89 to -31 Celsius (Viking 1)	-178 to 117 Celsius (equator)
Radiation (solar wind particles, galactic cosmic rays)	Some protection offered by atmosphere	Some protection offered by Earth's magnetic field
Surface reactivity	Perchlorates (highly oxidizing)	Reduced material (nanophase iron, elemental sulfur)

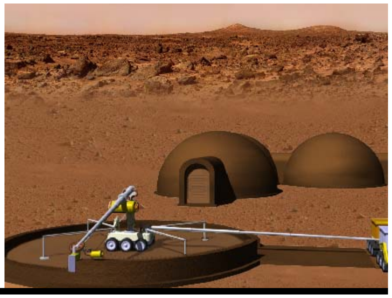
http://nssdc.gsfc.nasa.gov/planetary/planetfact.html

Material Requirements



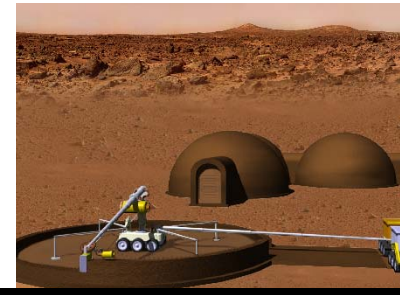
- For emplacement (extrusion) of additive construction material in a pressurized or ambient environment
  - Must flow and de-gas well
  - Must not set up (harden/cure) within the system
  - Must not shrink significantly while setting
  - Must allow for superimposed layer adhesion and support
- For accommodating internal pressurization
  - Must have significant tensile strength or the design of the structure must place the material in compression (e.g., inverted aluminum can and/or regolith cover)

Material Requirements



- For radiation and micrometeorite protection / shielding
  - Must have sufficient regolith cover and/or be composed of known shielding materials
- For long-duration use (resistance to aging)
  - Must withstand extreme temperature swings of the exterior environment while withstanding heating/cooling of the interior
  - Must withstand or self-heal damage due to radiation or micrometeorites by design or material
  - Must not become brittle over time
  - Must not be flammable, decompose, or become toxic when exposed to water, oxygen, or carbon dioxide (unless a liner/skin is used)

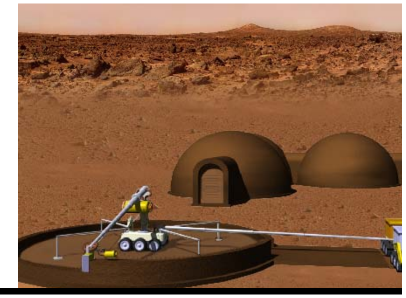
Material Considerations



- In-situ materials are site-dependent
  - Terrestrial example (PISCES involvement in ACME): Hawaii is interested in creating construction materials from basalt; all Portland cement, asphalt, etc. building material has to be brought in from the continental US.
  - Moon or Mars? Poles or Equatorial Region? Basalt or Sedimentary Rock?
  - Binder selection must reflect and complement available materials

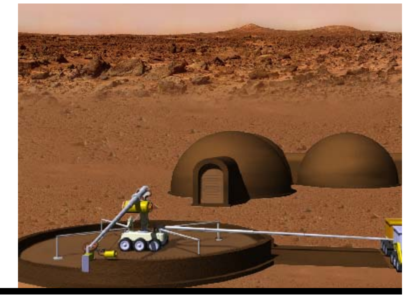
- USACE
  - Variations in globally available concrete
  - Need to regulate / accommodate for moisture in available materials

Available Materials - Mars



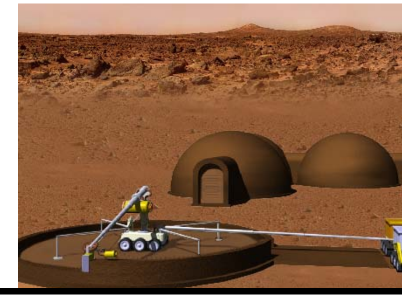
Mineral	Other Materials
Major minerals	**Present everywhere ("dew")**
Feldspar ($CaAl_2Si_2O_8$-(Na,K)$AlSi_3O_8$)	Perchlorates (ClO_4^-)
Pyroxene ((Ca,Mg,Fe)Si_2O_6)	**Atmosphere**
Olivine ($(Mg,Fe)_2SiO_4$)	CO_2 (95.32%)
Minor minerals	N_2 (2.7%)
Hematite (Fe_2O_3)	Ar (1.6%)
Magnetite (Fe_3O_4)	O_2 (0.13%)
Clays (Fe-Mg silicates, K-Al silicates)	CO (0.08%)
Sulfates (gypsum-Ca; jarosite-K,Fe; epsomite-Mg)	H_2O (210ppm)
Carbonates (calcite-Ca, dolomite-Mg)	NO (100ppm)
Poles – solid CO_2 (both) and H_2O (northern pole)	

Available Materials - Moon



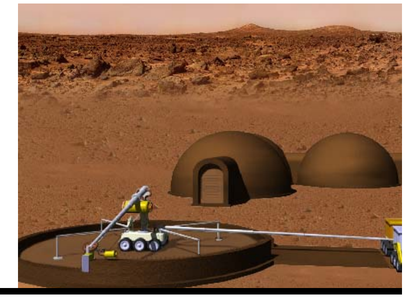
Minerals	Permanently Shadowed Regions
Highlands (Major Minerals)	**LCROSS (ejected material)***
Anorthite ($CaAl_2Si_2O_8$)	Regolith (~85%)
Pyroxene ($(Ca,Mg,Fe)Si_2O_6$)	CO (5.70%)
Olivine ($(Mg,Fe)_2SiO_4$)	H_2O (5.50%)
Mare (Major Minerals)	H_2 (1.39%)
Feldspar ($CaAl_2Si_2O_8$-$(Na,K)AlSi_3O_8$)	H_2S (0.92%)
Pyroxene ($(Ca,Mg,Fe)Si_2O_6$)	Ca (0.79%)
Olivine ($(Mg,Fe)_2SiO_4$)	Hg (0.48%)
Minor / Trace Minerals	NH_3 (0.33%)
Baddeleyite (Zr oxide)	Mg (0.19%)
Apatite (Ca phosphate)	SO_2 (0.18%)
Zircon (Zr, Si oxide)	C_2H_4 (0.17%)
Spinel (metal oxide)	CO_2 (0.12%)
Ilmenite (Fe, Ti oxide)	CH_3OH (0.09%)
Whitlockite (Ca phosphate)	CH_4 (0.04)
Troilite (Fe sulfide)	OH (0.002%)
Other phase of note – nanophase iron	* Larson et al. (2013)

Material Considerations



- The mix should:
  - Minimize water consumption
  - Be adjustable for slightly different compositions of regolith; not require a very precise mix
  - Be easy to emplace (including layer adhesion)
- The binder should:
  - Require a minimal amount of processing and energy to produce from in-situ resources
- The regolith used should:
  - Require a minimal amount of power to mine (i.e., use loose regolith when possible)

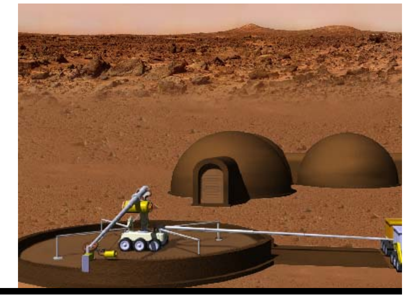
Some Previous Materials Work



- Sulfur used as a binder
  - Studied at MSFC in 2004-2007 timeframe with lunar simulant (R. Grugel, H. Toutanji)
  - NIAC to Dr. B. Khoshnevis
    - Scaling up contour crafting for full-scale sulfur printing
  - Currently studied by Northwestern University (among others)

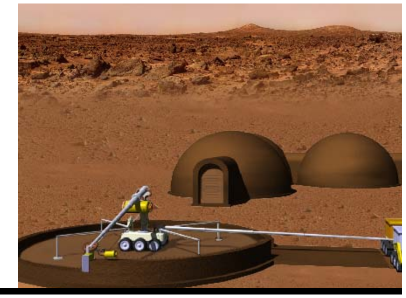
- Gypsum
- Polymers (e.g., Sen et al. 2010)
- Sintering
  - Laser, microwave, oven
    - Useful for Hawaiian material
- Basalt rebar/fibers

ACME Materials

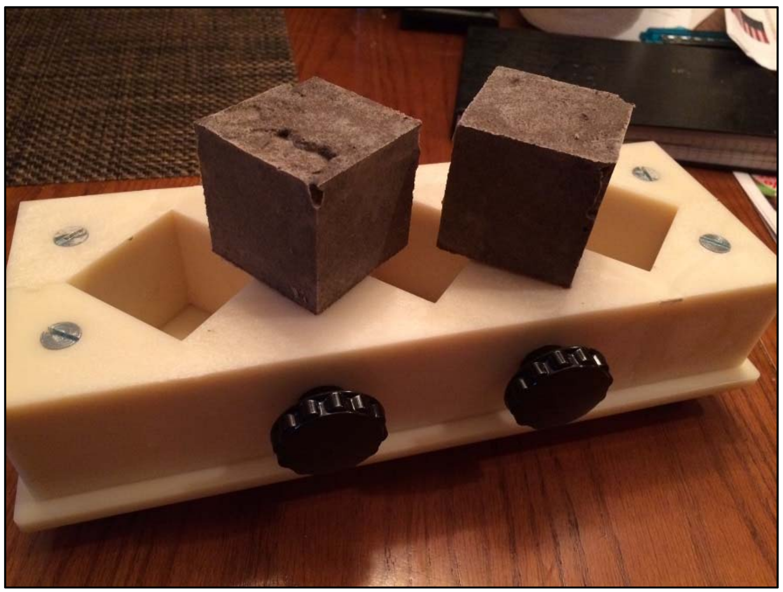


- Binders currently under study
  - Ordinary Portland Cement
  - Magnesium oxide-based cements
  - Sodium silicate (ACME and CIF)
  - Geopolymers
  - Polymers (KSC, Centennial Challenge Teams)
- Additives
  - Carbon nanotubes
  - Fibers
  - Polymers
- Simulants JSC Mars-1A (martian) and JSC-1A (lunar)

Compression Test Samples

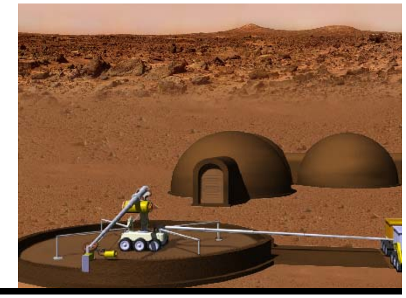


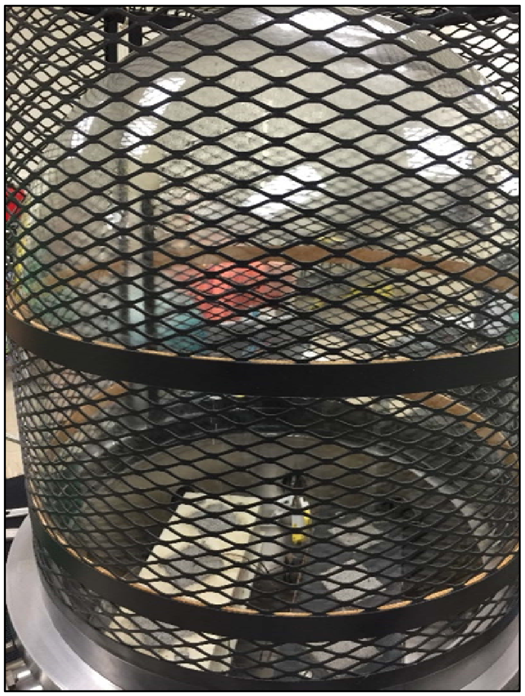
Sample prep in 4739



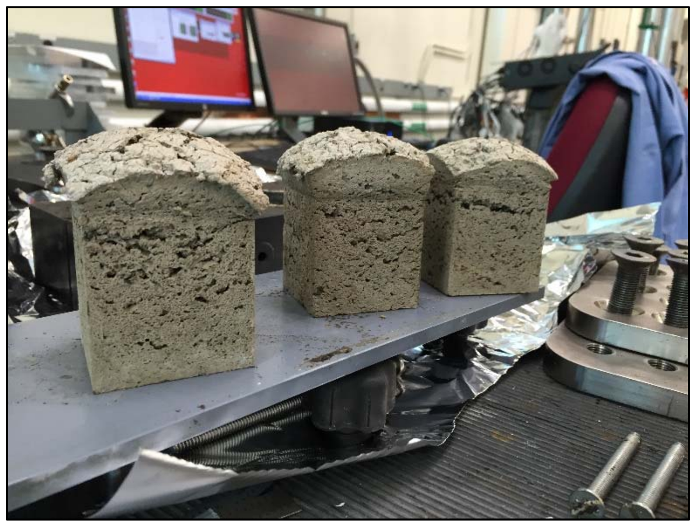
Test in 4602

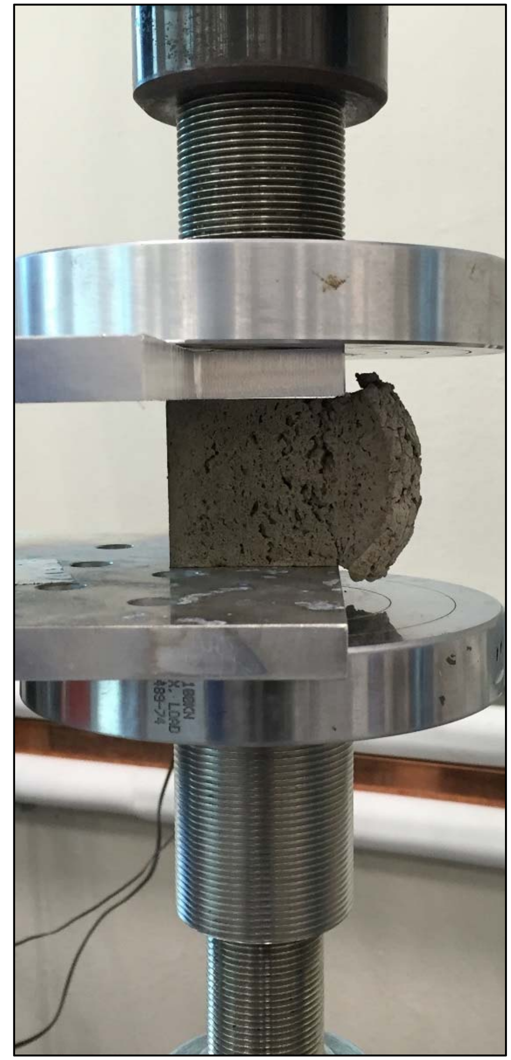
Compression Test Samples





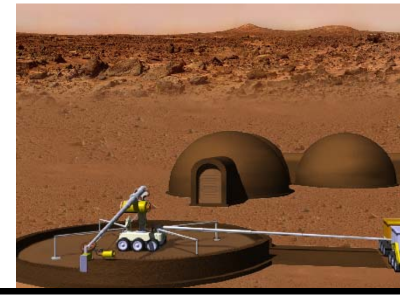
Sample prep in 4711 and 4464

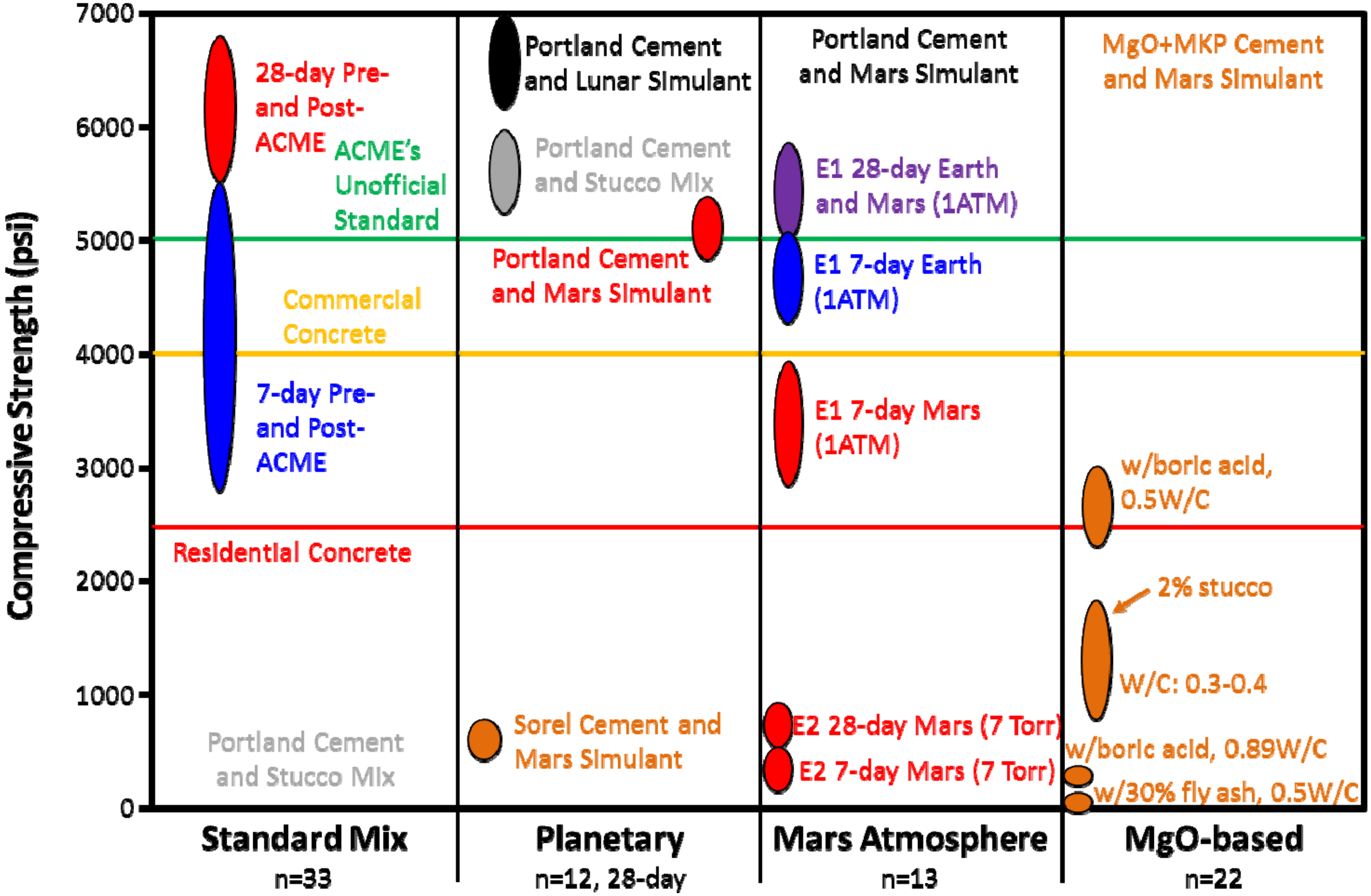




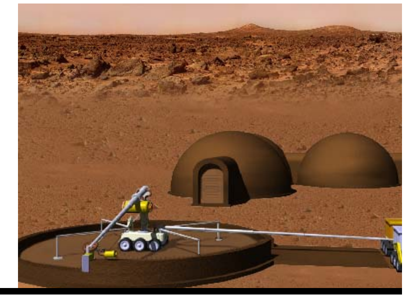
Test in 4602

Compression Test Results



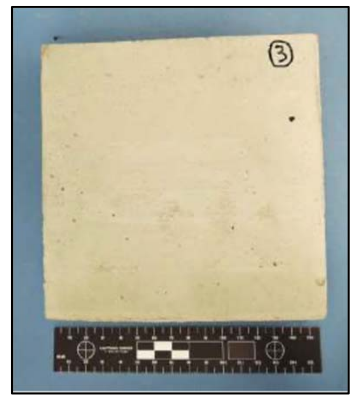


Hypervelocity Impact Test Samples

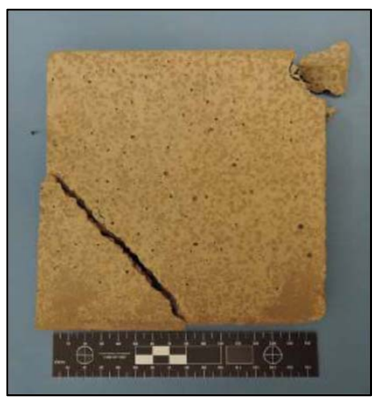


- Three samples were cast into 15.24cm x 15.24cm x 2.54cm molds

Martian simulant JSC Mars-1A, stucco mix, Portland cement, and water



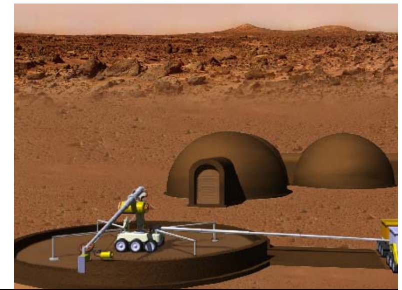
Lunar simulant JSC-1A, stucco mix, Portland cement, and water



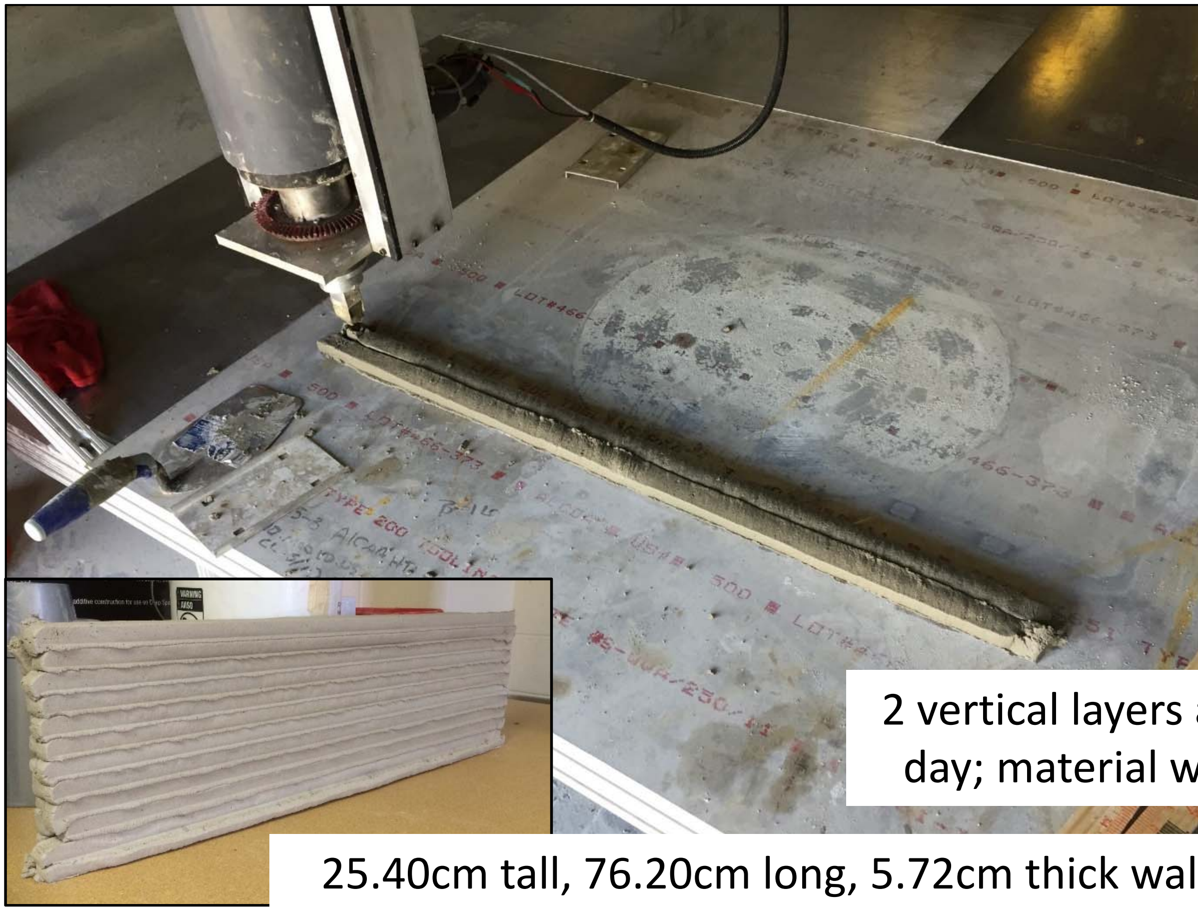
Martian simulant JSC Mars-1A, MgO-MKP cement, boric acid (set retardant*) and water – sample fractured during shipping to JSC prior to testing

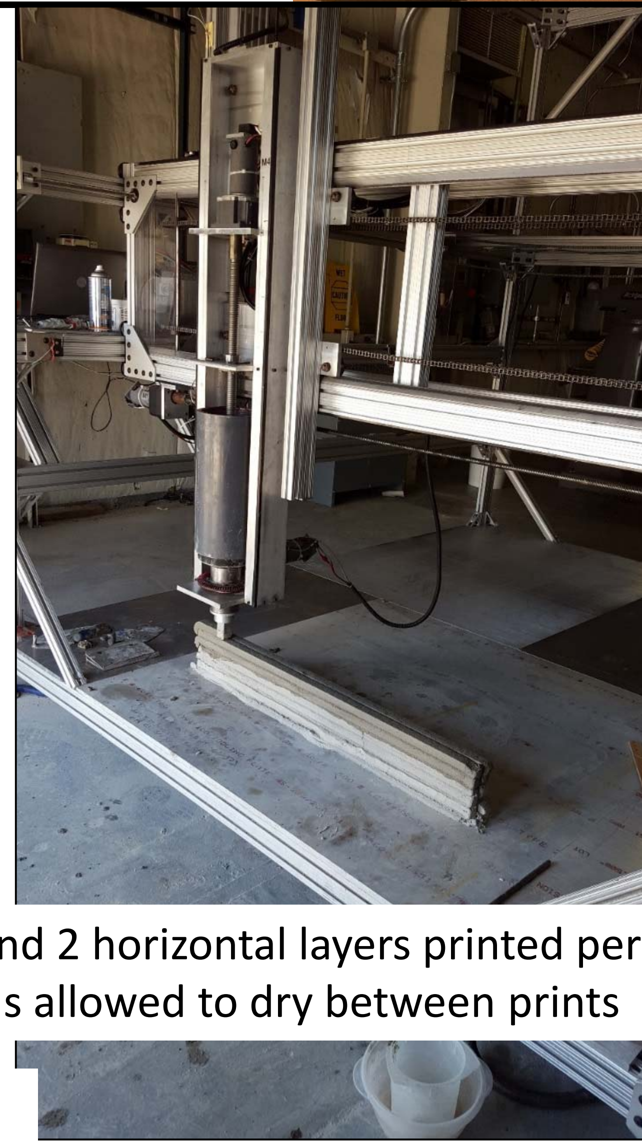
*Set retardant used because this cement sets up very quickly and would solidify within the ACME system prior to extrusion

Hypervelocity Impact Test Samples



Martian simulant JSC Mars-1A, stucco mix, Portland cement, rheology control admixture, and water

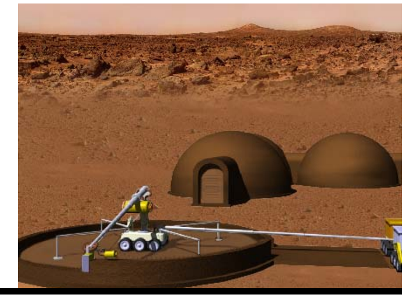




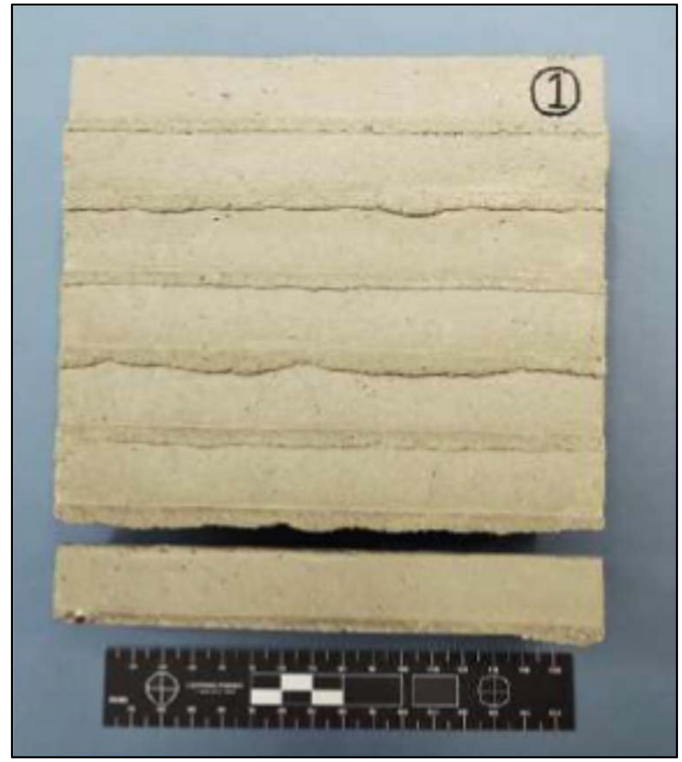
2 vertical layers and 2 horizontal layers printed per day; material was allowed to dry between prints

25.40cm tall, 76.20cm long, 5.72cm thick wall

Hypervelocity Impact Test Samples

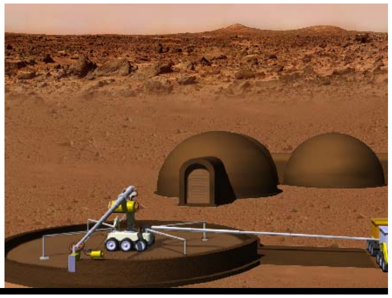


Martian simulant JSC Mars-1A, stucco mix, Portland cement, rheology control admixture, and water



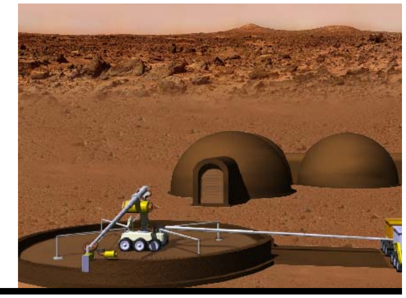
Sample delaminated during shipping to JSC on a boundary between prints made on different days

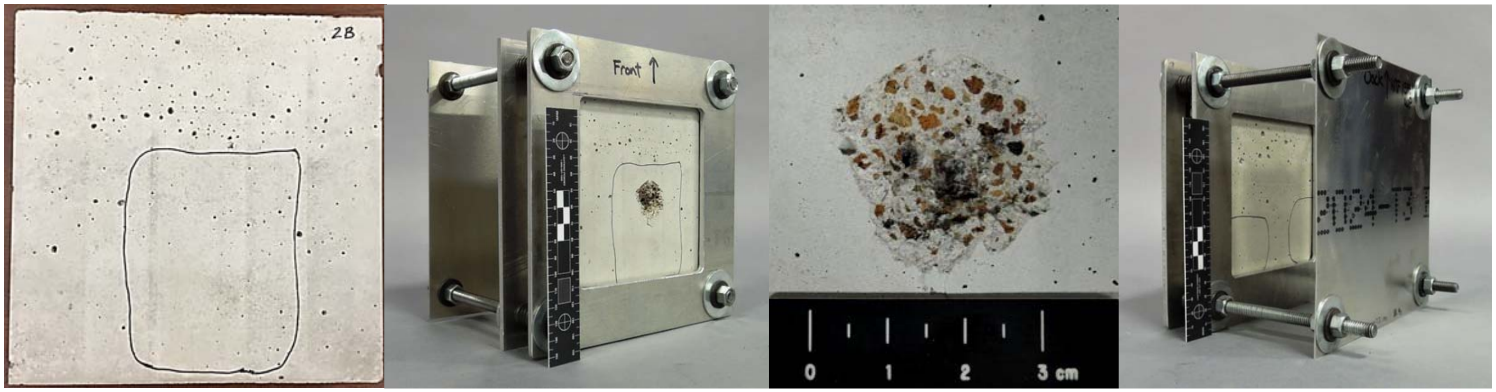
Hypervelocity Impact Testing



- 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.

Hypervelocity Impact Test Results

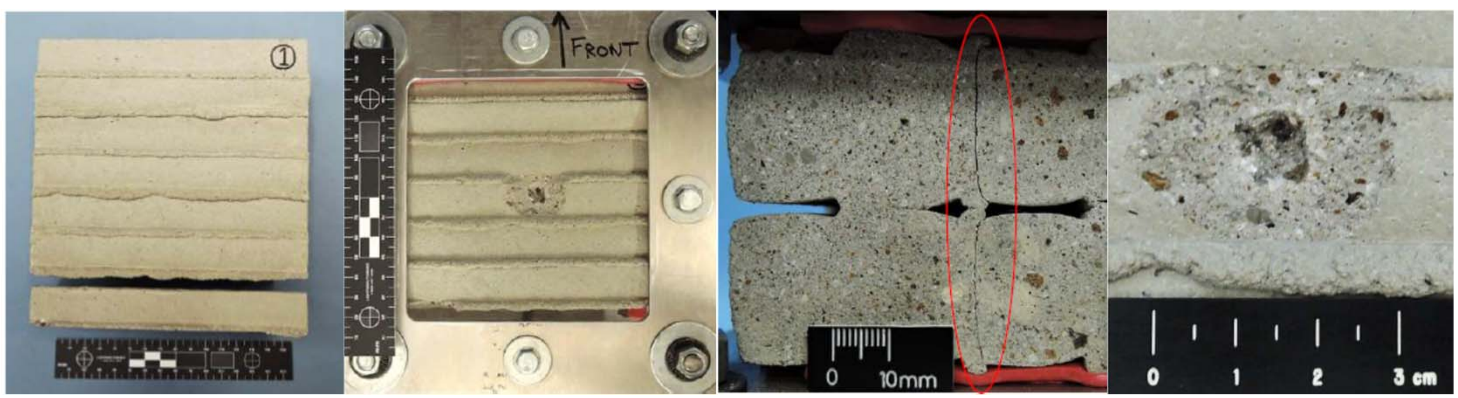




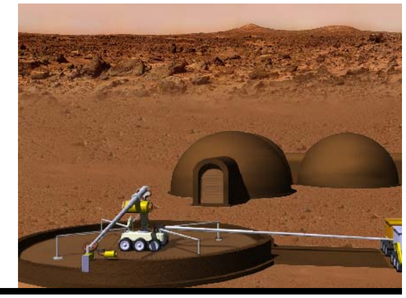
JSC Mars-1A
Portland cement
Stucco Mix
Water

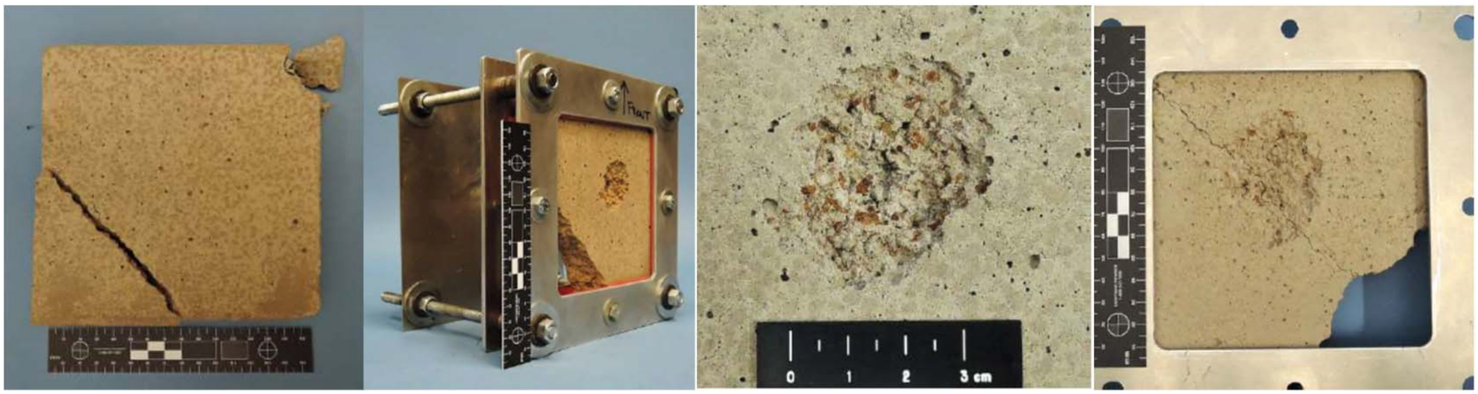
Photos courtesy of the Johnson Space Center Hypervelocity Impact Technology Group

JSC Mars-1A
Portland cement
Stucco Mix
Admixture
(Rheology Control)
Water



Hypervelocity Impact Test Results

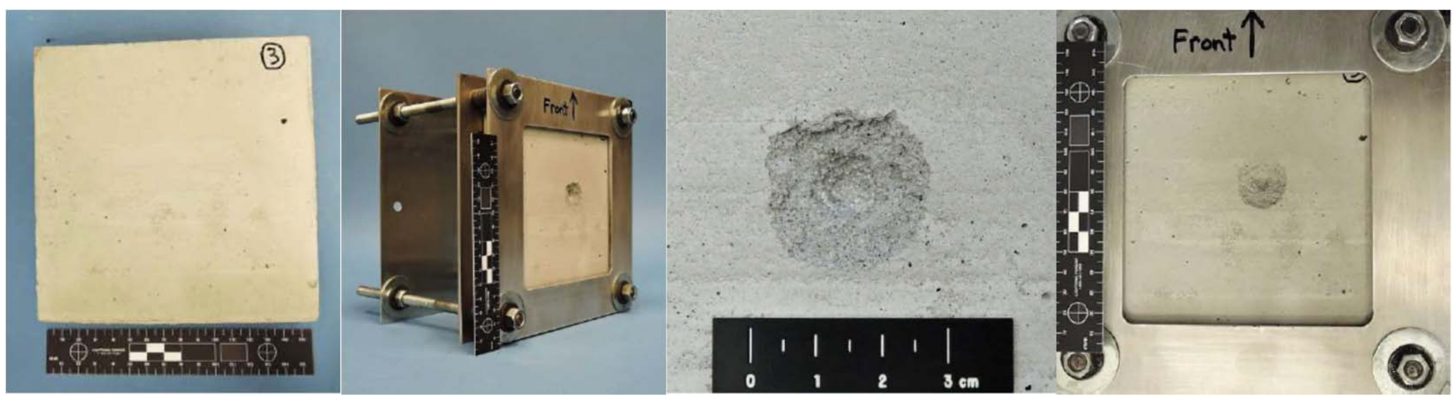




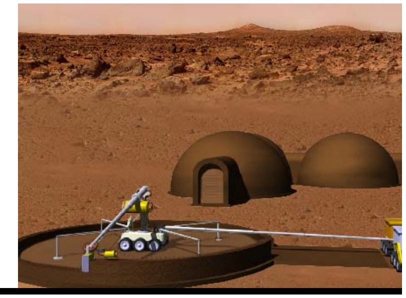
JSC Mars-1A
Sorel cement
(MgO + MKP)
Boric Acid (Set Retardant)
Water

Photos courtesy of the Johnson Space Center Hypervelocity Impact Technology Group

JSC-1A
Portland cement
Stucco Mix
Water

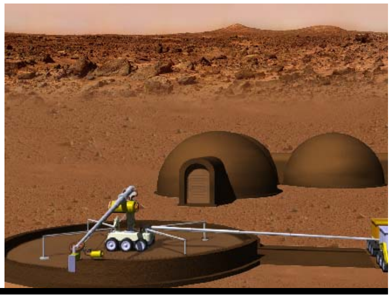


Future Work



- Continue to monitor human landing site workshops for Mars; optimize binder/regolith mixes for those sites
  - Continue to encourage planetary scientists to quantify available in-situ resources through remote sensing
- Establish an Artificial Neural Network to help optimize mixes
- Continue testing materials and identify promising new binders
- Spin-off technologies to industry
- Encourage involvement of the next generation in additive construction

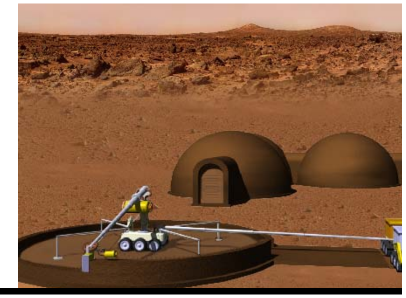
3D Printed Habitat Challenge



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


Q&A

ACME-2 System



Gantry Mobility System (good x, y, z positioning)

Mixer

Pump

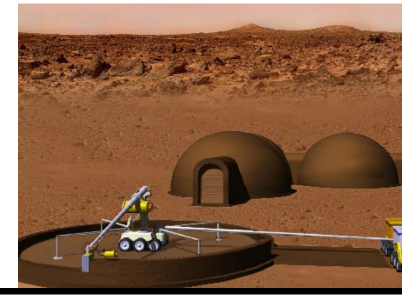
Accumulator (allows pump to stay on when nozzle closes for doors/windows)

Hose

Nozzle

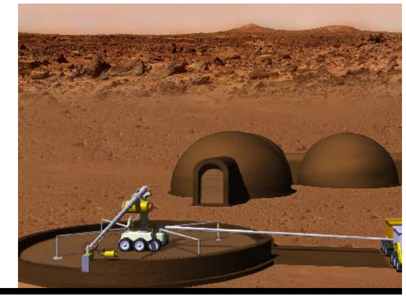
Control System

System Affects on Materials



Mixer	Pump	Hoses and Accumulator	Gantry	Nozzle
				
• Can inadequately mix • Amount (batch size) • Time to mix properly	• Can add air • Can redistribute air bubbles • Pressurizes the concrete • Clogs (needs more vibration) • Continuity of flow	• Can affect air distribution • Settling • Continuity of flow • Material (friction)	• Dictates hose position (vertical and horizontal drops, kinks in hose) • Size of printed structure	• Can stop flow • Trowel needs to be easy to use • Size of nozzle will dictate flowability and extrusion • Material of the nozzle (friction/ abrasion)

ACME-1 Materials



- Standard mix contains Portland cement, stucco mix, water, and a rheology control admixture
- Martian simulant mix contains standard mix with JSC Mars-1A simulant
- Printed at terrestrial ambient conditions