Hypervelocity Impact Testing of Materials for Additive Construction: Applications on Earth, the Moon, and Mars

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Outline

- Introduction to Additive Construction
- Additive Construction with Mobile Emplacement
- Fabrication of Samples
- Planetary Materials Requirements
- Hypervelocity Impact Testing
- Discussion of Results
- Conclusions
- Future Work

Additive Construction

- 3-dimensional (3D) printing (additive manufacturing) on a large (structure) scale
- Different geometries can be printed from a computer aided design model
- “Slicing” software produces code that allows layer-by-layer printing
- Permits construction of multiple types of buildings by one machine
- Currently being investigated by NASA and the United States Army Corps of Engineers

Additive Construction

Additive Construction with Mobile Emplacement (ACME)

- Use in-situ resources as construction materials, reducing material launched from Earth by over 90%
    - Not limited to water-based binders such as Ordinary Portland Cement (OPC) and Sorel (MgO-based) cement - sulfur, gypsum, ceramics, and polymers can be used
- Autonomously build multiple types of structures
- Increase technology readiness level (TRL) of additive construction technology in preparation for deep space missions

Additive Construction of Expeditionary Structures (ACES)

- Reduce imported material from 5 tons to less than 2.5 tons
    - Source concrete locally (in-situ resource)
- Reduce construction time from 5 days to 1
- Reduce construction personnel from 8 to 3 per structure
- Reduce construction waste from 1 ton to less than 500 pounds
- Build the structure to look like local housing using digital models; adaptable design that can serve the local community when troops leave

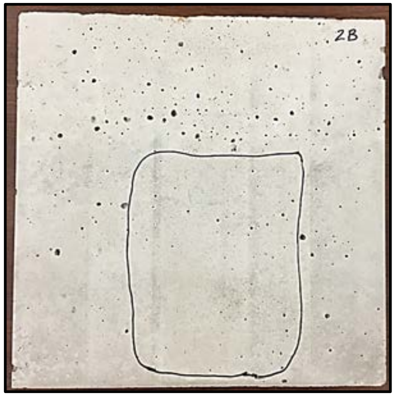
Additive Construction with Mobile Emplacement (ACME)

- Utilizing Contour Crafting technology (invented by Dr. Behrokh Khoshnevis, Contour Crafting Corporation)
- Currently investigating OPC and Sorel cements (water-based mixtures) to co-develop printing technology with USACE
  - OPC and Sorel cements can be produced on the surface of Mars
  - Sorel can be produced on the Moon
  - Independently examining polymer concretes and sodium silicate for planetary construction materials, plan to study other binders in the near future

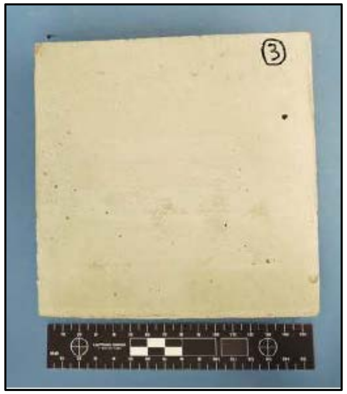
Upper image: Dome printed at MSFC using contour crafting technology, height ~1 meter. Lower image: Interior of dome during printing.

Fabrication of Samples

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



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



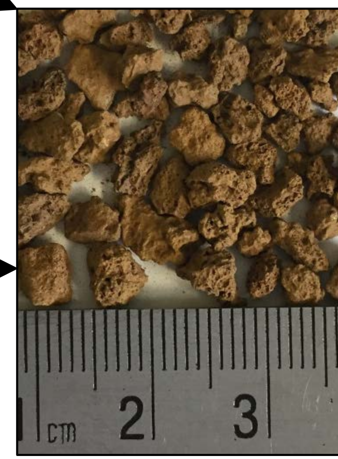
Lunar simulant JSC-1A, stucco mix, OPC, and water

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

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

Simulants Used

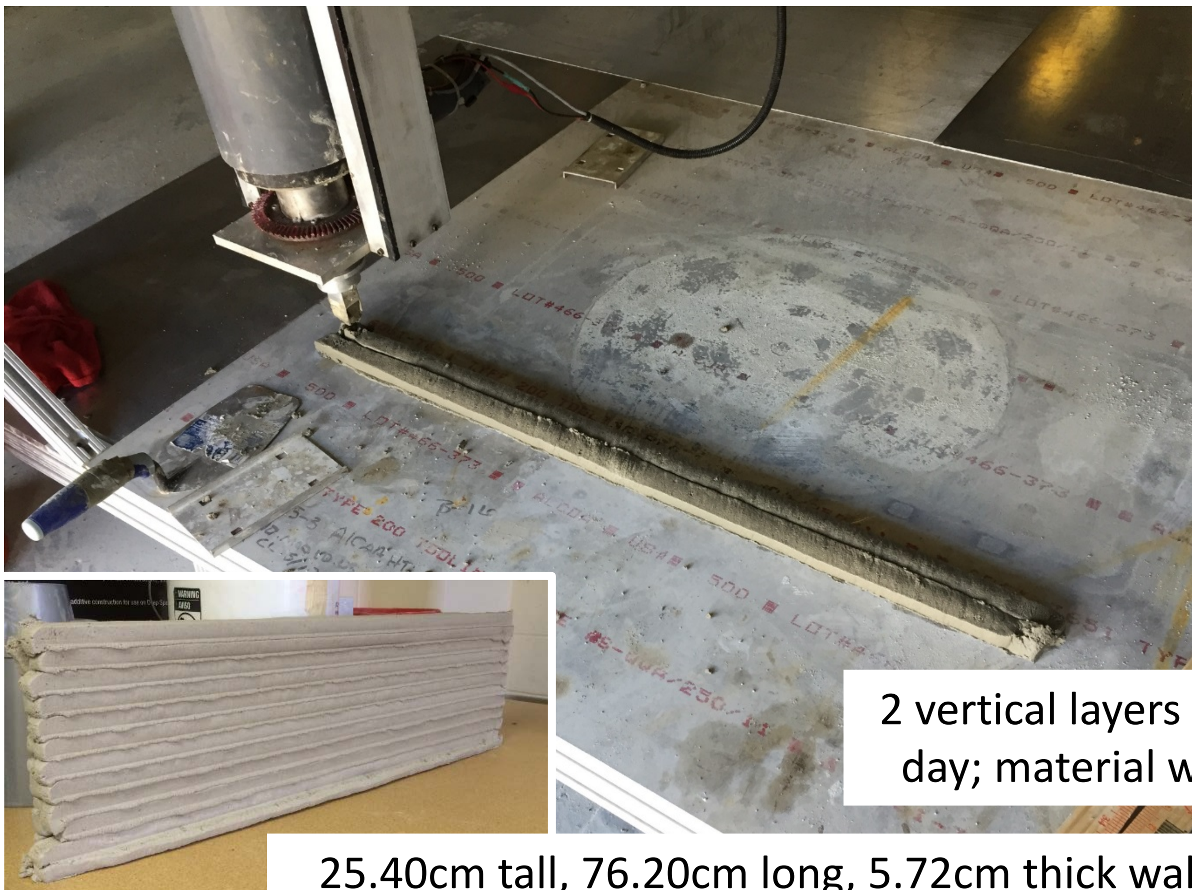
- JSC Mars-1A (martian simulant)
  - Basalt palagonitic tephra (weathered ash)
    - Appears red due to weathering
  - Vesicular grains
  - Not crushed or milled
  - Grain size ≤5mm
  - Density 0.8g/cm^3

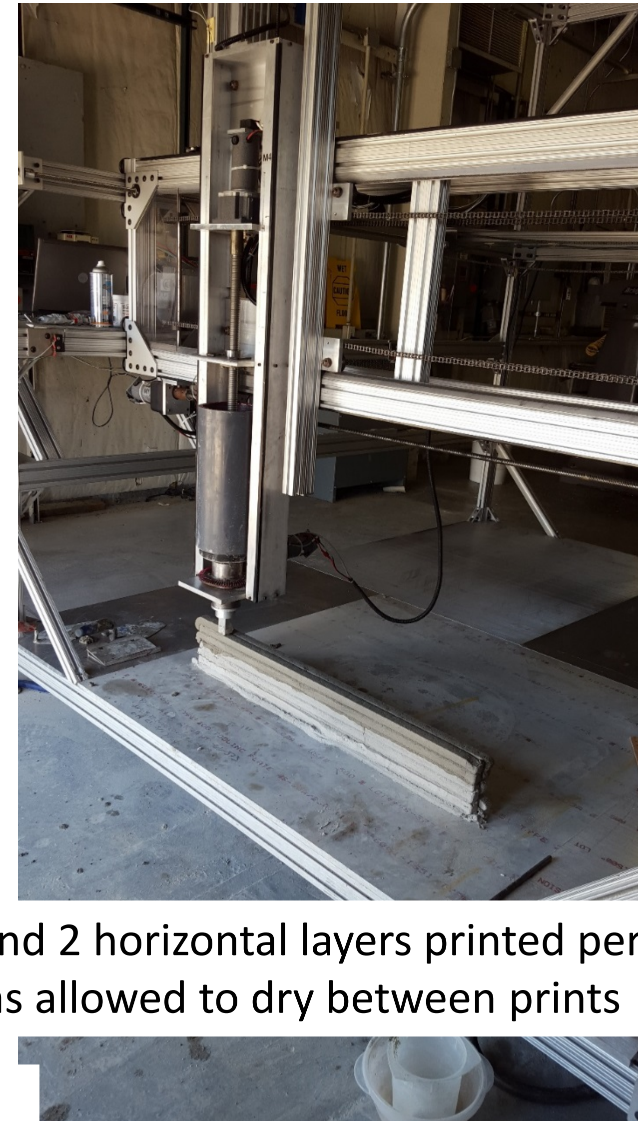


- JSC-1A (lunar simulant)
  - Crushed basalt
  - Grain size ≤1mm
  - Density 2.875g/cm^3

Fabrication of Samples – ACME-1

Martian simulant JSC Mars-1A, stucco mix, OPC, Navitas 33 (rheology control), and water





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

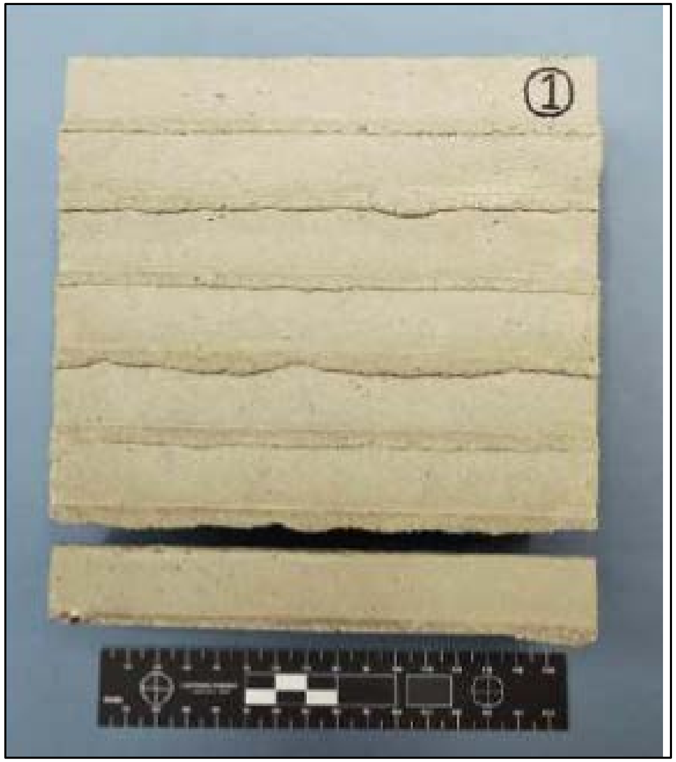
25.40cm tall, 76.20cm long, 5.72cm thick wall

Fabrication of Samples – ACME-1

Video by Diane Risdon

Fabrication of Samples

Martian simulant JSC Mars-1A, stucco mix, OPC, Navitas 33 (rheology control) and water



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

Planetary Materials Requirements

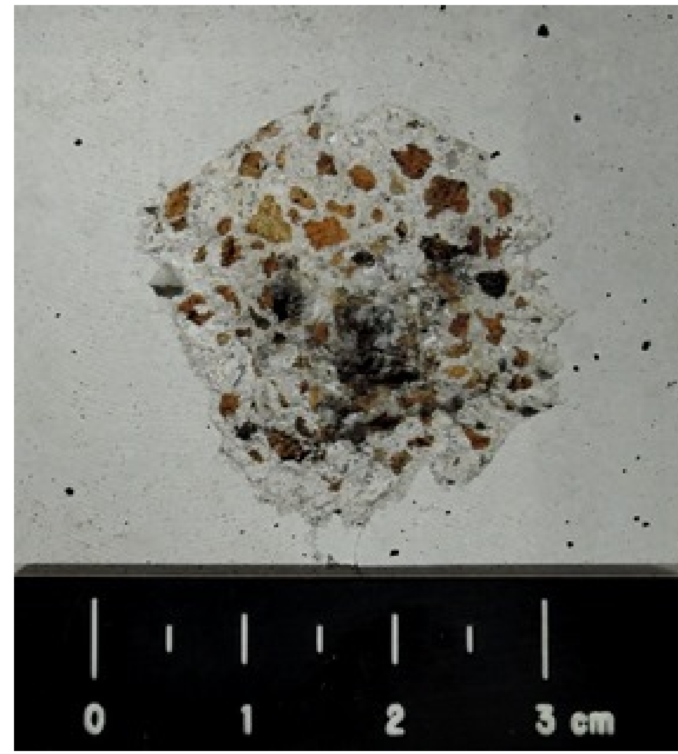
- Must be produced in-situ, with regolith (soil) as a component (aggregate and/or binder source)
  - This is a site-specific requirement; must account for spatial variation in the geology
- Must adhere to previously printed layers (or a binding agent must be used) for structural integrity
- **Must withstand micrometeorite impact**
- Must withstand temperature variations
- Must hold pressure (either by a compressive regolith load, lining, or design)
- May provide radiation shielding
- Minimizing water and energy consumed in the fabrication process is also a consideration

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 Testing

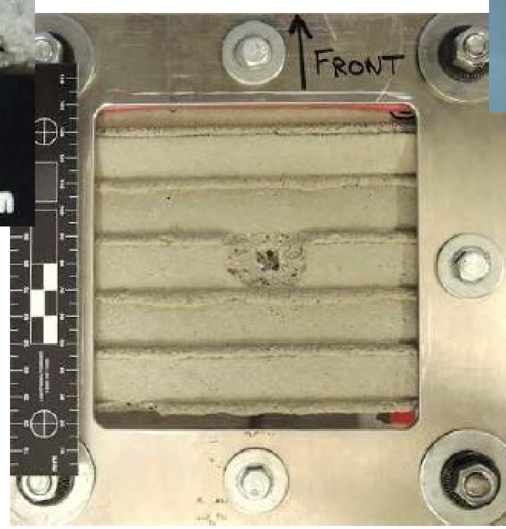
- Sample 1: JSC Mars-1A, stucco mix, OPC, and water

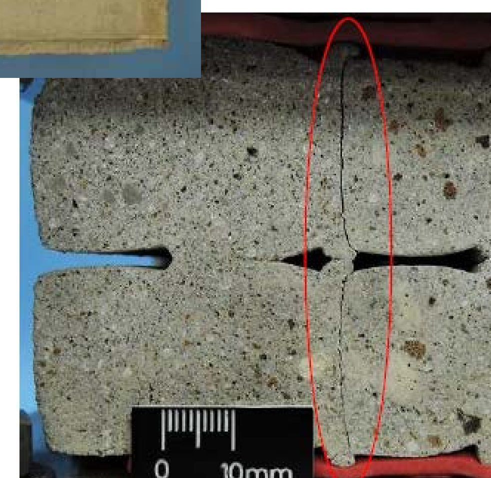


Area: 29.80mm x 27.10mm
Depth: 10.30mm

Hypervelocity Impact Testing

- Sample 2: JSC Mars-1A, stucco mix, OPC, Navitas 33, and water

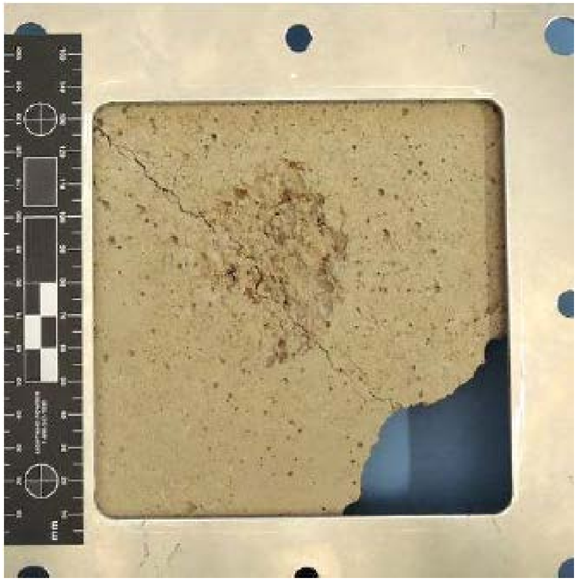




Area: 22.45mm x 32.78mm
Depth: 8.33mm
~2.48cm^3 material ejected (determined by density calculation)

Hypervelocity Impact Testing

- Sample 3: JSC Mars-1A, Sorel cement, boric acid, and water

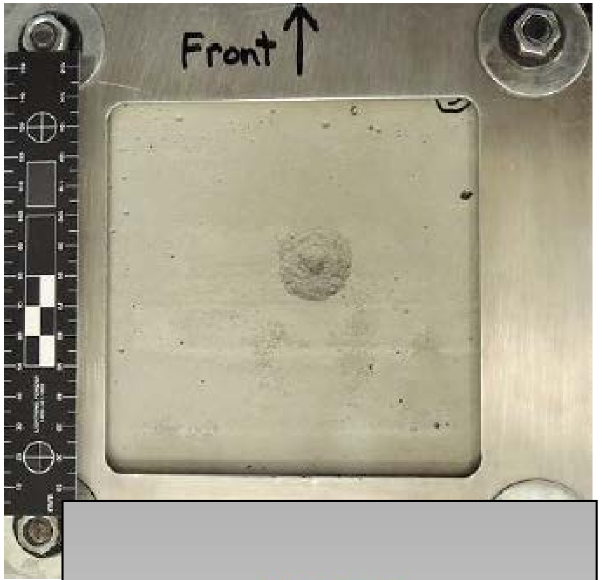


Front Crater Area: 41.26mm x 41.34mm
Depth: 10.12mm
~4.13cm^3 material ejected
(determined by density calculation)

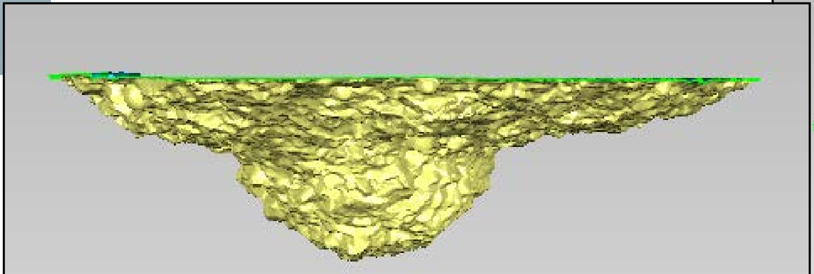
Spall Area: 64.99mm x 52.04mm
Depth: 9.96mm
~13.22cm^3 material ejected
(determined by density calculation)

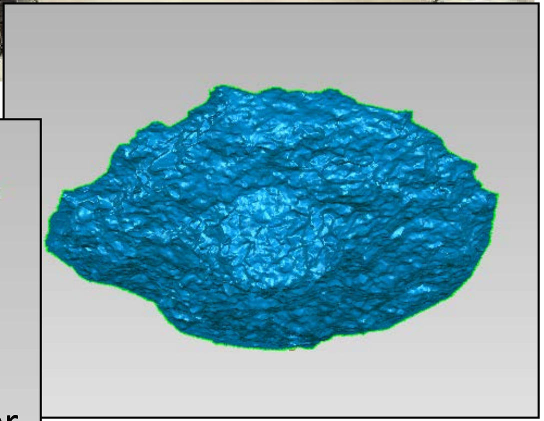
Hypervelocity Impact Testing

- Sample 4: JSC-1A, stucco mix, OPC, and water



Area: 25.60mm x 25.85mm
Depth: 6.48mm
0.98cm^3 material ejected
(determined by SLS)

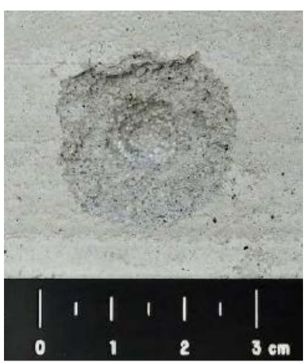




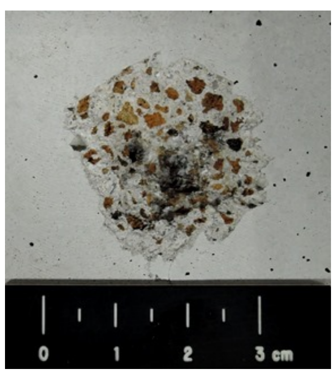
CAD crater geometry images by John Ivester

Discussion of Results

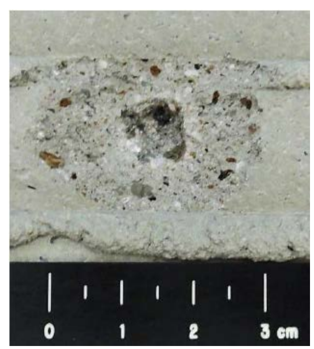
- Lunar simulant-bearing Sample 4 is more resistant to impact damage than martian simulant-bearing Samples 1 and 2, which are more resistant to impact damage than the martian simulant-bearing Sorel cement Sample 3.



Sample 4



Sample 1



Sample 2

Sample 3

Discussion of Results

- Sample 4 contains lunar simulant; the remaining samples contain martian simulant
  - Lunar simulant is more dense than martian simulant
    - 2.875g/cm^3 vs. 0.8g/cm^3
  - Lunar simulant is finer-grained than martian simulant
    - ≤1mm vs. ≤5mm
  - Lunar simulant does not contain vesicles
    - JSC-1A is crushed basalt; JSC Mars-1A was not crushed or milled
- Thus, grains that are crushed, smaller, and more dense should be used in planetary construction materials

Discussion of Results

- Sample 3 (Sorel cement) received more damage than OPC-bearing Samples (1, 2, and 4)
  - Testing at MSFC indicates Sorel cement formulations with boric acid (set retardant) and JSC Mars-1A simulant have compression strength of ~3000psi or less, lower than OPC formulations (~3000-5200psi) after 7 days.
  - Loss of strength compared to other Sorel cement formulations (with compression strengths up to 8000psi) likely due to the JSC Mars-1A aggregate and/or the addition of boric acid.
- More experimentation is needed to identify the source of lost strength

Discussion of Results

- Delamination of layers in Sample 2 occurred during shipping and testing
  - Delamination occurred between layers printed on different days, where wet cement bonded to dry cement
  - Wet-dry layer adhesion not as strong as wet-wet layer adhesion
  - Impact did not cause delamination of layers printed on the same day
- To minimize delamination during impact, samples should be completely printed when layer adhesion properties are maximized (i.e., on the same day)

Discussion of Results

- Additively constructed Sample 2 was not perforated during impact and did not spall
- Results are directly applicable to both NASA and USACE programs; additively constructed structures can withstand micrometeorite and ballistic impact (provided layer adhesion is maximized)

Conclusions

- Aggregate size and density influence material response to hypervelocity impact
- The Sorel mixture, in its current formulation, would not work as a planetary construction material
- Infrastructure elements that are additively constructed should be built to maximize layer adhesion during printing
- Structures that are additively constructed can withstand micrometeorite and ballistic impact (with maximum layer adhesion)

Future Work

- Investigate new binders (cements), including sodium silicate, polymers, ceramics, and others
- Create a test plan for emplacement on planetary surfaces (in a vacuum or pressurized volume)
- Study the aging of material due to thermal cycles, multiple impacts, and radiation
- Adapt to the geology of the site selected for human landing in order to create in-situ binders
- Increase the Technology Readiness Level of additive construction technology, as well as resource extraction and processing technology

Backup Slides

9x17mm Browning Short Bullet

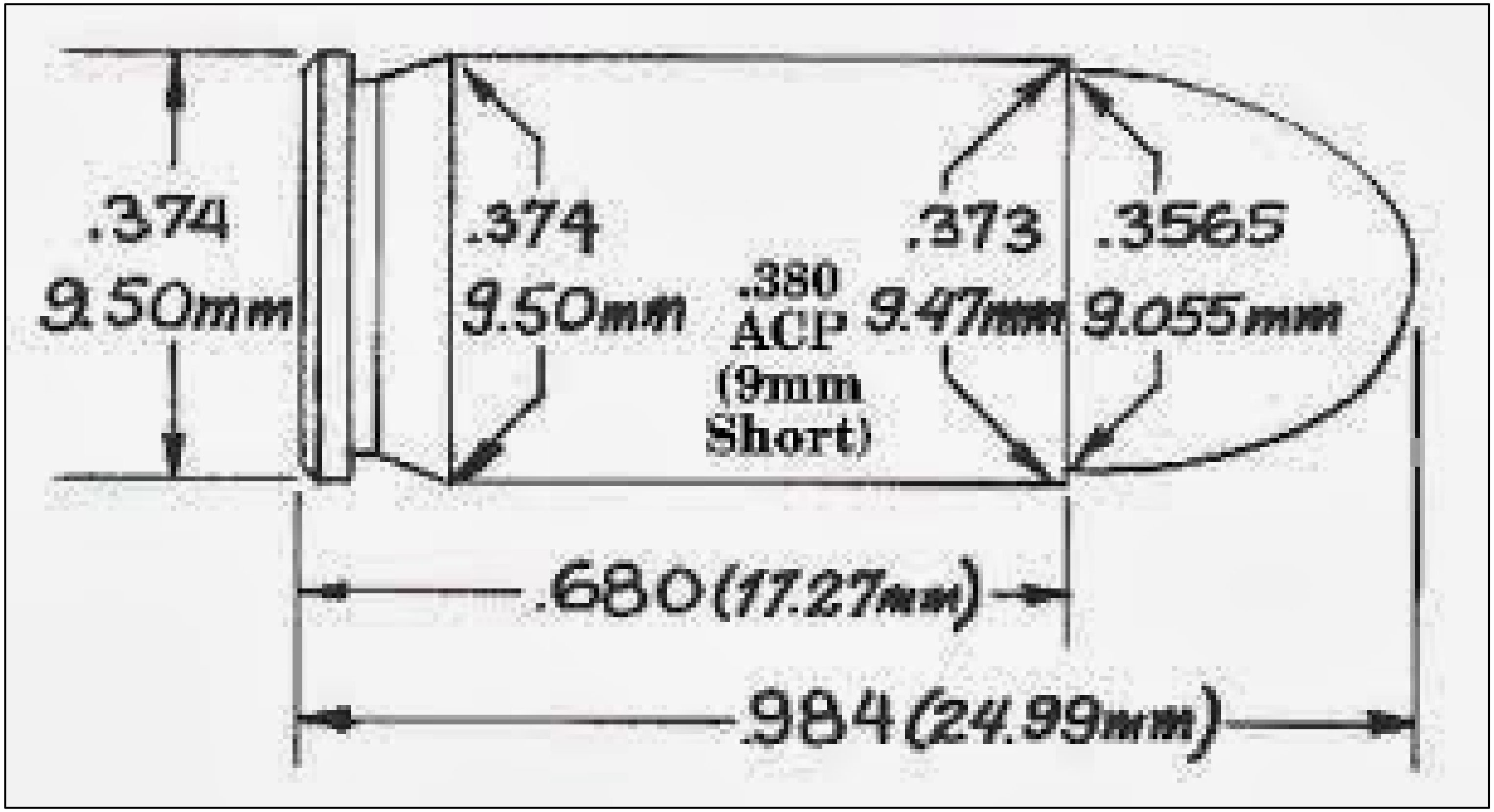
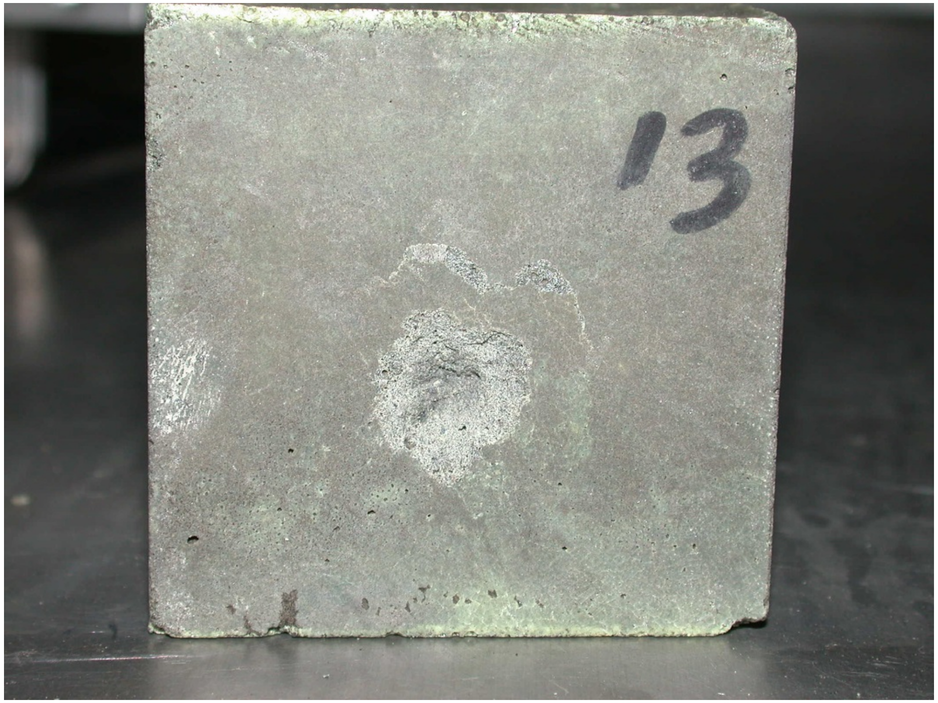


Image from: http://xgmbullets.blogspot.com/2013/10/380-acp-9x17mm.html

Sulfur Concrete

- Sulfur concrete was investigated at MSFC in ~2005
  - Included lunar simulant (JSC-1A, ≤1mm grain size)
  - Sulfur concrete does not require water (a precious resource on planetary surfaces)



- Cube size 5.08cm x 5.08cm x 5.08cm
- 1mm aluminum sphere
- 6km/s
- Presented in Bodiford et al. (2006) Proceedings of the 10th ASCE Earth and Space Conference

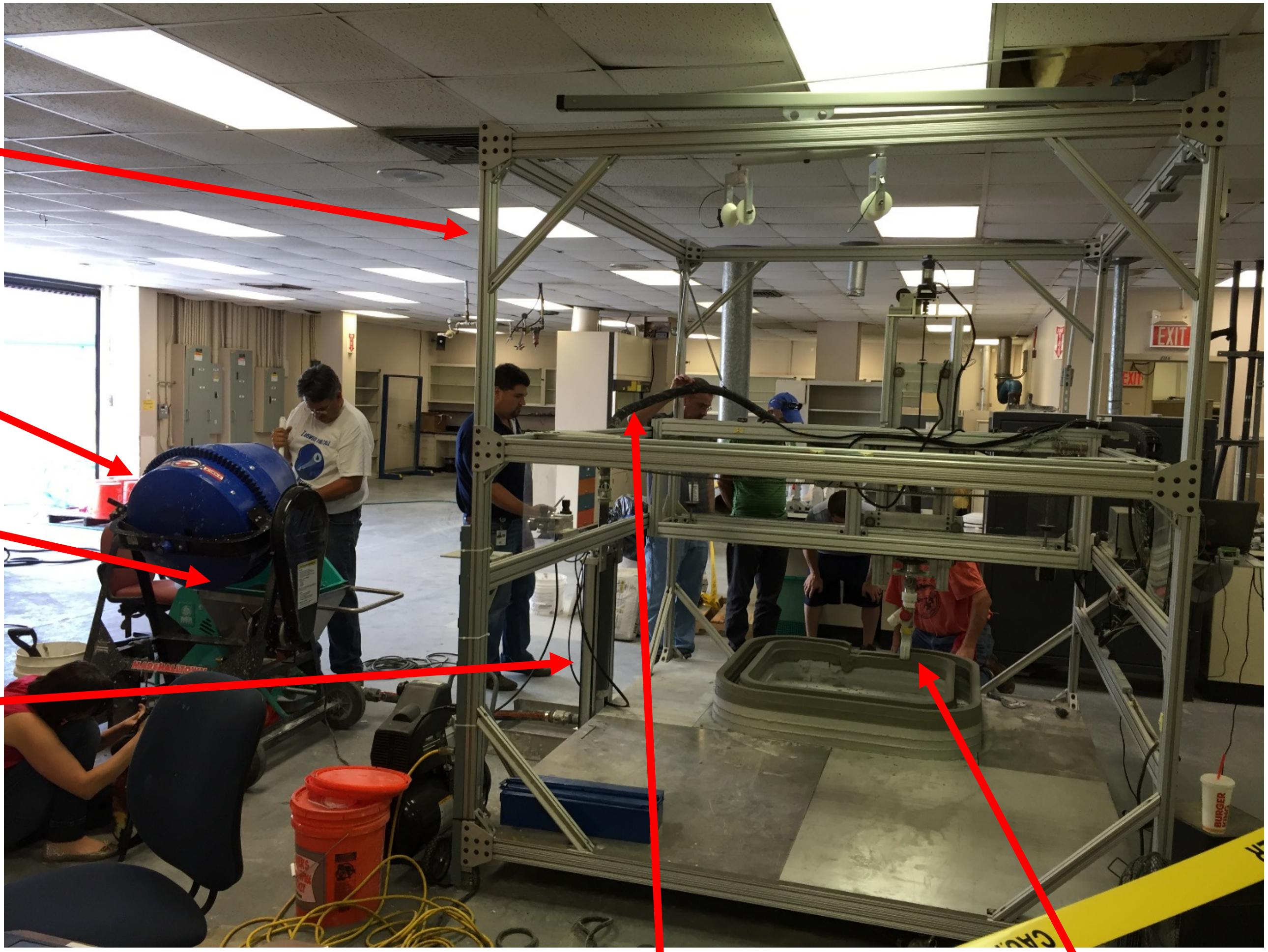
ACME-2 System

Gantry Mobility System

Mixer

Pump

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



Hose

Nozzle