Additive Construction with Mobile Emplacement: Planetary Construction Materials Development and Constraints

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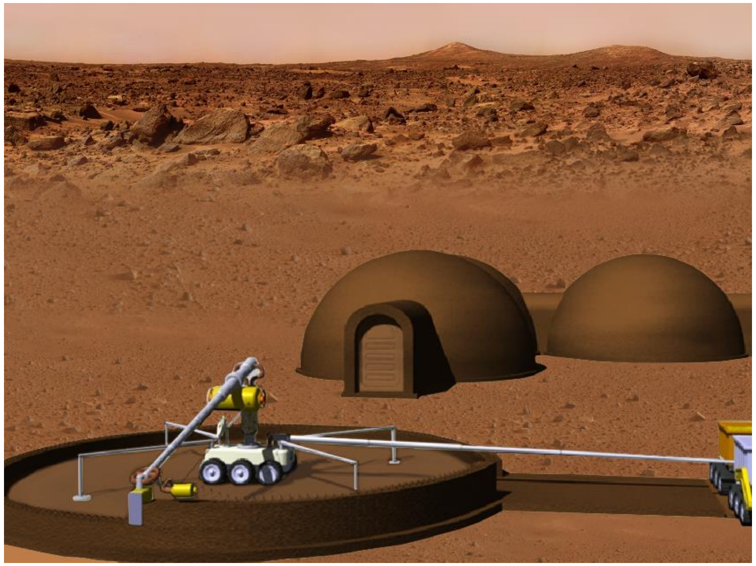
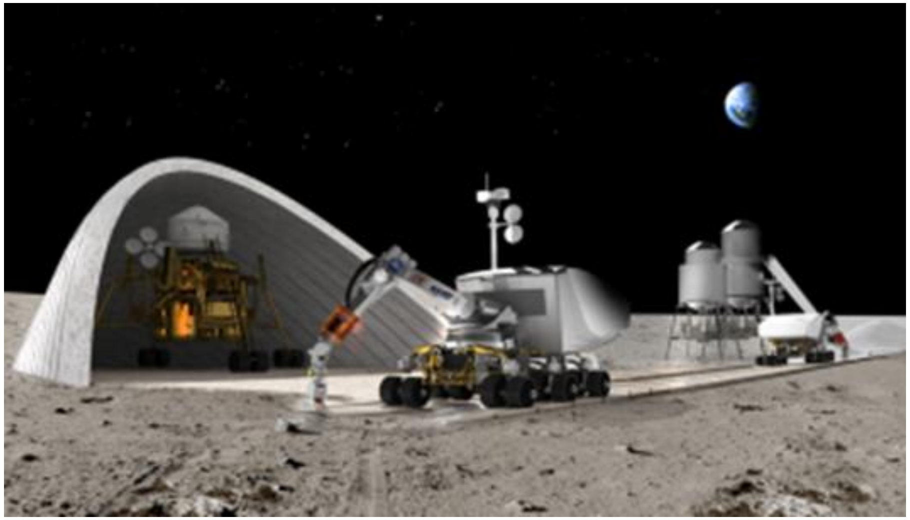
Introduction

- Additive Construction with Mobile Emplacement (ACME)
- Funded by NASA/STMD-GCDP and USACE-ERDC
- Partnership between NASA MSFC and KSC, Contour Crafting Corporation, USACE, and the Pacific International Space Center for Exploration Systems (PISCES)
- Additional contributions from the University of Mississippi



Goals

- Reduce the amount of material brought from Earth (90% or above) or into theater (50% or more)
- Reduce the amount of crew / people needed for construction
- Reduce construction waste
- Reduce the amount of time needed to build a structure
- Multiple geometries / structures possible
- Protect crew and troops



Current NASA System

- Gantry Mobility System
- Mixer
- Pump
- Hose
- Accumulator
- Hose
- Nozzle

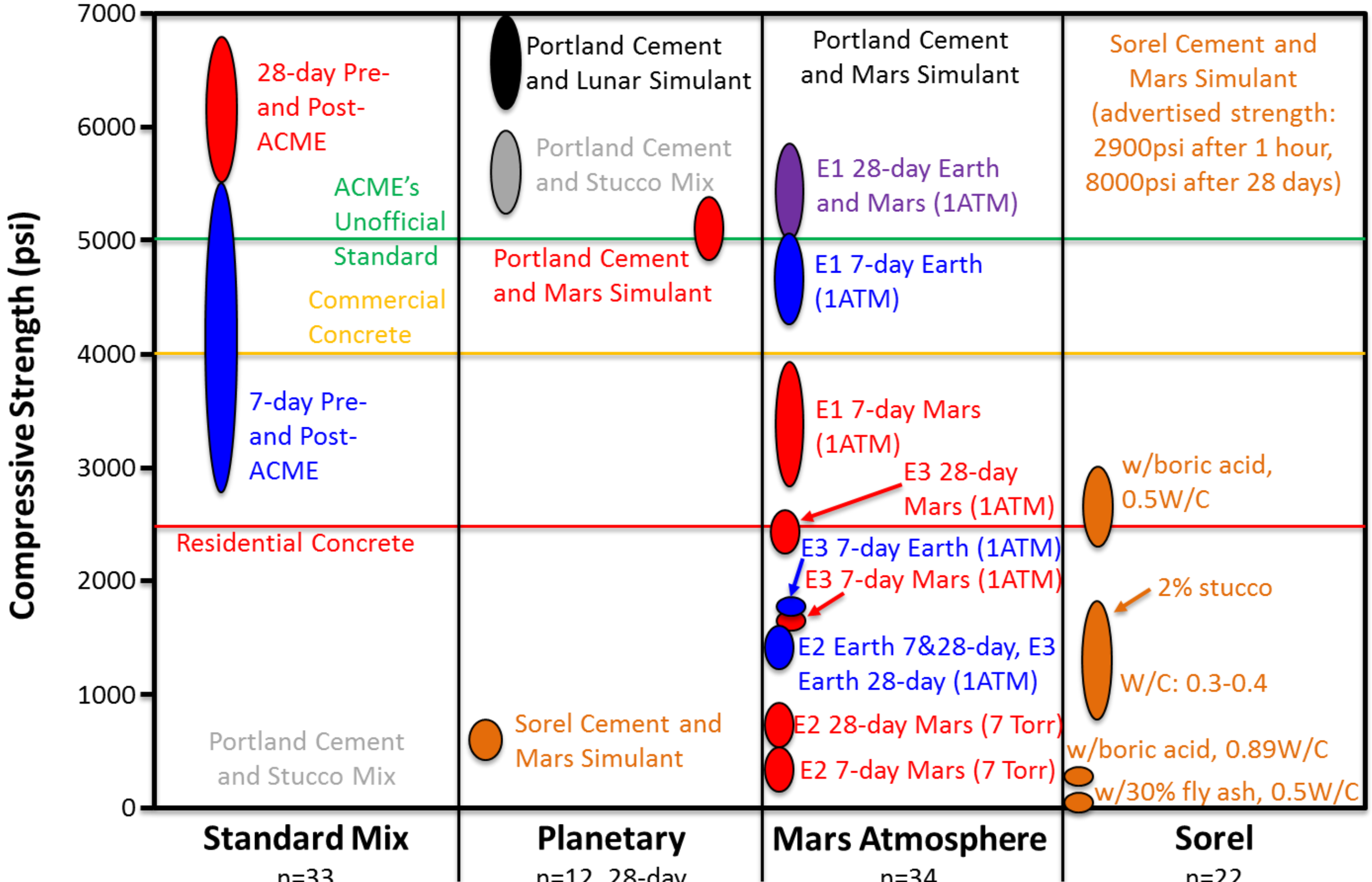
Materials Requirements - Earth

- Must not set for 60 minutes
- Must be capable of pumping through 40 feet of hose
- Must be capable of being flushed out water for cleaning
- Must have a certain viscosity (5-20 Pa*s, up to 40 Pa*s for USACE)
- Must have a strength of 2000 psi within 24 hours of emplacement to support a roof (USACE)
- Must be compatible with common structural reinforcement materials (fiber mesh, rebar, etc.) (USACE)

Current Mixes

- Ordinary Portland Cement (OPC), Stucco Mix (sand, OPC, plaster of Paris/calcined gypsum), Water, Admixtures ± Simulant
- Sorel cement (MgO + MKP or $MgCl_2$ among others) + Simulant + Admixtures (primarily set retardant)
- Martian (JSC Mars-1A) and lunar (JSC-1A) simulant
  - Both are basaltic
  - Martian simulant grain size ≤5mm
  - Lunar simulant grain size ≤1mm

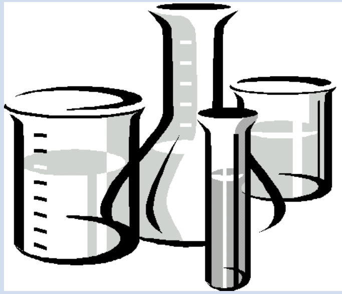
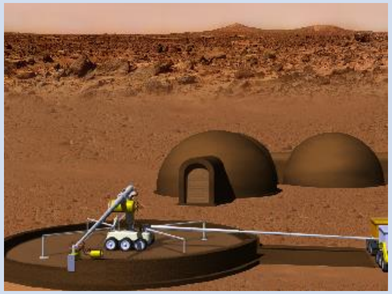
Compressive Strength



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) • Flowability continuation	• 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)

Other Affects on Materials

Original Mix	Emplacement Environment
	
• Composition • Viscosity • Extrudability • Initial strength to support layers • Initial setting time • Weather conditions	• Temperature • Pressure • Vapor pressure • Gravity • Available resources
	• Can affect settling • Set time • Porosity (vaporization) • Prohibits printing at specific times without heaters

Other Materials Considerations

- Emplacement (extrusion) in a pressurized or ambient environment
- Tension – internal pressurization
- Radiation and micrometeorite protection / shielding
- Aging (thermal, radiation, micrometeorites, settling, etc.)
  - Embrittlement
- In-situ materials are site-dependent
  - 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

Materials Requirements - Planetary

- Must be produced in-situ, with regolith (soil) as a component (aggregate and/or binder source)
- 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

Materials – Planetary (Bonus Points)

- The less water involved or consumed, the better
- The less power or resources consumed during mining and processing / binder production, the better
- The easier it is to emplace (including layer adhesion), the better
- The less precise the mixture has to be, the better
- The more simplistic the design of the mobility system, the better
- The less insulation, skin, or liner needed, the better
- The less toxic the material is when exposed to oxygen or water, the better
- The less cost for development, the better!

In-Situ Materials (Mars)

Mineral	Other Materials
Major minerals	**Present everywhere ("dew")**
Feldspar ($CaAl_2Si_2$, Na,KSi_3,O_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)	

In-Situ 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 ($CaAl_2Si_2$, Na,KSi_3,O_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)
Other phase of note – nanophase iron	OH (0.002%) * Larson et al. (2013)

Potential Binders

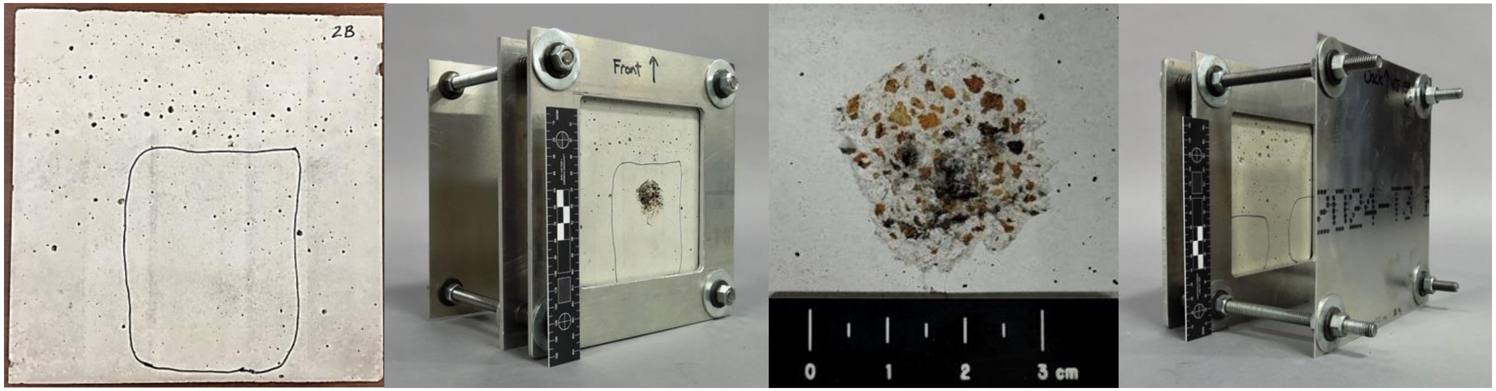
- Ionic liquid epoxy
- Polymers
  - Carbon-based
    - Ethylene vinyl alcohol
    - Polyethylene
    - Polyurethane
  - Silica-based
    - Sodium silicate
    - Silicone
- Glass
- Cementitious Materials
  - Ordinary Portland Cement
  - Sorel Cement
    - MgO + MKP, $MgCl_2$, etc.
- Sulfur
- Urea
- Biopolymers (protein), Kerogen
- Thermites
- Water-Ice

Surface Environments

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)

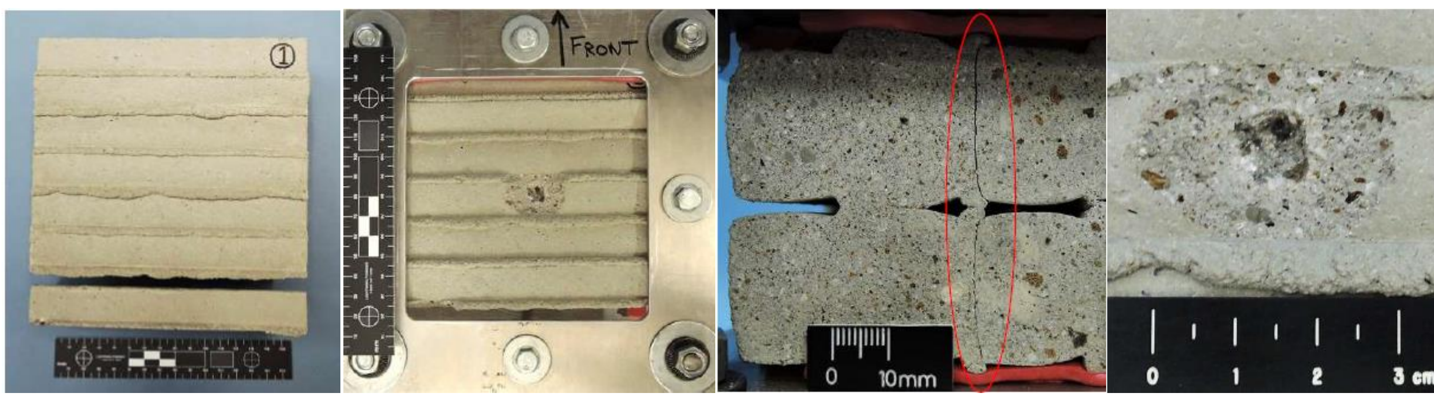
http://nssdc.gsfc.nasa.gov/planetary/planetfact.html

Hypervelocity Impact Results

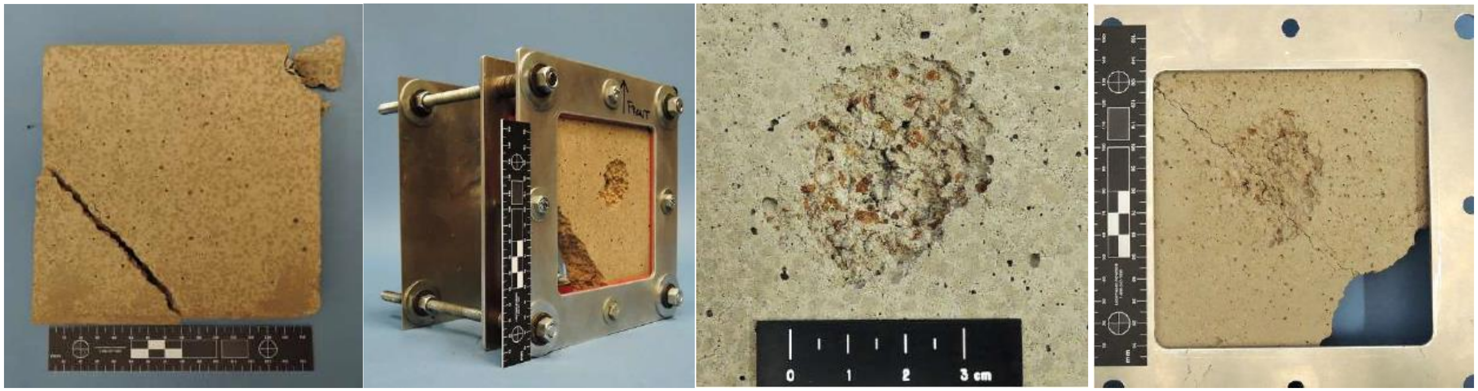


JSC Mars-1A
OPC
Stucco Mix
Water

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

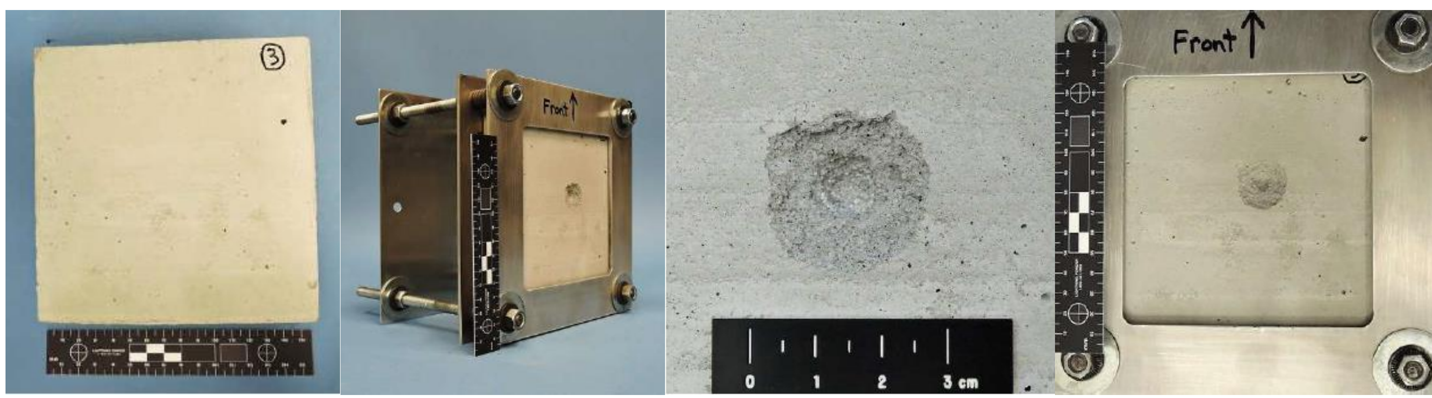


Hypervelocity Impact Results



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

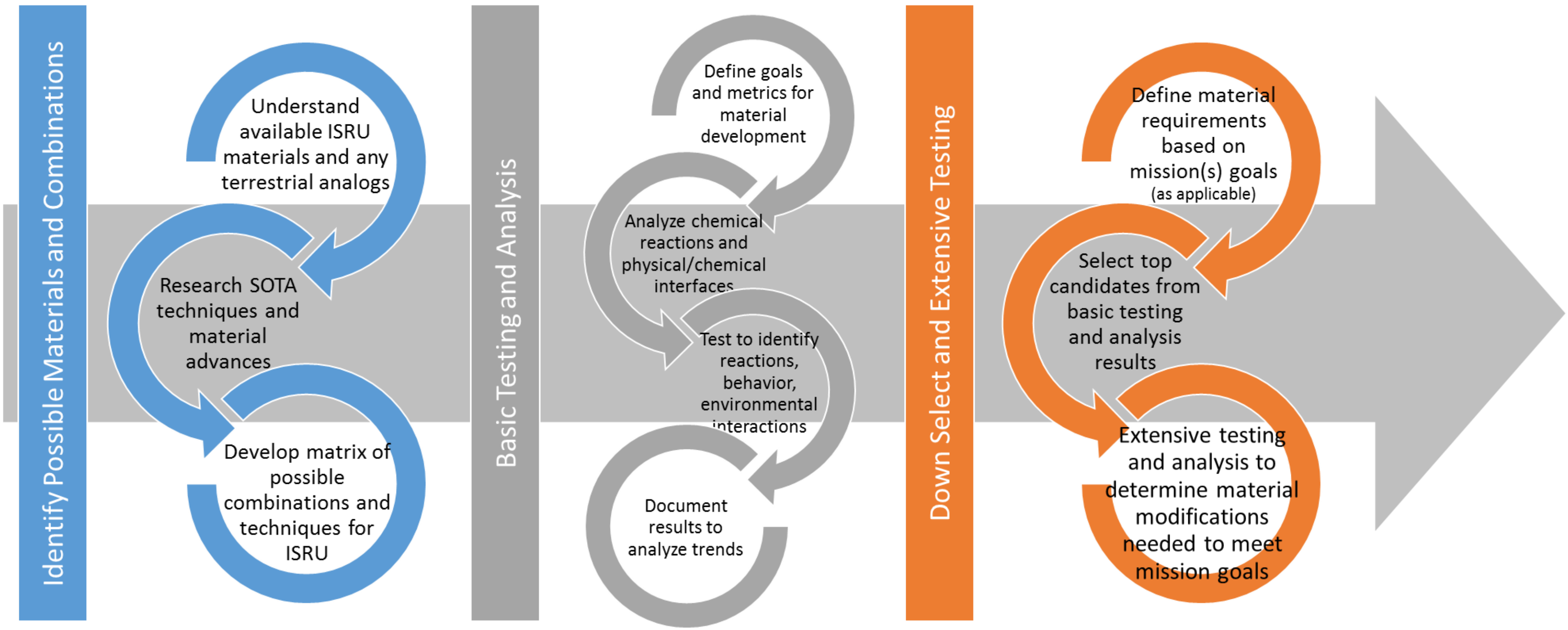
JSC-1A
OPC
Stucco Mix
Water



Future Mixes

- Continue Sorel cement research
- Sodium Silicate
  - Center Innovation Fund work at MSFC
- Carbon-based and other silica-based polymers
  - Producing polymers from the atmosphere and commonly available materials
- Catering to landing site(s) selected by NASA
  - Monitoring the Landing Site / Exploration Zone Workshops for Human Missions to the Surface of Mars
  - Increased reconnaissance of specific locations on Mars
  - Greater assessment of available resources
- Establish an Artificial Neural Network to help optimize mixes

Down-Selecting Materials



Spin-Offs

- Increase in in-situ resource utilization planetary science research to identify and quantify the available materials at landing sites
- Continued materials development
  - Applications of binder production in terrestrial cement industries
- Additive construction technology / lessons learned
  - Continued improvements to nozzle and continuous feedstock delivery technology
    - Hose management concepts
  - Robust design of a gantry system or large 3D printer that is deployable
    - Both NASA and USACE have transportation requirements
- Commercialization of additive construction technology
- 3D Printed Habitat Challenge http://www.bradley.edu/challenge/