Selection, Production and Properties of Regolith Polymer Composite for Lunar Construction

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REACT

Relevant Environment Additive Construction Technology

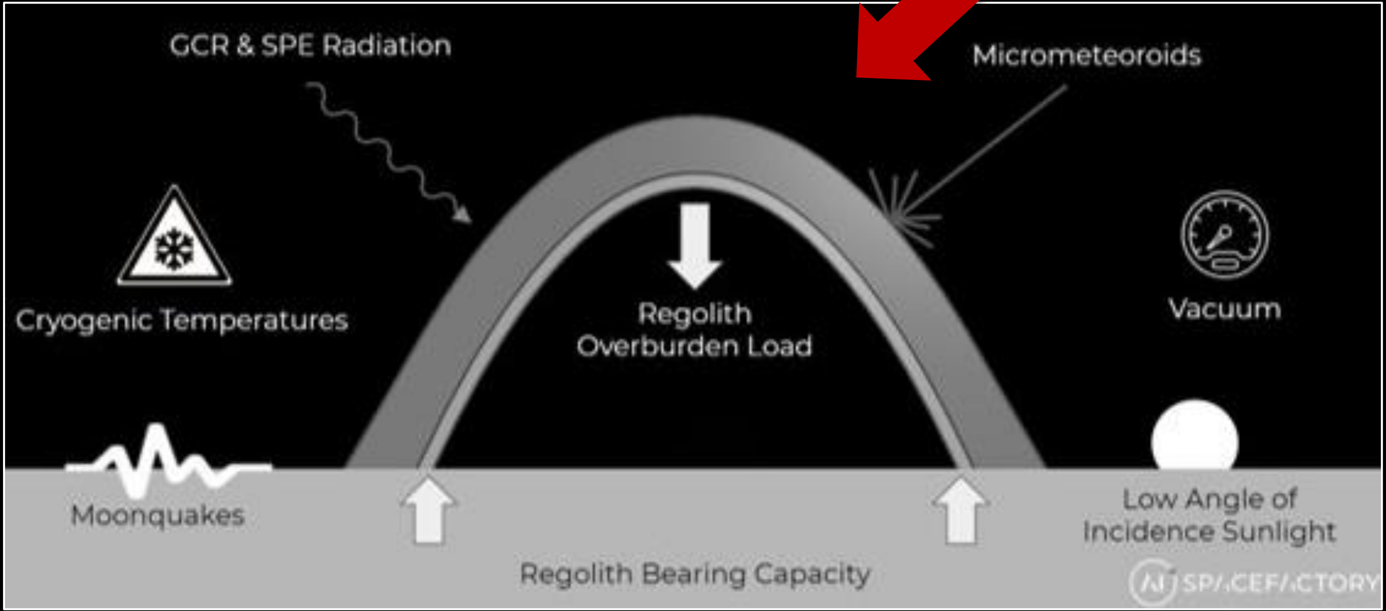
SWAMP WORKS
NASA KENNEDY SPACE CENTER

SPACEFACTORY

LERA
Consulting Structural Engineers

Project Origins and Intent

SpaceFactory won NASA' 3D Printed Habitat Centennial Challenge



Intent is to mature this technology by exercising it in simulated lunar conditions and building a sub-scale unpressurized protective shelter

Goals and Objectives

Goal	To demonstrate construction of a civil engineered, unpressurized, protective shelter in simulated Lunar Dirty Thermal Vacuum (DTVAC) conditions using Regolith-Polymer Composites (RPC) in a Fused Granular Fabrication (FGF) additive process

Objective #1	Develop regolith-polymer composites and characterize material/strength properties achieved under DTVAC
Objective #2	Develop the shelter's architectural and structural design based on protective needs, design criteria established from environmental conditions, and validation/optimization using terrestrial industry techniques
Objective #3	Demonstrate additive construction of a sub-scale protective shelter in simulated lunar conditions

Polymer Selection Summary

NASA

Lunar environmental challenges	Material selection considerations
Thermal extremes (-212 to -91 °C at 85° latitude)	Mechanical strength across thermal range, thermal cycling fatigue, melting point, glass transition temp., coefficient of thermal expansion
Hard vacuum (10-12 to 10-14 torr)	Mass loss, off gassing
Galactic cosmic ray and solar particle event radiation	Material degradation
Meteoroid impacts	Impact strength

Candidate Polymer	Benefits	Drawbacks
Polyetherimide (PEI) (e.g., Ultem)	Superior mechanical properties, flight heritage (MISSE 9 & 10 test coupons, COSMIC-2 antenna support), low off gassing and cryogenic toughness	Expensive, high processing temperature (400 C)
Polypropylene (PP)	Terrestrial business use case, low cost, minimal moisture absorption, recycling of space packaging material	Average mechanical properties, high CTE, not formulated for space environments, no spaceflight heritage
Polylactic Acid (PLA)	Superior "printability", low cost, biopolymer with potential for ISRU through nonedible plant mass or bioremediation processes, cryogenic tensile strength comparable to PEI	Low heat distortion temp (134 C), average mechanical properties, not formulated for space environments, no spaceflight heritage

Regolith Simulant Selection Summary

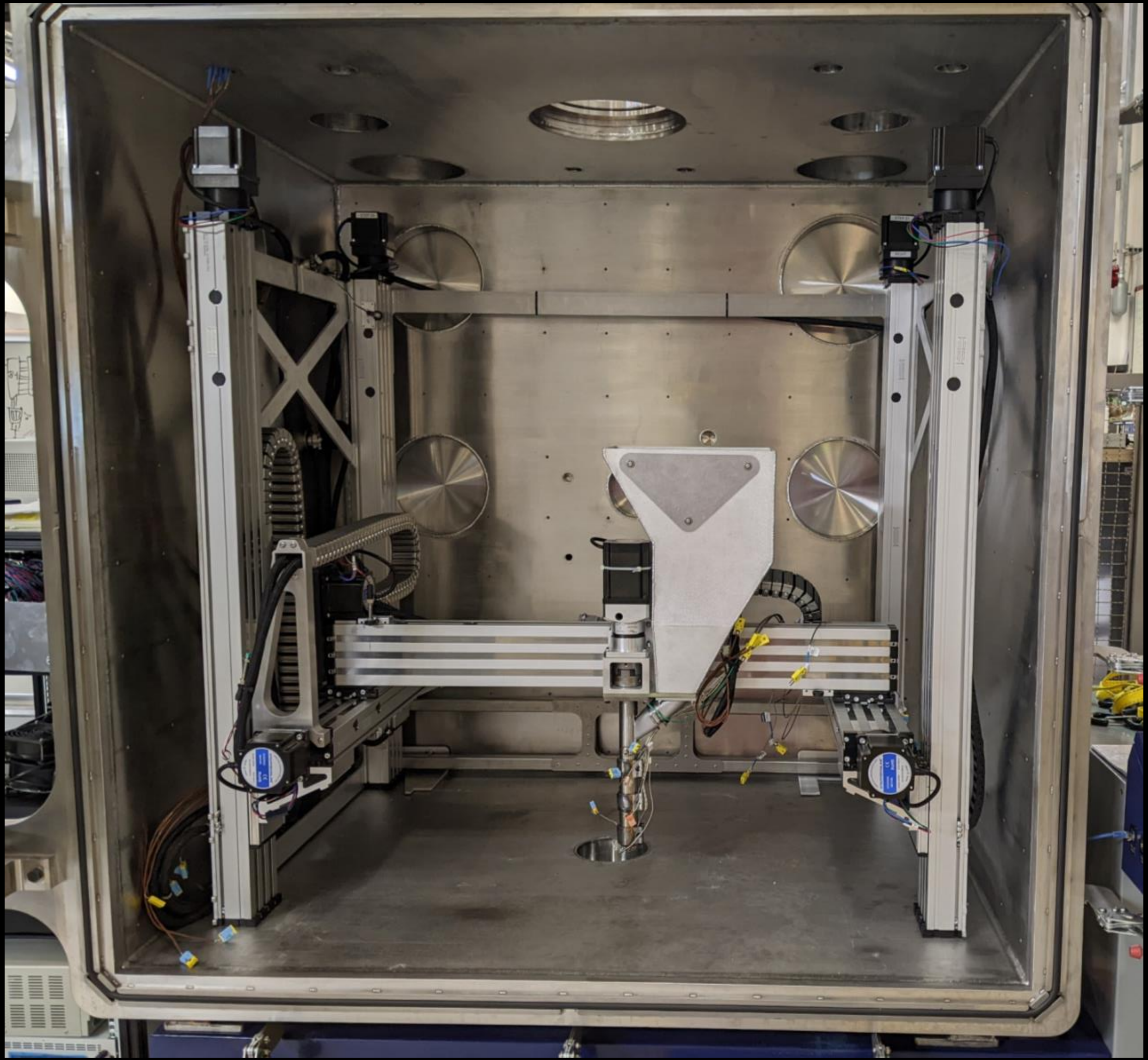
Simulant	Benefits	Drawbacks
Black Point -1 (BP-1)	Comparable particle size distribution and geotechnical properties to lunar regolith, low-cost and abundantly available at Swamp Works	Mare simulant that is basalt based. No agglutinates, nanophase iron, or solar wind deposited elements. Low glass content
Lunar Highlands Simulant – 1 (LHS-1)	Highlands simulant composed of anorthosite (74.4 wt.%) and glass-rich basalt (24.7 wt.%). Comparable particle size distribution and mineralogy to highlands regolith	No agglutinates, nanophase iron, or solar wind deposited elements. Low glass content

Regolith Polymer Composite Formulations

Testing Phase	Simulant	Polymer	Additive	Mass Percentage (wt%)	Purpose
Alpha	BP-1	PP	Compatibilizer*	50:48:2	Initial vacuum printing feasibility testing
	BP-1	PP	-	50:50	
	BP-1	PLA	-	50:50	
Beta	BP-1	PLA	-	70:30	Evaluate effects of high simulant loading
	BP-1	PLA	-	80:20	
	BP-1	PLA	-	85:15	
	BP-1	PLA	Processing Aid**	80:18.5:1.5	Evaluate effects of a flow improver additive
	LHS-1	PLA	-	80:20	Evaluate effects of a highlands simulant

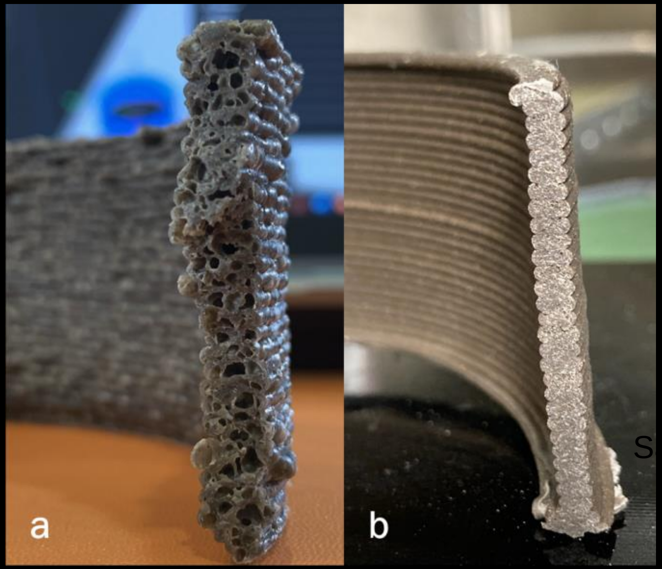
*BYK, SCONA TPPP 9212 GA
**CAI Performance, CP-L01

RPC Production and Sample Construction

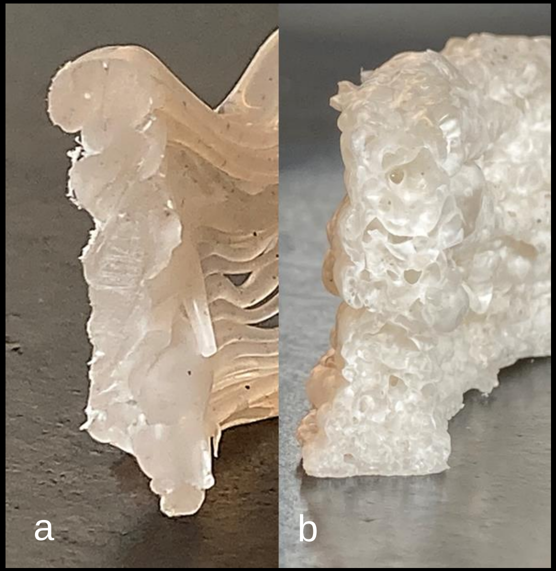


Alpha Initial Feasibility Tests

RPC is printed at 0.250 torr on a heated build plate



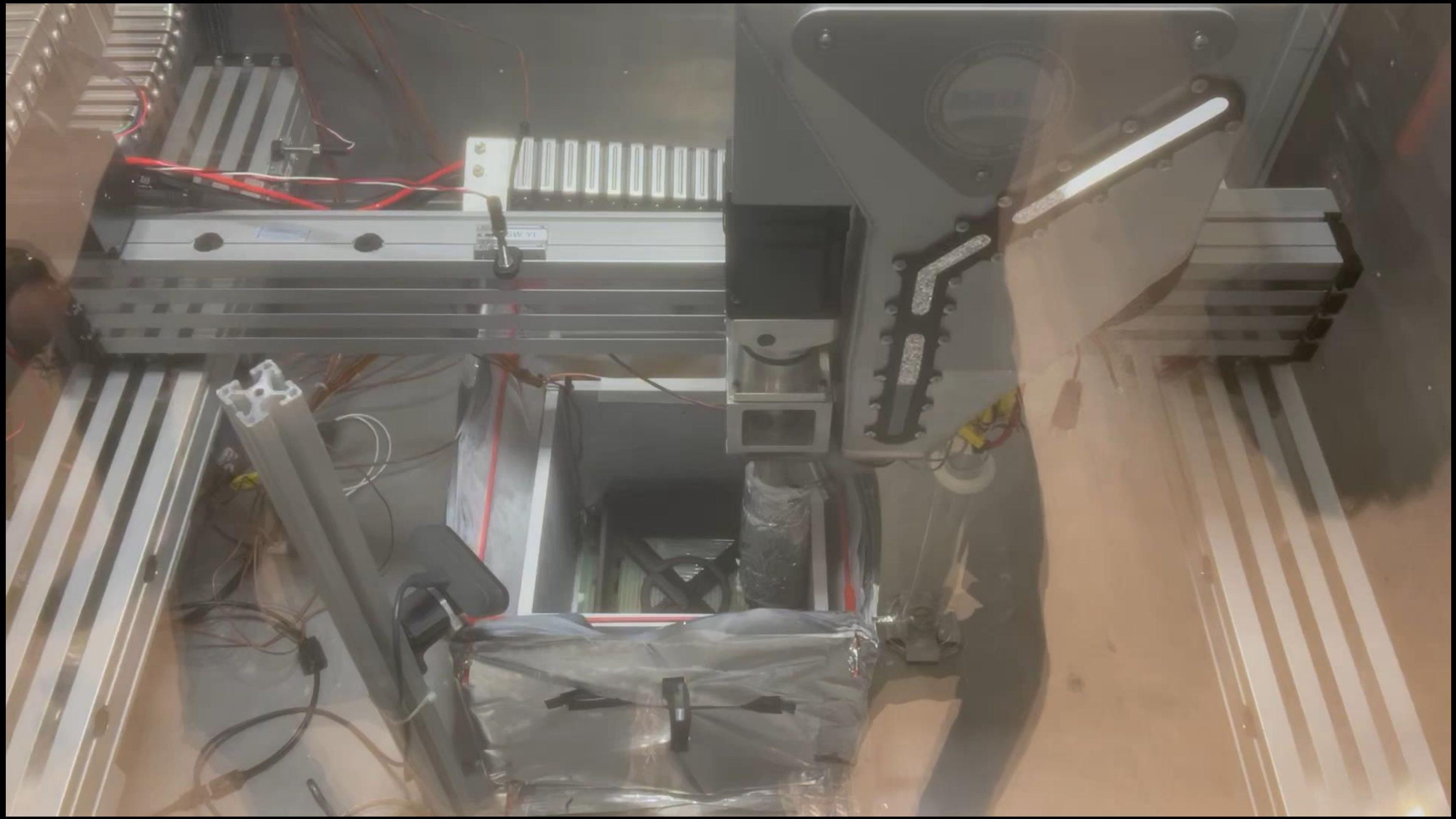
50:50 wt% BP-1:PP (a), and BP-1:PLA (b)



PP neat (a), and PP: Compatibilizer (b)

RPC pellets are produced on a compounding extruder

Beta Test Sample Construction



Test samples are printed in TVAC. A thermal shroud was kept below -190C. Vacuum pressure started at ~10-3 torr ends at ~0.8 torr likely due to water sublimation off the shroud when warmed by the extruder and printed structure

Printed test samples prior to water-jetting

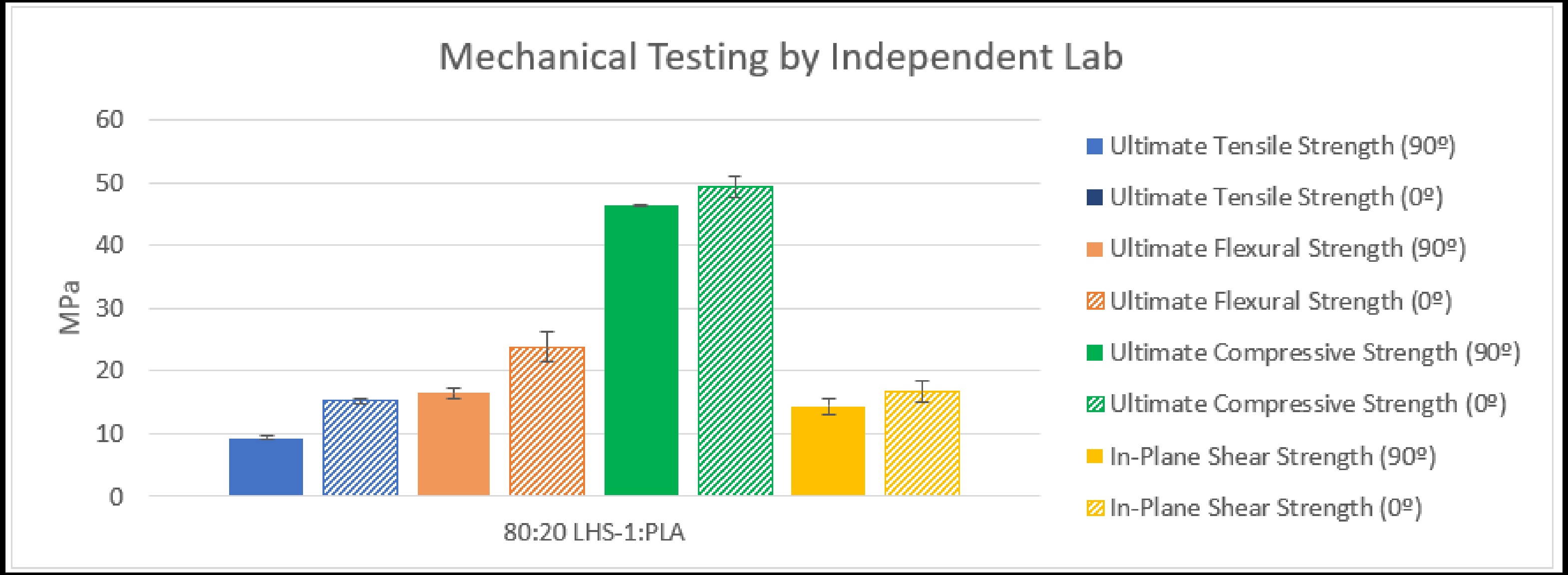
Achieved Mixture Ratios

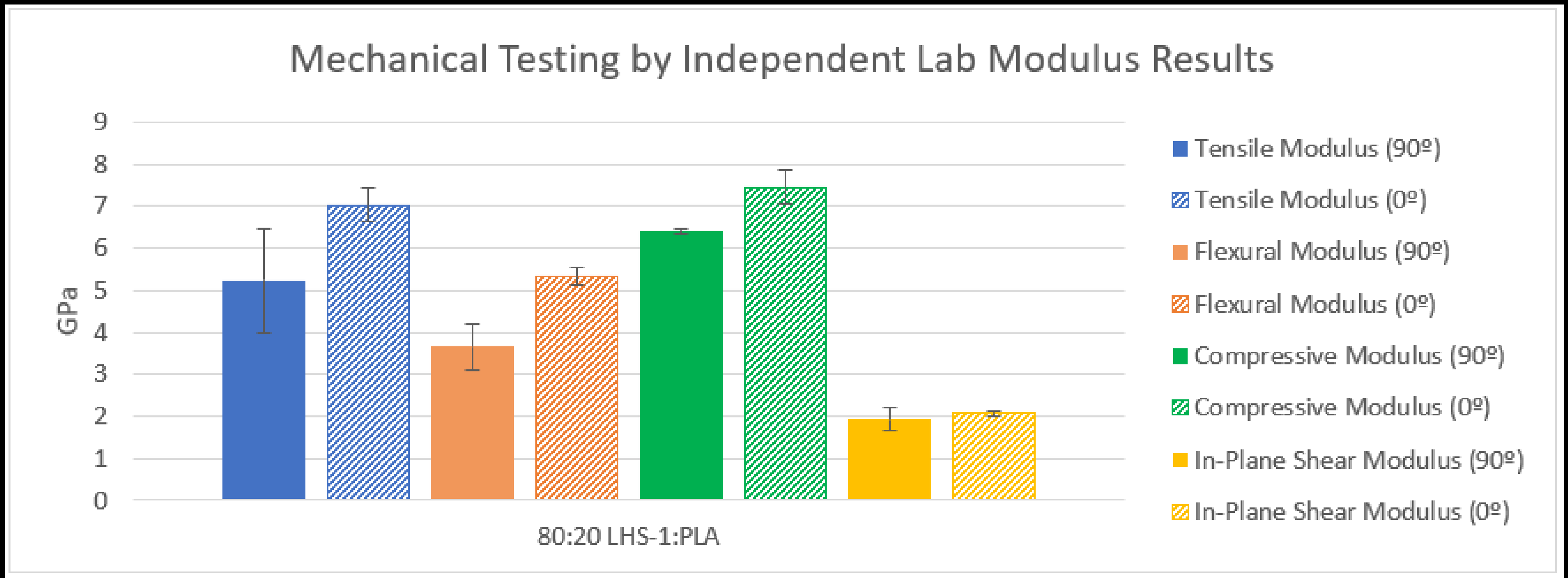
Composition	Target wt.% Ratio	Actual wt.% Ratio, TGA	Actual wt.% Ratio, Ash Test	Averaged % Deviation from Target
BP-1: PLA pellet	70:30	61:39	62:38	12.3
BP-1: PLA pellet	80:20	70:30	-	12.5
BP-1: PLA: CP-L01 pellet	80:18.5:1.5	72:28*	71:29*	8.7
LHS-1: PLA pellet	80:20	75:25	74:26	7.0
BP-1: PLA pellet	85:15	78:22	78:22	8.5

*CP-L01 is consumed during compounding

- Results were similar for samples printed in TVAC and ambient conditions
- Gravimetric feeders would reduce the deviations from target

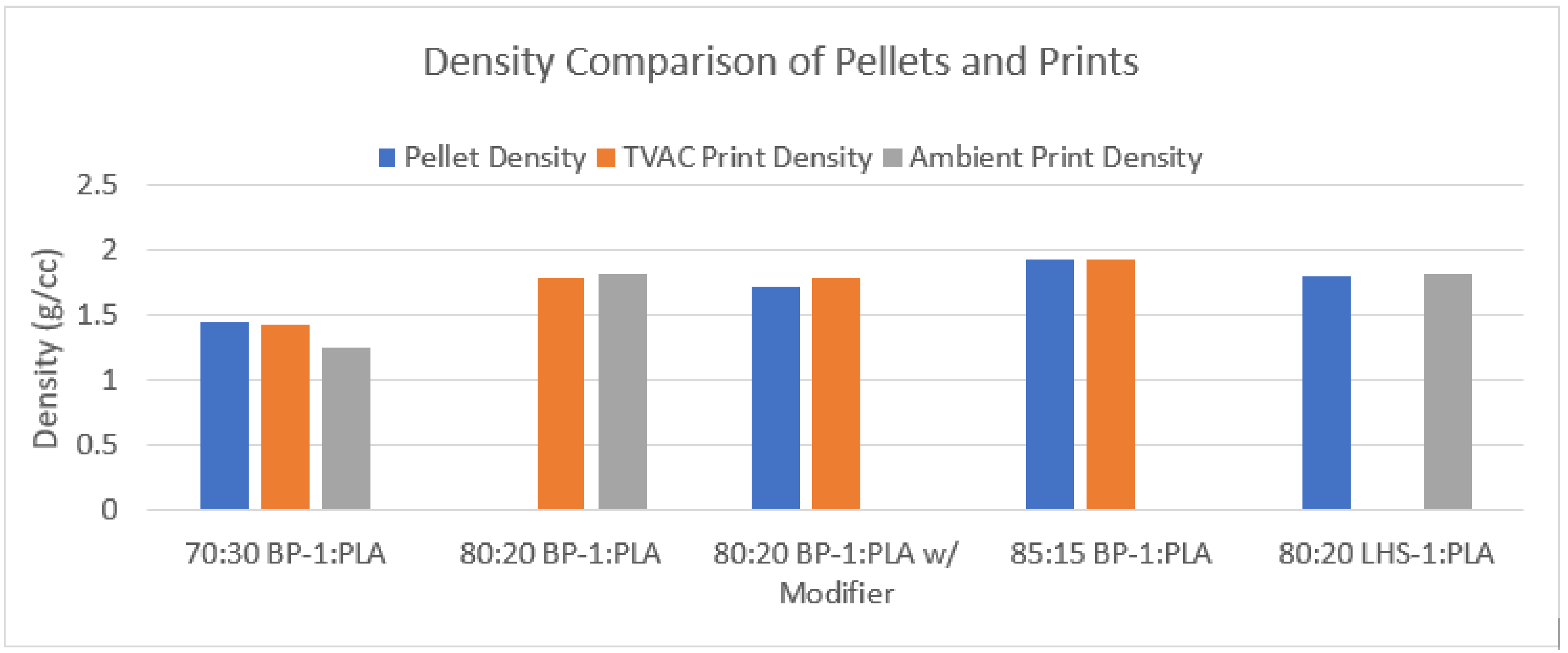
Strength and Modulus Results





- Initial tests showed that 80:20 LHS-1:PLA was superior in flexural properties
- Anisotropic behavior, average used for LINA structural design
- 80:20 LHS-1: PLA Properties:
  - Flexural Modulus = 5.3 Gpa @ 0˚
  - Flexural Strength = 24 MPa @ 0˚
- Typical lumber properties
  - Flexural modulus of 6-10 GPa
  - Flexural strength of 4-8 Mpa
- Typical unreinforced concrete:
  - Flexural strength 3-5 GPa.
- Potentially suitable for lunar construction
- High performance polymers will likely improve performance
- <u>Mechanical properties across the expected lunar thermal range are necessary</u>

Density Comparison



- Volume was measured via pycnometer and displacement. The pycnometer values appeared to be in error, so displacement densities were used whenever possible.
- Similar density of pellets, ambient prints and TVAC prints show that the environmental conditions do not have a significant effect
- A density of 1.8g/cc was used for LINA structural design

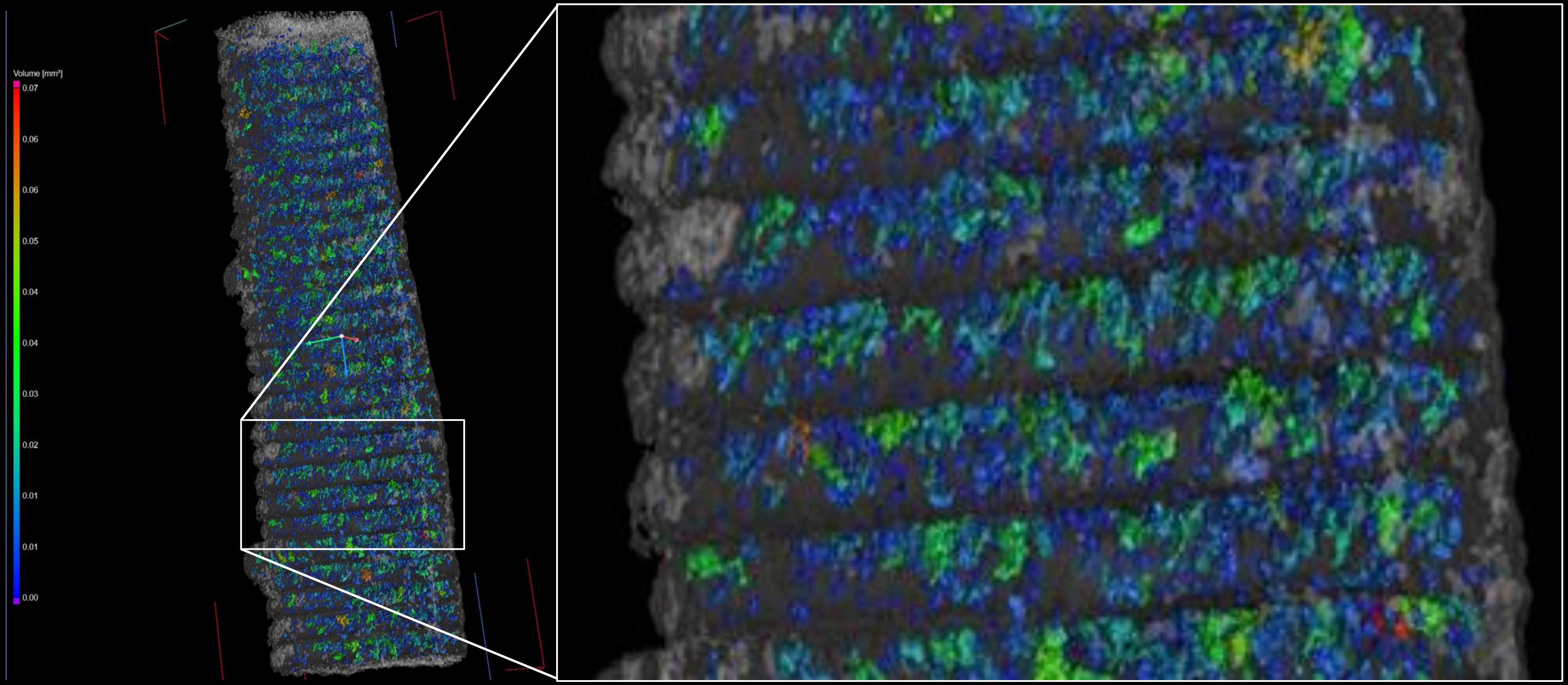
Porosity

Composition Type	Pellet Porosity (%)	Ambient Print Porosity (%)	TVAC Print Porosity (%)	Ambient Print CT-Scan Porosity (%)	TVAC Print CT-Scan Porosity (%)
70:30 BP-1: PLA	25.1	-	25.8	-	2.48
80:20 BP-1: PLA	24.1	11.3	13.1	1.64	2.49
80:18.5:1.5 BP-1: PLA: CP-L01	16.6	-	14.1	-	2.39
80:20 LHS-1: PLA	13.8	15.1	8.8*	0.76	1.24
85:15 BP-1: PLA	11.6	-	11.6	-	1.94

*Density via pycnometer

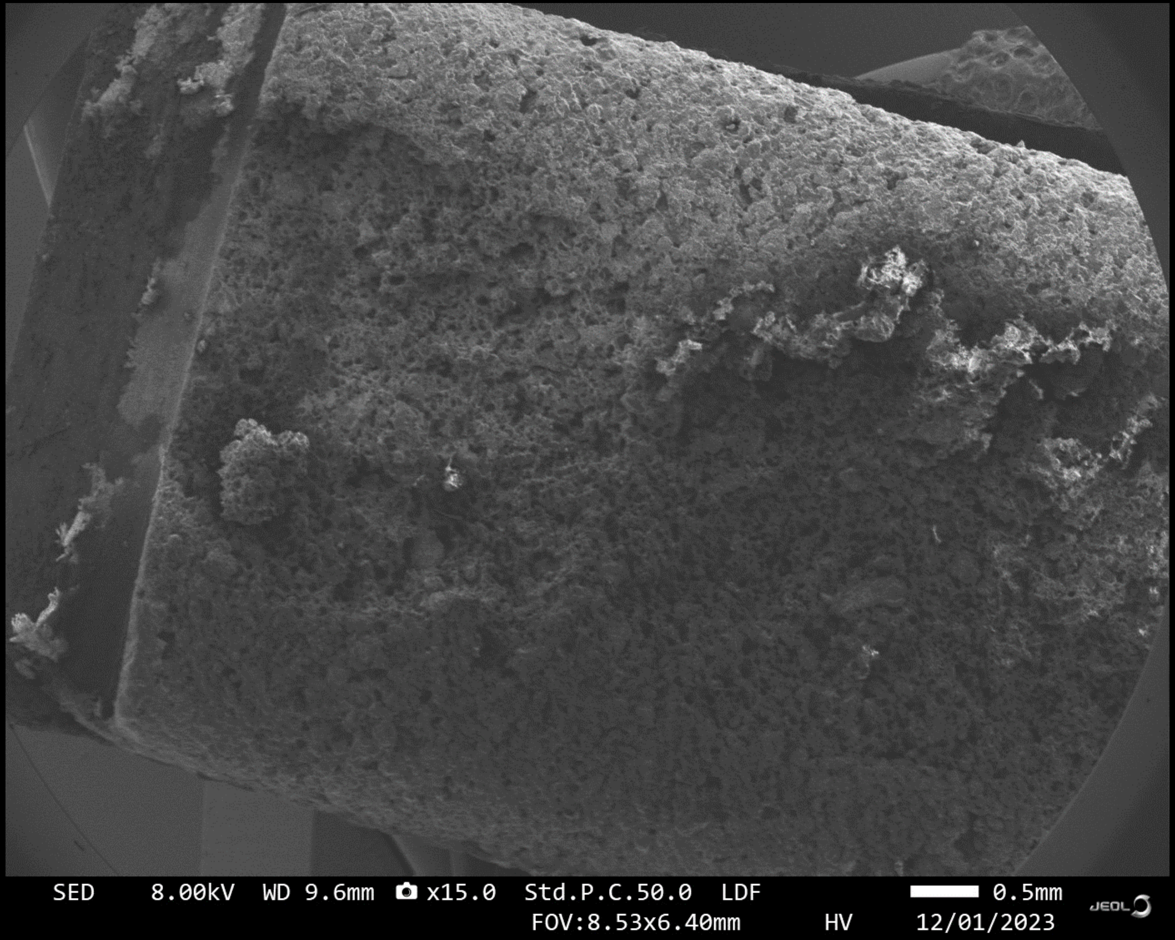
- Two methods of determining porosity were used:
  - Calculated from the theoretical and measured densities
  - CT-Scan
- The two methods produced significantly different results, the true porosity value is likely in-between
- Most of the calculated porosity values showed agreement across pellet, ambient print and TVAC print forms indicating that the form and environment had little effect
- CT-Scan data showed a trend of increasing porosity from ambient to TVAC print indicating that vacuum may have induced some porosity

Porosity Spatial Distribution

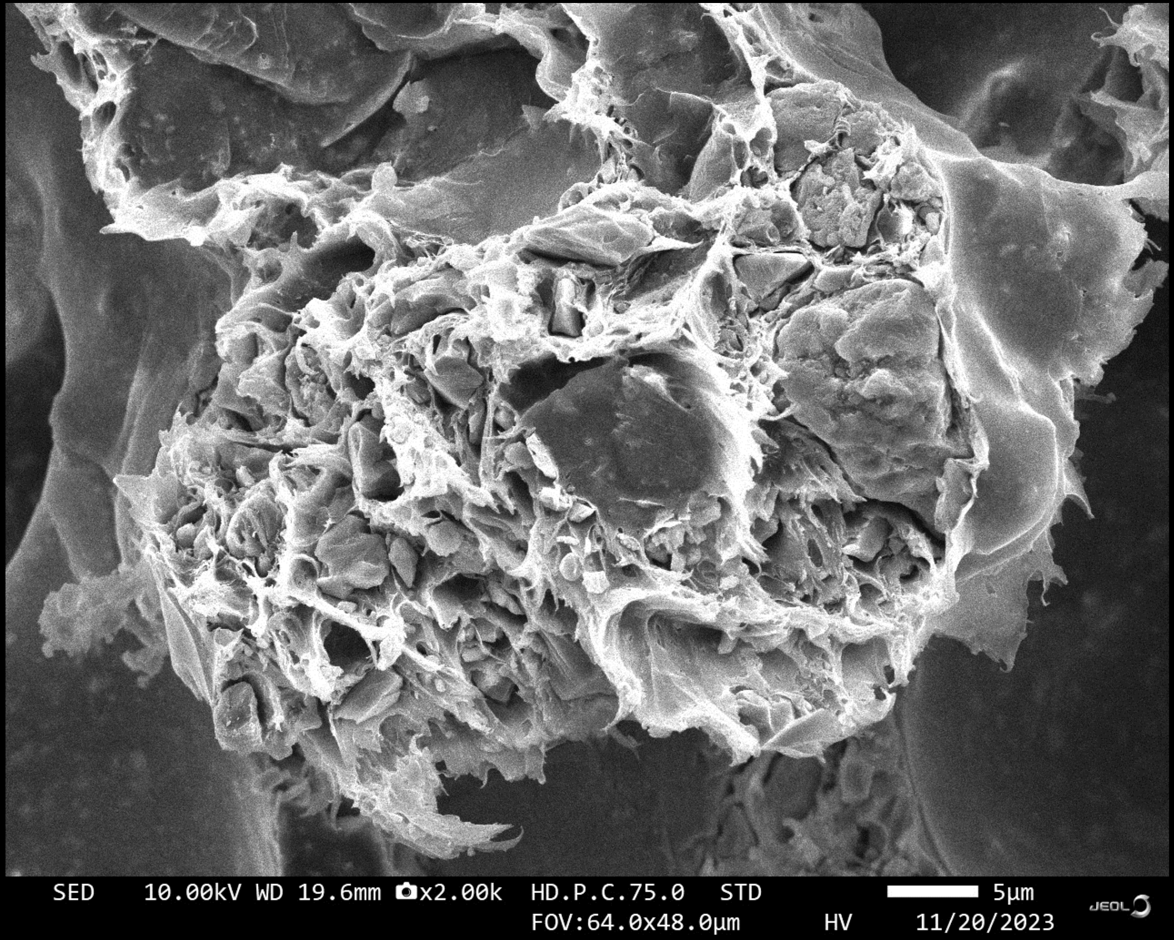


- CT-Scan of a 70:30 BP-1: PLA sample
  - The vacuum pressure rises as the print time and height increase, but there is not a clear reduction in porosity along the height. This indicates that porosity may not be a function of vacuum pressure
  - Porosity appears less dense at the bottom of each layer indicating that the deposition process has an effect

Microscopy

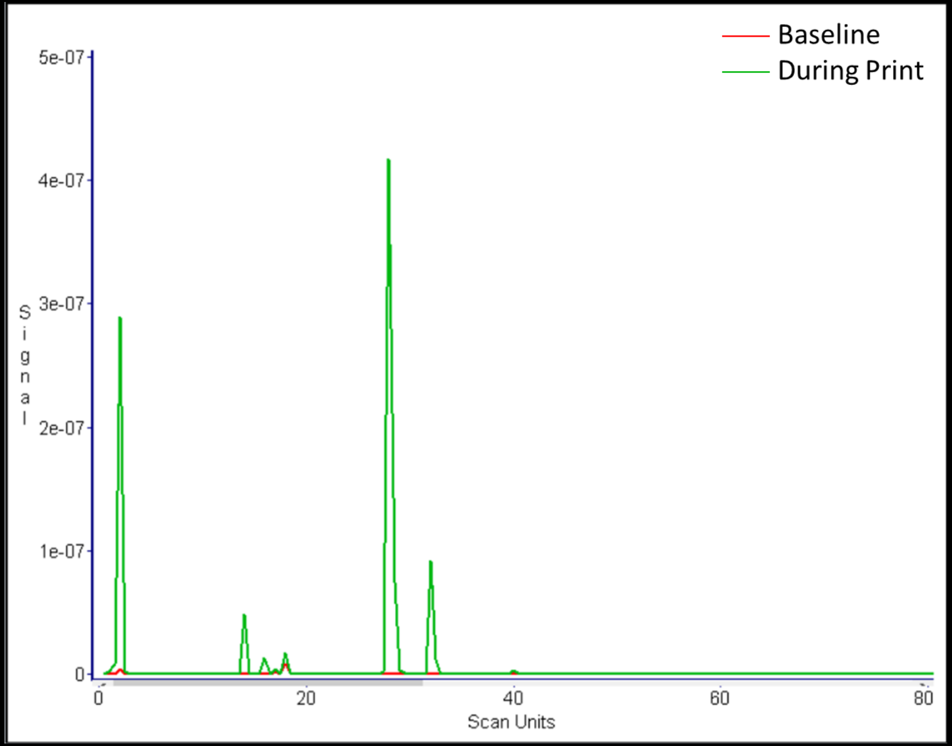


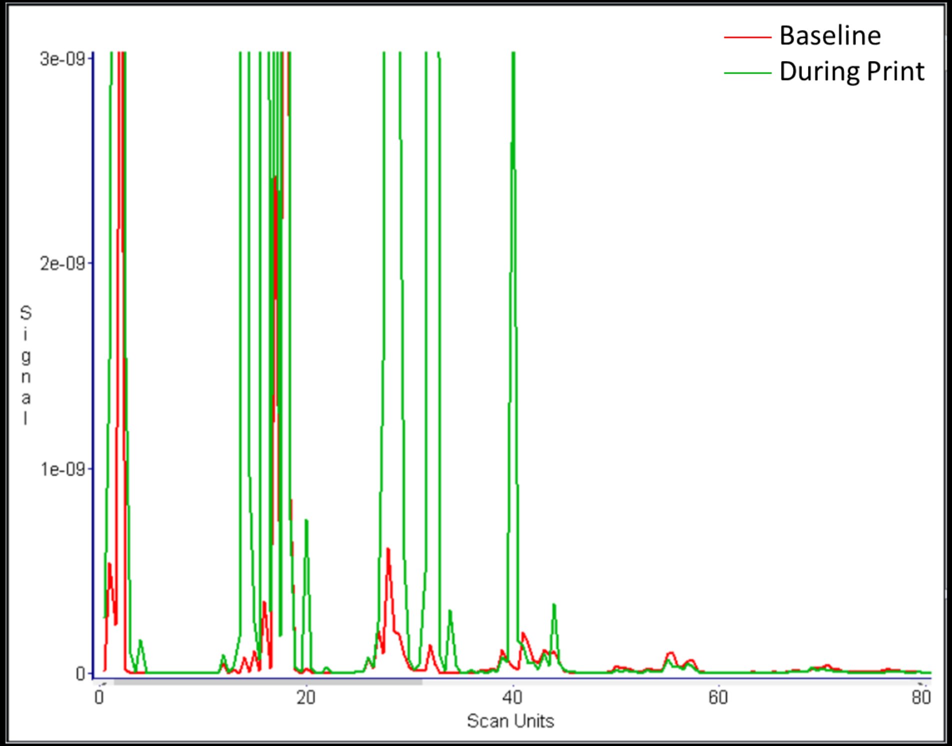
80:20 BP-1: PLA tensile fracture surface parallel to layers showing failure at a layer interface



85:15 BP-1: PLA ductile tearing of PLA and delamination at the polymer-regolith interface

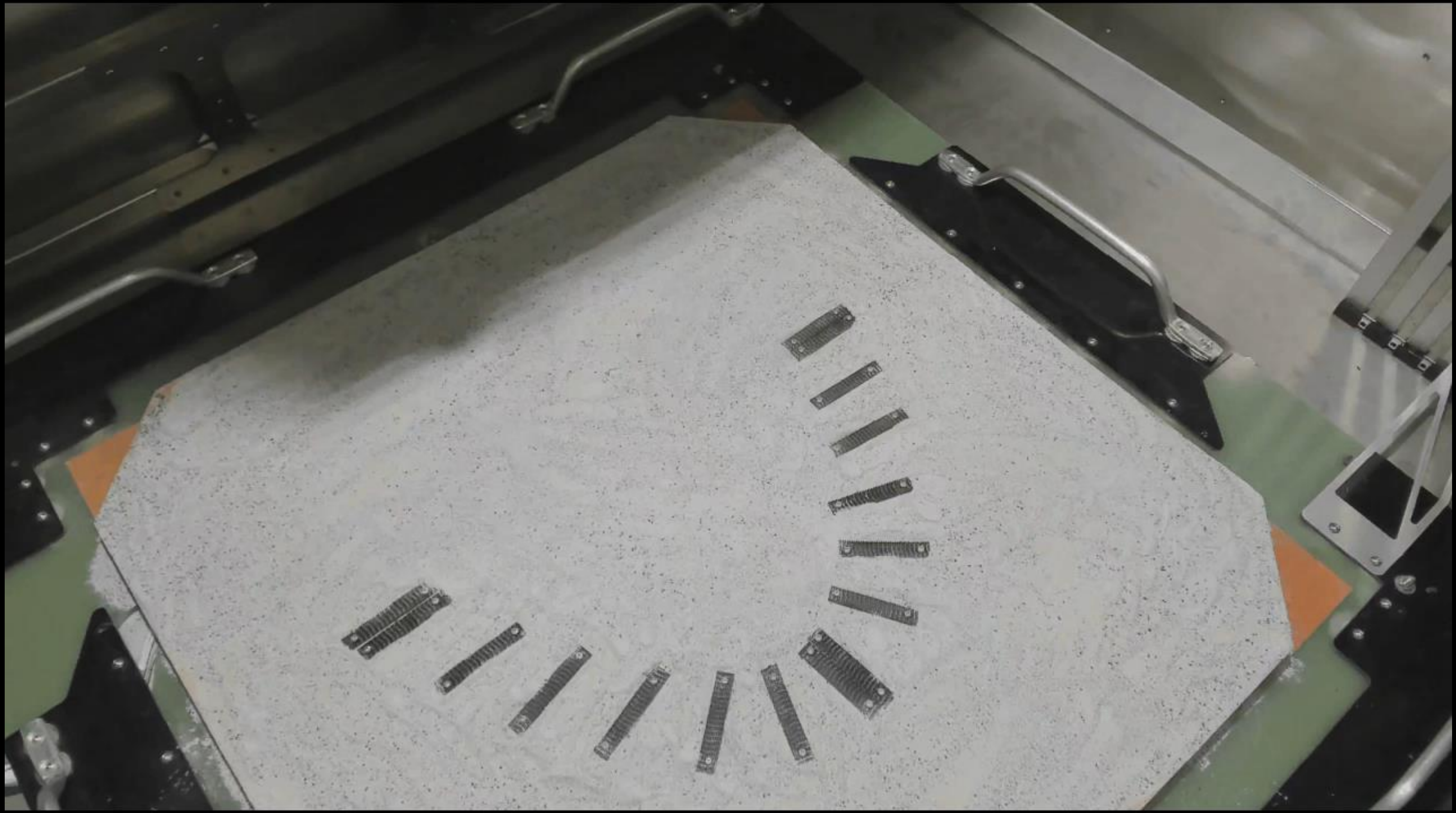
Residual Gas Analysis of 80:20 LHS-1:PLA





- Major (left) and minor (right) peaks recorded before (orange) and during (green) TVAC printing
- Peaks at nitrogen (7, 14, 28 amu), oxygen (8, 16, 32 amu), carbon dioxide (44 amu), and water (18 amu) both before and during the printing process indicate the presence of air.
- Air could be from a known leak. Water could be from moisture adsorbed to the chamber walls.
- The peak at 28 amu (typically nitrogen) is higher in ratio to the oxygen peak at 32 amu than air. This may indicate that another compound, perhaps carbon monoxide (CO) is contributing to 28 amu.

Lunar Infrastructure Asset (LINA) Construction



Second generation protective shelter is printed at ~10^{-4} torr on LHS-1 Simulant

First generation shelter design

Second generation shelter design

Lunar Infrastructure Asset (LINA)

Conclusions

- Basic feasibility of Regolith Polymer Composite (RPC) construction materials and systems was proven and is approaching TRL 5
- Need to explore polymer trade space and use higher fidelity simulants
- Remaining tests: strength properties across lunar temp range, thermal fatigue, vacuum mass loss
- Assess potential lunar environmental impacts/contamination

- Highest TRL ISRU based construction technology based on TVAC demonstration/characterization and large-scale demonstration at the Centennial Challenge
- Recommend further development towards a small scale CLPS demonstration mission

ARTEMIS