Structural Members Produced From Unrefined Lunar Regolith

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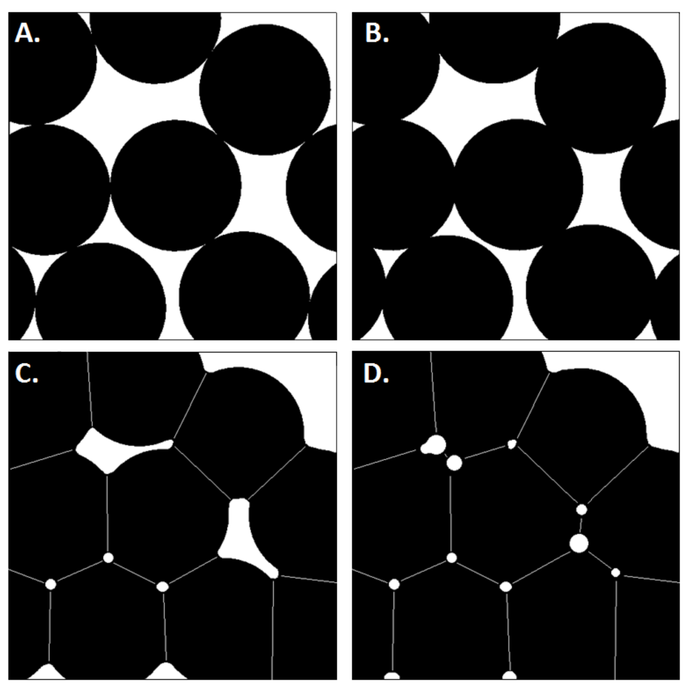
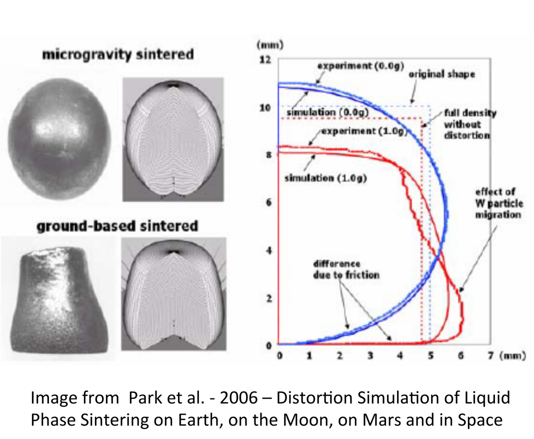
Introduction:

The potential of utilizing lunar regolith as the raw material for manufacturing structural members is very appealing for future exploration of the Moon [1,2]. Future lunar missions will depend on in-situ resource utilization (ISRU) for structural components. Manufacturing structural components directly from unrefined lunar regolith would have the advantage of needing less specialized material processing equipment in comparison with refining the lunar regolith for its raw elements. Sintering lunar regolith has been proposed as a structural material by previous researchers but has not been evaluated for its elastic material properties. Sintering can be a highly variable process and only with the material constants can a structure be designed from this material.



Phases of sintering:

A. Adhesion, rearrangement and repacking.
B. Initial-stage neck growth.
C. Intermediate stage.
D. Final stage. The grains are black, white is empty space or pores and the white lines are grain boundaries.

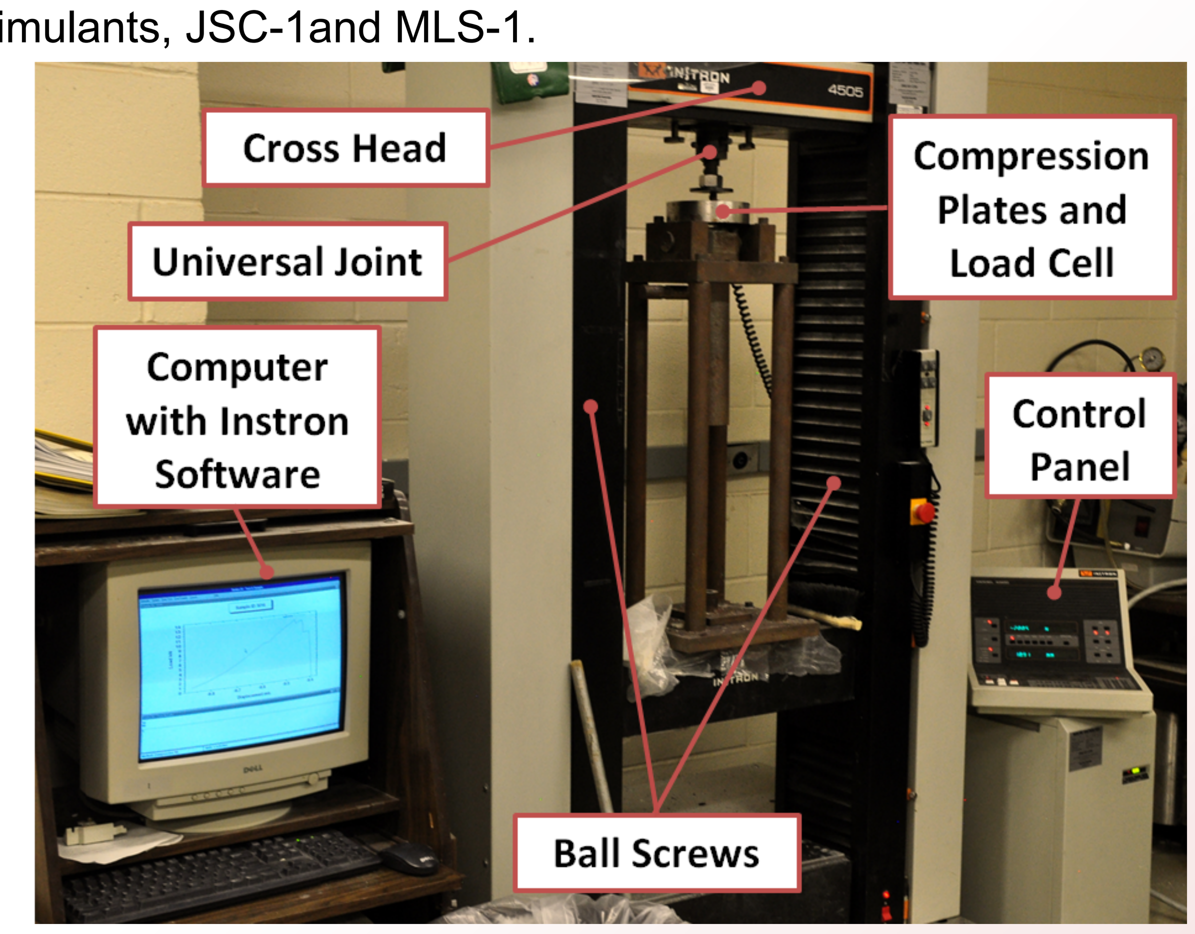


Attribute	Terrestrial Gravity	Microgravity
Densification	Yes	No
Distortion	Some	Considerable
Porosity	Little	Considerable
Pore Size	Small	Large
Buoyancy	Yes	No
Contiguity	High	Low

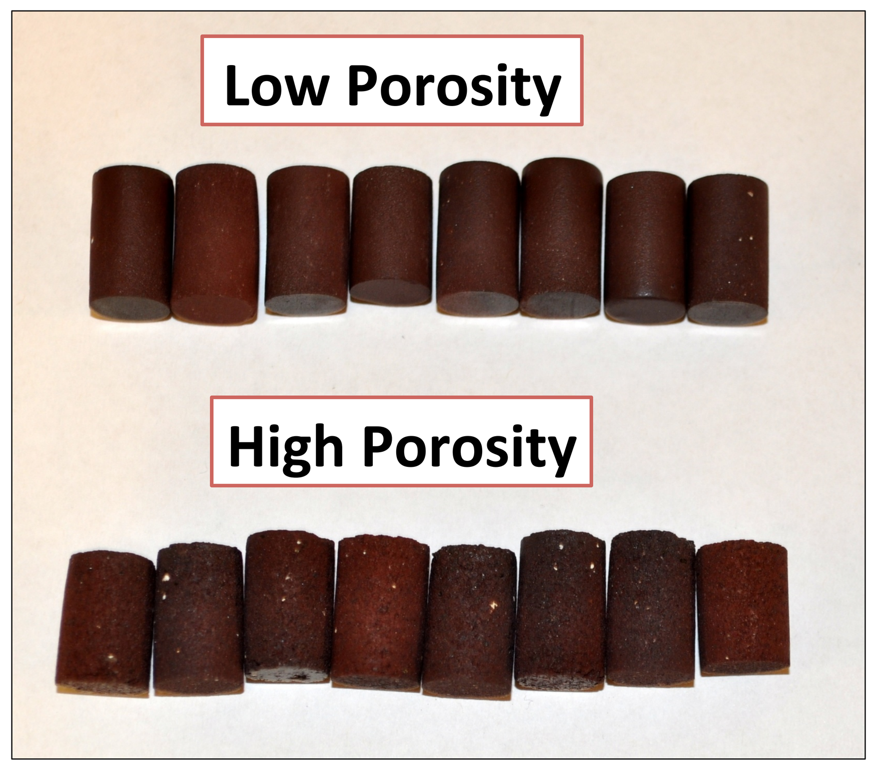
Summary of sintering differences between terrestrial gravity and microgravity conditions from German (2003). It would be expected that sintering on the Moon would produce conditions between terrestrial gravity and microgravity.

Background:

Sintering of actual lunar regolith has been accomplished by Taylor and Meek [3] using microwaves. However, there is not enough lunar regolith available for destructive testing to accurately quantify the mechanical material properties of sintered regolith. Lunar simulant substituted for lunar regolith in experiments then becomes the commonplace. The lunar simulant JSC-1A has become the standard for researchers in the topic of structural ISRU and has been used in a multitude of structural member fabrication processes. Through a geothermic reaction produced by the inclusion of additives, JSC-1A has been used to fabricate bricks for constructing a voissoir dome as performed by Faierson et al. [4]. In addition, Balla et. al. [5] has utilized JSC-1A, filtered for particle size, as the base material in a selective laser sintering (SLS) machine to prove the simulants additive manufacturing potential. As a proof of concept, fabrication of small solid cylinders was performed and the parameters for the SLS machine were evaluated. Focusing on developing an optimal method of sintering lunar simulant, Allen, et al. [6] compared the fabrication of bricks with two unrefined simulants, JSC-1and MLS-1.



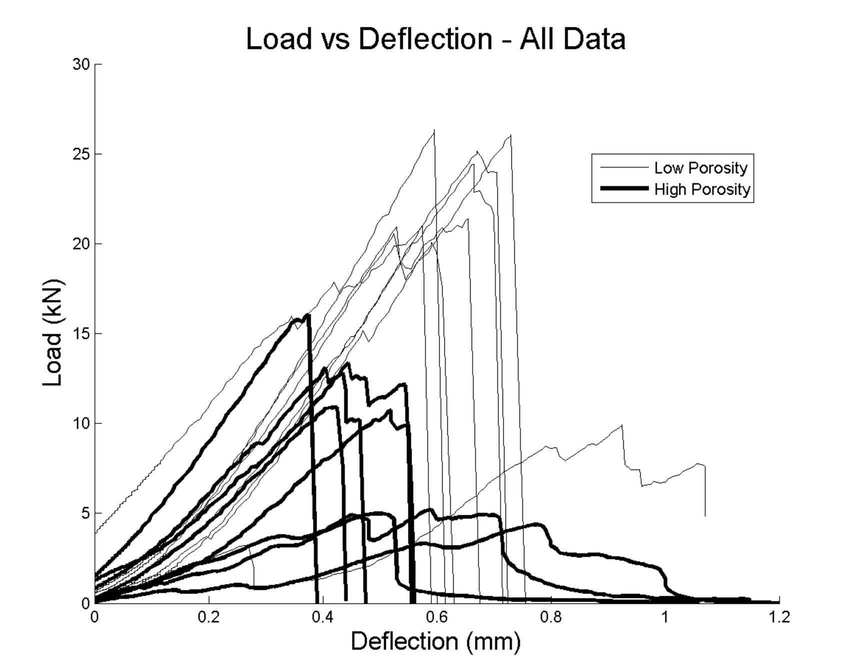
Instron Series 4500 Universal Test System



True color image of a low and high porosity sample. Samples have an approximate length of 19 mm and are 12 mm in diameter. 16 samples in total.

Test Results:

Quantification of the material properties was performed for sintered lunar regolith by testing sintered lunar regolith simulant. Two batches of sintered lunar regolith simulant, Figure 1, JSC-1A samples with porosities 1.44% and 11.78% underwent compression testing using an Instron series 4500 Universal Test System machine. Figure 2 shows the stress vs strain until failure of each specimen. Material properties were evaluated from the load vs. deflection data acquired. Stress, strain, modulus of elasticity, toughness, the compression strength, bulk modulus, Poisson's ratio and compressive strength were evaluated as a function of porosity and data were aggregated as probability density functions. The average compressive strengths of the low porosity material were 202 MPa, and 84 MPa for the high porosity material. By comparing these values with other ISRU derived structural materials, sintered lunar regolith is expected to be one of the strongest material derived from lunar sources.

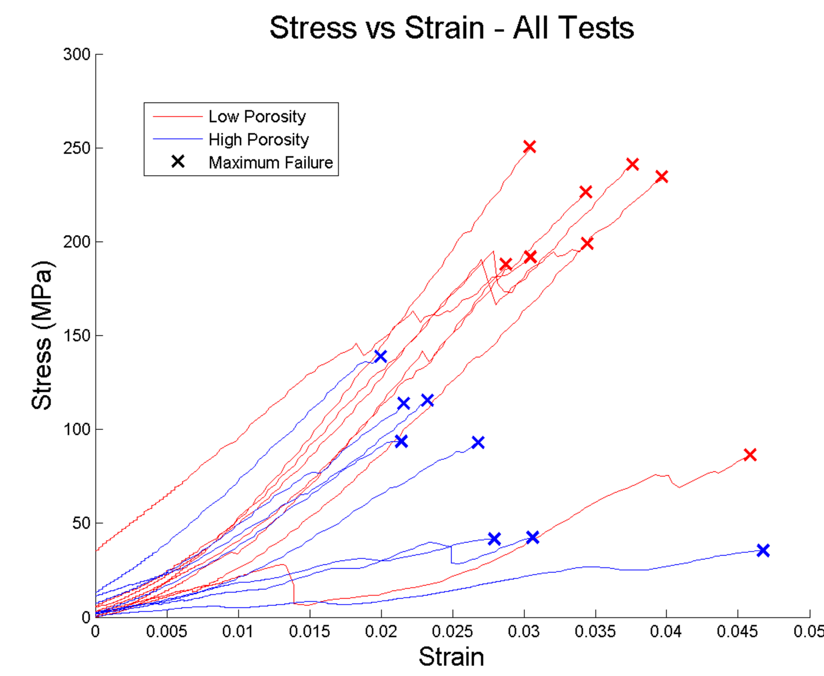


This is an overlay plot of all data from all the compression tests. It becomes evident that the low porosity samples were able to sustain the highest loading conditions where the high porosity samples were able to sustain loads about half the magnitude of the low porosity samples.

Application of data:

Our goal for the data collected and analyzed was for the purpose of designing a lunar structure or other infrastructure, such as roadways, utilizing regolith in a simple way. Summarizing our results for the low and high porosity simulant samples that can be used in preliminary structural designs. Comparing compressive strength values for five simulated lunar materials from our literature review. Three compressive strength ranges for the materials can be identified that also share similar manufacturing techniques.

Aside from the fundamental material properties, fabrication processes need to be considered as well. Reducing initial and post processing time and equipment would be greatly beneficial to making a certain material more attractive for use. All the materials discussed here depend on extracting the lunar regolith from the surface, so excavating equipment will be required regardless of lunar regolith derived ISRU. *Utilizing the regolith in its raw form has the advantage of not requiring refining of the raw minerals out of the regolith. Refining would require additional equipment for this additional step which increases transportation costs from the Earth to the Moon cost, as well as increase the complexity of manufacturing construction material on the Moon, leading to an increase in the chance of mechanical malfunction and down time of manufacturing in the lunar environment.*



The clustering of low porosity maximum failure data points becomes apparent in the ~240 MPa range where the high porosity maximum failure data points becomes apparent at ~120 MPa. Four data points were from samples which crumbled during testing, three high porosity and one low porosity samples all below the ~100 MPa value. The three high porosity samples which crumbled all had a very consistent maximum stress value.

Summary of the Experimental Sintered Samples Material Properties

Material Properties at Maximum Failure	Low Porosity All Data (n=8)		High Porosity All Data (n=8)		Units
	Mean	STD	Mean	STD	
Compressive Strength	202.3	49.0	84.3	37.0	MPa
	29.3	7.1	12.2	5.4	ksi
Bulk Modulus	5961	1693	3586	2062	MPa
	864.6	246	520.2	299	ksi
Elastic Modulus	8358*	748	5475**	782	MPa
	1212	108	794	113	ksi
Torsion Modulus	3300	-	2198	-	MPa
	479	-	319	-	ksi
Average Density†	2.6	0.1	2.2	0.1	g/cm^3
Poisson's Ratio	0.266	-	0.246	-	-

*n=6, **n=5, †From unloaded measurements

Note: n= sample size, STD = standard deviation, COV = Coefficient of Variation.

Measured Compressive Strengths for Various Lunar Resource Derived Structural Materials

	Compressive Strength (MPa)	Compressive Strength (psi)
Geothermite, simulant & aluminum[1]	10 - 18	1,450 - 2,611
Additive manufacturing, simulant & binding agent[2]	20	2,951
Lunar sulfur concrete[3]	31	4,500
Lunar concrete[4]	74	10,000
Sintered lunar simulant[5]	203 - 232	29,400 - 33,600
Sintered lunar simulant[6]	77 - 237	11,168 - 34,374

Faierson[1], Cesaretti[2], Houssam[3], Lin[4], Gualtieri[5], Indyk[6]

Conclusions:

Sixteen manufactured sintered samples of two different porosities created for this research underwent compression testing. The load and deflection were recorded and the effect of porosity on the modulus of elasticity and bulk modulus were calculated. Sintering lunar regolith simulant produces a structurally strong material that can be used as an analogue to what could be formed on the lunar surface with actual lunar regolith.

References:

[1] Benaroya, H., et al., Engineering, design, and construction of lunar bases. Journal of Aerospace Engineering, 2002.

[2] Benaroya, H. and Bernold, L. Engineering of lunar bases. Acta Astronautica, 2008.

[3] Taylor, L.A. and Meek, T.T., Microwave Sintering of Lunar Soil: Properties, Theory, and Practice, Journal of Aerospace Engineering, 2005.

[4] Faierson, E.J., et al., Demonstration of Concept for Fabrication of Lunar Physical Assets Utilizing Lunar Regolith Simulant and a Geothermite Reaction, Acta Astronautica, 2010.

[5] Balla, V.K. et al. First demonstration on direct laser fabrication of lunar regolith parts, Rapid Prototyping Journal, 2012.

[6] Allen, C.C., Graf, J.C. and McKay, D.S., Sintering Bricks on the Moon", Proceedings of the ASCE Specialty Conference (Space'94), 1994.

[7] Indyk, S.J., Structural Members Produced from Unrefined Lunar Regolith, A Structural Assessment, Masters Thesis, Department of Mechanical and Aerospace Engineering, Rutgers University, October 2015.