**sLiterature Review**

**A structural assessment of unrefined sintered lunar regolith simulant**

* Future lunar missions will depend on in-situ resource utilization (ISRU) for structural components, among other things. Sintered lunar regolith has been proposed as a structural material.
* **Two batches of sintered lunar regolith simulant JSC-1A samples, with porosities of 1.44% and 11.78%**, underwent compression testing.
* Regolith is very fine grained, and its **mean grain size ranges from 40 to 900 μ**m with most mean values being between 45 and 100 μm. Particles below 20 μm in size have also been found. Materially**, regolith contains heavy metals with many minerals common to those on Earth**. includes hard rocks and minerals such as basalt, anorthosite and olivine. Once disturbed, the **regolith is electrostatically charged** and can remain suspended 1–2 m above the surface for long periods of time. All of these properties make the **regolith a serious threat to any mechanical system**, leading to accelerated wear due to the regolith's abrasiveness.
* There have been **investigations into utilizing the lunar regolith to make concrete**. Testing of both actual lunar regolith and lunar simulant has been conducted, resulting in compressive strength measurements. Two works of note involve actual lunar material, and an additive laden lunar concrete.
  + Researchers led by Lin [1] created lunar concrete using 40 g of a sample of regolith. The sample was acquired by Apollo 16, and is from the lunar mare, the large dark basaltic plains on the Moon formed by ancient volcanic activity. **Testing of the samples found a compressive strength of 74 MPa (10,000 psi), a tensile strength of 8.3 MPa (1200 psi), a modulus of elasticity of 21,400 MPa (3.1 106 psi) and a thermal expansion coefficient of 5.4 106 cm/cm/C (2.9 106 in/in/F).**
  + Toutanji et al. [2] created cast blocks of **lunar concrete using JSC-1 mixed with sulfur powder in a 65%–35% ratio and measured a 31 MPa compressive strength**. Sulfur, previously shown to be on the Moon, is another viable ISRU option for lunar concrete.
  + Landis [9] developed refining processes that could produce several heavy metals from lunar ISRU. Aluminum, iron, calcium and magnesium were among those elements that could be reacted with fluorine. Material properties of these metals would be expected to be the same as those on Earth and depend on the quality of the refining and material processing.
  + Benaroya et al. [10] specifically **advocated the use of magnesium as an ISRU derived structural material. High strength to weight ratio, high impact resistance and vibration damping 30 times that of aluminum were cited as favorable characteristics for refining magnesium for use in structures**.
* Sintering is a thermal treatment for bonding particles into a coherent, predominantly solid structure via mass transport events that often occur at the atomic. The bonding from sintering leads to improved strength and lowers system energy. This is not to be confused with melting which results in a phase transition of the material from a solid to a liquid. For a lunar application where resources would be limited, sintering would be more efficient at producing solid material than melting, **require less energy since sintering occurs at about 50–70% of the melting temperature**, depending on the material.
* **Sixteen manufactured sintered samples of two different porosities created for this research underwent compression testing**. The loads and deflections 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**.
* We expect that **on the Moon**, **very strong 1.44% porosity sintered material is ubiquitous due to the effects of constant meteor bombardment**.
* Even the **worst performing 1.44% porosity sample performed better than the average 11.78% porosity sample set**. And even though the material may be brittle, it can hold high compressive loads even after fracture.
* The ability of porous sintered regolith to absorb micrometeorite impacts should be promising.

**A review towards the design of extraterrestrial structures: From regolith to human outposts**

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* In particular, these experiments were conducted using sulfur-based concrete, and sintered Lunar regolith simulant (JSC-1A) mixed with steel or copper powder, or even without any additives. The results showed that CC technology can indeed be combined with such materials. **The compressive strength of sintered plain regolith and mixture could reach 55.16 MPa, which is strong enough for building ET structures such as landing pads, blast walls and hangers**. Two main uses of the sintered regolith are proposed in this project:
  + (a) Regolith sintering can be carried out on the construction site for the production of the main construction material.
  + (b) **The regolith can be sintered into regular shapes such as blocks, voussoirs and bricks; then a layer of regolith bricks can be combined with sulfur concrete extrusion, a second layer of regolith bricks may be paved above the first, with a compression force applied; this combination will enhance the strength of the extraterrestrial constructions.**

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**Evaluation of Lunar Regolith Geopolymer Binder as a Radioactive Shielding Material for Space Exploration Applications**

* The geopolymer binder described in this paper (Lunamer) is a **construction material that consists of up to 98% lunar regolith**, drastically reducing the amount of material that must be carried from Earth in the event of lunar construction.
* Lunamer specimens were manufactured in the laboratory and **compressive strength results of up to 16 MPa when cast with conventional methods and 37 MPa when cast using uniaxial pressing** were obtained.

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* Radiation shielding use:

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**Indigenous Materials for Lunar Construction**

* Nearly all the materials needed for the construction and maintenance of permanent lunar bases are available on the surface of the Moon.

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* Lunar **regolith exhibits cohesion and tensile strength in the absence of moisture and cementation unlike equivalent terrestrial soils** [12]. The top layer (-15 cm) of regolith is loosely compacted fine soil particles. **Below this surface layer, the density increases rapidly with depth achieving relative densities of greater than 95% at depths below 1 meter.**
* Sintered regolith bricks and blocks:
  + Sintered regolith simulant generally has **low and highly variable mechanical strength**. The **material is highly heterogeneous** and the material properties are difficult to exactly characterize [20], Reported **values for modulus of rupture vary from 1300-2600 psi (9-18 MPa)** [18]. **Compressive strengths are about the same**. Various additives improve the strength properties somewhat.
* Lunar glasses and glass-glass composites:

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* Cast regolith (cast basalt):
  + The regolith is scooped from the surface, with any rocks larger than 18 cm (7") removed and dumped into the **furnace**. There it is **melted, tapped into a ladle, poured into molds, and cooled slowly.**
  + Vacuum melting and casting should enhance the quality of the end product. Although cast basalt is not commonly used for construction on Earth, it is manufactured and used for corrosion resistant pipes and furnace linings, so there is terrestrial experience with the material.
  + Cast basalt has **extremely high compressive strength and moderate tensile strength** (1:15 ratio). It can **easily be cast into structural elements** for ready use in prefabricated construction. Feasible shapes include beams, columns, slabs, shells, arch segments, blocks and cylinders.

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* + **Production of cast regolith is energy intensive because of its high melting poin**t. The estimated energy consumption is 360 kWh/MT. If a 100 kW power supply is available then 8 metric tons (MT) could be melted in a 29 hr period. This estimate includes losses due to furnace inefficiencies
* Lunar concrete
  + Casting of concrete into structural elements also requires extensive formwork. Furthermore, **lunar concrete cannot be cast in a vacuum. It has to be cast and cured in a pressurized environment.**

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* Comparison between proposed materials:

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**The technology of lunar regolith environment construction on Earth**

* Although advances in investigating and simulating lunar regolith have achieved unprecedented progress, **producing simulated lunar regolith environment on Earth with adequate fidelity remains challenging**.
* Taking inspiration from tofu making procedure, this work presents a comprehensive methodology for LRE construction. **The outgassing rate of LRS provides reference for LRE simulation and makes the vacuum realization of LRS calculable**. **Convection and conduction coupling mechanism demonstrates the feasibility to estimate the heat transfer of LRS under any pressure and temperature**. Engineering demonstration of penetration in LRE produced by the methodology indicates the possibility of its future applications in planetary exploration technologies.

**An ISRU-based architecture for Human Habitats on Mars; the 'Lava Hive' concept**

* The habitat concept is based on a hybrid approach, with structural elements of a central habitat arriving from Earth conventionally, while an additive manufacturing (AM) process is used in situ to expand the central habitat workspace using locally sourced construction material, namely Martian regolith soil and sand.
* Lava Hive is a modular additive manufactured Martian habitat concept using a proposed novel ‘lava-casting’ construction technique, utilizing recycled spacecraft materials and structures, and represents a Class III ISRU derived structure as defined by NASA

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* The material within these Aeolian dunes and beds are well understood in terms of their particle size distributions from thermal inertia measurements (500 ± 100 µm, medium to coarse sand
* The utility rovers deployed will identify and collect from the loose regolith or sand from dunes present in craters, natural beds or depressions. Transporting these to the base site, the utility rover, capable of a sintering process, will begin the production of the foundations for the smaller habitat sections.

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* A number of advantages are realized by utilizing this casting approach and the final basaltic rock building elements. Firstly, as a building material in terms of structural strength, it is a superior to thermally induced sintered material
* The higher density of the basaltic lava would have considerable benefits in terms of providing radiation shielding on the surface environment, from galactic cosmic rays (GCR) and solar proton events (SPE). The permeability of basalt stone [20] is also superior to that of a sintered process, which is an important consideration for forming a hermetic seal.

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**In-situ resources for infrastructure construction on Mars: A review**

Construction materials and materials for energy conversion equipments in space must meet the following three requirements: resiliency, durability and economy.

* Resiliency: Construction materials are expected to perform in extreme environments of Mars with low pressure and cold temperature and other variable environmental conditions. For instance, the Martian temperature conditions require construction materials to be able to withstand high temperatures, low temperatures and large temperature differences, as well as meet the needs of human thermal insulation. In addition meteorite impacts cannot be ignored. Currently, NASA’s Additive Construction with Mobile Emplacement (ACME) project is investigating planetary construction materials and additively constructed materials for their resistance to hypervelocity impact.
* Durability: Materials used in additive construction have specific requirements such as the ability to be deposited in a specific predictable shape, the ability to support a superimposed layer after a period of time, the ability to bond to the layers above and below, and the ability to have structural integrity for use. Considering the harsh environmental conditions, it is necessary to ensure the strength of the material in the low temperature and low pressure environment, and to have the function of preventing strong ultraviolet radiation and solar radiation. A certain reflective material can be used to prevent the aging of the material and achieve duability.
* Economy: The reason for IRSU is that transportation from Earth to space is expensive and future research could consider the economic trade off between producing construction materials from in-situ resources on Mars and transporting necessary materials from the earth during the whole life cycle.

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**Mars X-House: Design Principles for an Autonomously 3D- Printed ISRU Surface Habitat**

* **Mars X-House 1** responded to the use of bulk surface material regolith as primarily a compressive material. Compression-intensive structures have not typically been used in space due to the fact that pressure differentials are expanding forces that are more efficiently managed using tensile structures. Building on years of research into inflatable structures, the 3D-printed regolith portion of the habitat was mainly conceived as radiation shield. Two redundant inflatables brought from Earth constituted the habitable area while the design and construction of the structure overall responded to expressive possibilities for the regolith shield, which was generated as a formal resultant from environmental and internal planning constraints.
* **Mars X-House 2** is based on the same environmental and architectural principle as Mars X-House 1 but assumes and supports the competition challenge brief that the 3D-printed structure may also provide the necessary pressure boundary. By developing a form which maximizes the compression forces of regolith to respond to outward pressure, in addition to integration of ISRU basalt fiber reinforcement to take additional tension forces, ISRU high density polyethylene (HDPE) as a non-porous lining and protection, Mars X-House 2 developed into a multi-level habitat which imagined the potentials of creating habitats without the need for additional Earth-constructed enclosures.

Both Mars X-House 1 and 2 followed the same architectural principles and through the rigorous and evidence based design development process led to different and specific results out of the same human-centered approach for health and safety with material and methods for autonomous fabrication at the core.

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**Plastics** will be an additionally critical material to support construction in space. It would provide a non-porous boundary layer for air-tight structures, a layer of shielding from potentially toxic regolith, and also provide for many additional components of the architecture such as window, walls, doors, and floors. Plastics such as HDPE will be produced using local ethylene resources on Mars. Methane fuel produced by the Sabatier reaction is expected to be a necessary component of future Martian missions derived from subsurface water and atmospheric carbon dioxide. Methane may then be polymerized to form complex hydrocarbons via the Fischer Tropsch process, including plastics. While this is an energy intensive process, it is expected that Martian missions will need to be energy rich with nuclear power to ensure crew and mission safety. A portion of polymer production may be generated by grinding, melting and re-using / re-cycling materials from the spent spacecraft. Additional plastics can be made using similar processes. Polycarbonate windows can also be made with in-situ materials. Polycarbonate has high visual transmissivity offering the potential for true vision windows necessary to connect the crew to their new landscape.

**The efficacy of passive shielding is driven by three things**: material selection, thickness, and order. The importance of material selection essentially falls out of the above equations; some materials will be more effective than others at attenuating space radiation. In particular, habitats constructed from aluminum-2219 or pure Martian regolith will provide similar shielding per unit mass, but polyethylene will be significantly more efficient per unit mass. With respect to material thickness, thicker materials tend to provide more opportunity for attenuation as incident particles attempt to pass through. However, for metals and metal-like materials, fragmentation processes can actually increase the dose equivalent behind shielding at moderate thicknesses (>20 g/cm2). The same behavior is not observed in hydrogen-rich materials, presumably because more electronic stopping and less fragmentation is taking place. Finally, when there are multiple shielding materials, the order of those materials also makes a difference in the shielding efficacy of the layered composite. This principle can be notably relevant in satellite design, where graded-Z shielding can be used to provide aluminum-equivalent protection at a reduced mass.22 In the context of habitat design, using a hydrogen-rich material as an interior lining for both regolith shielding and a metallic pressure vessel enables a habitat designer to reap the benefits of all three: the regolith provides in situ shielding, the metal provides structural integrity and holds pressure, and the hydrogen-rich lining helps attenuate both primary and secondary particles.