# Topical: Manufacturing from Regolith

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The Artemis program is about to start a new era of space exploration and a new chapter of history[1]. As humans pursue exploration beyond Low Earth Orbit (LEO), the ability to manufacture critical infrastructure on extraterrestrial surfaces from regolith is essential to ensure human survival, safety and mission success. This necessitates fundamental research on formulating resilient materials for infrastructure utilizing in-situ resources available on extraterrestrial surfaces, such as regolith. These materials will be used to construct shelters that provide protection for critical assets, including astronauts and equipment, and to construct greenhouses for food production (plant growth in regolith has already been tested successfully[2]).

The main scientific rationale supporting research in manufacturing from regolith aligns with NASA's Technology Taxonomy TX 12: Materials, Structures, Mechanical Systems, and Manufacturing[3]. Local manufacturing and sustainment by way of in-situ resource utilization (ISRU) are essential to accomplishing exploration beyond LEO, and the next decade of exploration needs to ensure that a sustained presence on the Moon is possible.

## Background

Current launch costs are estimated to be between 1 and 1.2 million dollars per kilogram for delivery to the Moon's surface. This significant cost underscores the need for utilizing resources available in-situ on the lunar surface. Thus, a paradigm shift from "bring everything from Earth" to "make it, don't take it" is crucial. Utilizing lunar regolith for construction of shelters is woven into the complex chain of processes and materials needed for a sustained presence on the Moon. All these are linked via the need to extract necessary elements from regolith. However, rather than competing, these processes can be complimentary.

Infrastructure elements required for sustained human presence on the Moon range from starting and landing pads to blast shields and habitats. Additional infrastructure elements that will facilitate life on the Moon include roads, garages, systems for energy generation and storage, and thermal wadis. Not only will these structures need to be manufactured in-situ and on-demand, they will also need to be outfitted. Outfitting includes, but is not limited to, the manufacture and installation of spare parts, brackets, insulation, plumbing, penetration sealing, hatches, windows, furniture, sinks, toilets, septic tanks, air ducts, doors, and partitions.

Different materials will be required for each of these components and applications based on the varying design requirements for each infrastructure element or outfitting piece. Landing pads must withstand large amounts of thermal and mechanical loading. Habitats must withstand internal pressurization and, potentially, mechanical loads from regolith layers covering them for thermal insulation, as well as radiation and micrometeorite shielding. Penetration seals must withstand dimensional changes of pipes and habitats due to extreme thermal swings. In order to provide the multiple classes and types of materials required for the manufacture of this large diversity of components and applications, the extraction or separation of particular components of regolith (e.g., Ca, Al, Fe, Mg, Ti and $SiO_2$) is necessary. Additionally, it is critical to develop new and improved extraction and processing techniques for the utilization of the various constituents of regolith, since their current technology readiness levels (TRLs) are only 2-3.

## Problem Statement

**There is a need to acquire the fundamental knowledge required to build resilient infrastructure on the lunar surface out of in-situ resources.**

In the first instance, materials characteristics of regolith need to be well understood in order to build large structures and the infrastructure that will protect astronauts and enable them to successfully complete missions. Despite the decrease in shipping costs to LEO in recent years (because of the increase in available rockets and advancements in reuse technology[4]), it will not be feasible to supply construction and repair materials from Earth. In parallel to advancements in rocket reuse technology, it will be essential to develop sustainable manufacturing techniques and re-use of primary materials and the by-products where possible.

Both Moon and Mars have surface environments unlike any of those that traditional terrestrial construction materials have experienced. The gravity levels are 1.62 $m/s^2$ and 3.71 $m/s^2$, the atmospheric pressures are $3\times10^{-13}$ kPa and 0.7 kPa, for Moon and Mars, respectively[5], and wide temperature variations occur. Infrastructure must be able to reliably operate for extended periods of time under these conditions.

A potentially low-cost way to address explore the various challenges posed by the condition on Moon and Mars will initially be to perform experiments on Earth using compositionally equivalent regolith simulants. Through these it will be possible to determine the critically important fundamental characteristics of regolith, such as structure, properties, and process behavior. Understanding, for example, the sensitivity to compositional changes will be important. While lunar regolith became available for research through the Apollo missions, Martian regolith is yet to be brought to Earth for extensive analysis, so that its material properties remain less studied, understood and certain. Known differences between the two regoliths include shape, mineralogy, geotechnical, mechanical, and physical properties, shape, and the type of glasses they form. Actual lunar regolith includes agglutinates, which pose challenges to manufacture samples on a scale needed for research. Thus, also the fidelity of the simulants must be further explored and kept in mind for research progress.

While lunar regolith offers materials science and engineering opportunities, since it has many unique properties and features not found on Earth, the lunar surface is from a compositional perspective comprised of largely the same minerals: plagioclase feldspar, olivine, pyroxene, and ilmenite. On Earth, we have been using these materials to make ceramic products and concrete materials for centuries.

Experimentation has been key to process and product development. However, the TRL for processing and fabrication of lunar regolith products can be greatly improved by experimentation with lunar simulants in a vacuum and partial vacuum environment. To date, there has been a shortage of lunar simulants which has impeded these developments, but current work on synthetic lunar minerals and simulant blends continues[6]. As synthetic lunar materials become available, the processing, structure, and property relationships can be thoroughly explored. In addition, development of robotic equipment for extraction and processing requires some level of scale up with lunar simulants. New methods will focus on ISRU and avoid typical Earth based processing methods that will minimize dependence on water, strong acids or solvents.

## Why is this research question important?

We focus in this concept paper on three key basic and applied research areas: regolith extraction, utilization in near-as-mined states, and utilization in refined states. Each of these areas contributes a critical step towards the development of capabilities enabling the extraction of the required resources and manufacturing of supplies and components necessary for successful missions on extraterrestrial surfaces that cannot sustainably be supported with transportation from Earth.

A multitude of materials science and engineering opportunities and challenges exist related to the efficient utilization of regolith and thus its entire life-cycle: from extraction and processing to use and recycling; all require urgent research attention. The most abundant elements of moon regolith are O (60%), Si (16-17%), Al (6-10%), Ca (4-6%), Mg (3-6%), Fe (2-5%), and Ti (1-2%). While regolith can directly be used as a raw material for the production of ceramics, glasses and geopolymers[7], individual metal oxide production will require extraction[8]. Similar is the case of production of metals, which will become available also as by-products of oxygen production from regolith[9]. There exists also research scope for the simultaneous extraction of $H_2O$, $TiO_2$ and Fe from ilmenite.

For the manufacturing of components either directly from regolith or extracted ceramics, glasses, and metals, traditional and new processing techniques for component shaping, joining, and finishing will need to be tested to determine how they need to be adapted for use in microgravity, which significantly affects structure and artefact formation and through these material function and performance[10],[11]. Additionally, there is considerable scope and need to explore manufacturing techniques that result in multifunctional materials and components for resource efficiency in terms of energy, time, and cost for the entire life-cycle of the product. Most manufacturing techniques will initially need to be explored as batch processes to obtain the desired material. With further maturation, also the potential for the upscaling of in-situ production without quality loss will be of interest to ensure that component size, volume, and production rate can be assured by ISRU in the long term[12].

In addition to the adaptation to microgravity of more traditional manufacturing techniques, such as pressing/hot pressing, resistance and microwave sintering for the manufacturing of ceramics, molding and melt spinning for the manufacturing of products from glasses, and casting for metals, as well as manufacturing of composites, and materials with attractive profiles of anisotropy, we see great promise in the development and further exploration of new and improved manufacturing techniques optimized for extraterrestrial use. Among these new techniques are comparatively “cold” shaping processes, such as additive manufacturing on small and large scales[13], and freeze casting[14], to name but a few that are already being explored for use in microgravity. Attractive for many applications will be manufacturing processes for the manufacturing of components and objects that offer scope for custom-design, modularity, adaptability, and repair, such as brick-like building blocks with different property profiles that can be combined in construction, for example. Similarly attractive are processes for the manufacturing of not only dense, but also of porous materials, because the latter are not only lightweight, but additionally offer considerable potential for multifunctionality[15]. Pores in materials and/or voids in components can be filled with functional materials, e.g. with air or gas for thermal insulation, with phase change materials for energy storage[16], or with clean water or waste water as radiation shield.

Components will need to be joined and finished and materials and processes adapted for this function. Challenges and limitations posed by microgravity in this area are well illustrated taking traditional cement-based binders as an example. Testing their hydration in microgravity onboard ISS showed that entrapped air does not exit the paste due to the effective absence of buoyancy and sedimentation forces[17], and that also the separation of water from the paste, termed bleeding, is minimized[18]. This specific case motivates research towards binders that are solely based on in-situ resources and under various gravity levels and highlights the required focus of the next decade of space investigations on regolith utilization.

Fundamental science on multiple materials utilizing regolith simulant is needed to enable resilient infrastructure. No material completely encapsulates all the engineering applications faced on extraterrestrial bodies. The capacity to tailor materials to the requirements of different applications in-situ will be crucial. Proving scalability is essential to progressing materials development (Figure 1).

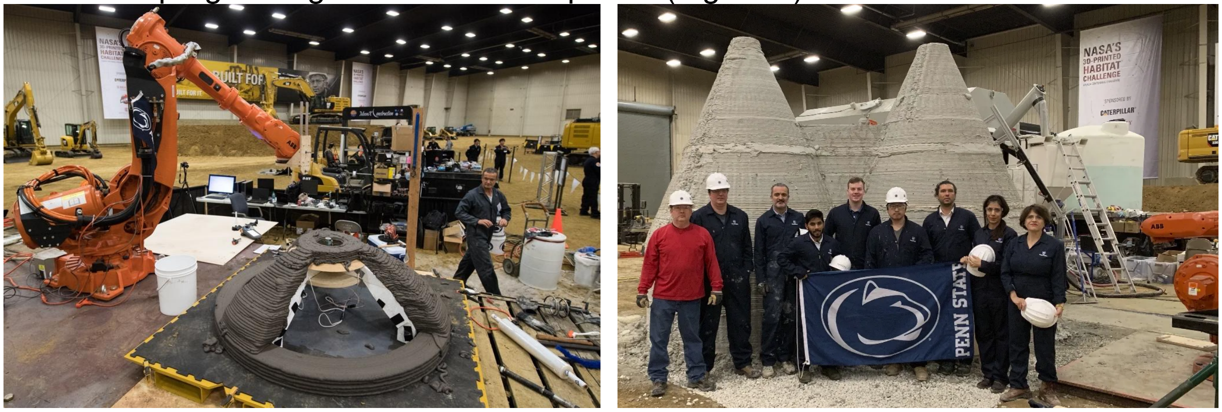

**Fig.1: NASA Habitat Challenge brought preliminary solutions to large scale autonomous construction for extraterrestrial applications: autonomously printed dome with in-situ-like materials (left), fully enclosed habitat in 1/3rd scale printed during the final competition (right).**

## Research Impacts

The research impacts will be spread over time with early applications using resources in near as-mined state. This will enable progress to using resources in extracted and more refined forms, and ultimately in recycled and optimized forms. Research invested in manufacturing processes and materials, including new and improved materials, will enable technology required for the sustained presence on the Moon and beyond.

Applications of carefully manufactured materials will enable and ensure a safe habitat, with the required supply of oxygen and water. Roads for travel and construction for work, life and recreation, thermally insulated against extreme temperatures, and equipped with radiation shielding, will be made by additive manufacturing or from regolith building blocks, joined by regolith cement. Dense regolith blocks or phase change material filled structures will store the solar energy directly, regolith-based silicon photovoltaics and regolith-based aluminum-coated glass mirrors will enable the collection of solar power and their storage in silicon batteries or hydrogen storage devices. Porous regolith-based substrates for plant growth in greenhouses will ensure food supply and production of polymers for textile production and clothing.

Researching these unique and novel materials that can be manufactured from regolith will identify the material properties that can be achieved. Knowing such properties can help set design and certification methods to ensure safe and resilient infrastructure and form the regolith into desired shape. Guidance on the use of regolith simulants for the intended application is crucial. Certain technologies may rely on different material properties (mineralogy versus geotechnical) of the simulants and identifying which simulant meets the quality needed is critical for manufacturing advancement. Conducting fundamental research on such novel materials will lead to advancements through computational simulations by adding the extreme environmental influences that are difficult to reproduce on Earth.

## Transformative research

Development of extraterrestrial manufacturing techniques by ISRU is a transformative process. Development of human space technology research has been beneficial for both the space and terrestrial environment[19]. With that in mind, any advancement in extraterrestrial construction will lead to technological breakthroughs in Earth-based construction. This can address housing shortages for densely populated areas and developing countries, as well as construction in remote locations with harsh climatic environments. Moreover, autonomous construction will lead to novel architecture and new architectural expressions. Such technologies will prompt the use of less conventional materials and lower $CO_2$ input, which is desperately needed. The construction sector is the second largest carbon dioxide emitter, accounting for roughly 33% of the total global carbon dioxide emission[20]. Simultaneously furthering methods of recycling and reusing of various resources will greatly benefit infrastructure development on Earth and beyond.

## Recommendations

In-situ resource utilization research is transformative and cross-disciplinary. It will require numerous biological and physical sciences components to successfully use local resources (i.e., lunar regolith) for manufacturing and potential life support applications. Instead of a single research path, multiple viable options should be researched as no option will be universal. This is not limited to, but includes, new concrete binders, production of fibers from regolith, 3D printing of building components, and outfitting parts and supplies. Composite materials need to be explored and research synergies with manufacturing and sintering identified. While engineering principles will govern this research, a challenging science needs to be explored.

Constructing infrastructure on the Moon using materials extracted from regolith is an essence to extraterrestrial exploration. The process we want to focus on in this concept paper includes extraction and separation that is equally crucial to processing energy and food in lunar environment. We will focus on the chemistry needed to process regolith into a range of building materials suitable for extraterrestrial construction. As such, it is a strong belief of the authors that the Decadal Survey's deliberations need to take the scientific benefits of manufacturing out of regolith into account in planning comprehensive vision and strategy for a decade of transformative science at the frontiers of biological and physical sciences research in space.

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