STRATEGIC REGOLITH PROCESSING ON THE MOON AND MARS.

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Introduction: Many different regolith-based ISRU processes have been described and tested in the laboratory over the years (Table 1). For the most part, these processes have been studied in isolation; they involve taking an input material–usually a regolith simulant, or a particular fraction thereof–processing it, and producing both a useful output and some kind of waste or residue. Here, we build on the work of [1] and describe a logical sequence where these processes are chained together to extract the maximum value out of an initial parcel of raw regolith. We then demonstrate parts of the sequence using high-fidelity, mineral-based lunar and martian regolith simulants we previously developed.

Table 1. ISRU processes involving regolith [1].

ISRU Process	Example Reference(s)
Microwave sintering	[2]
Molten Regolith Electrolysis	[3,4]
Volatile extraction & distillation	[5,6]
Additive manufacturing	[1]
Basalt fiber production	–
Ceramic production	[7]
Slaking and concrete production	[8]

Processing Sequence: Our notional processing sequence is laid out in Fig. 1. This is not yet comprehensive, but includes previously described uses for regolith and some novel ideas. The flow begins with extracting key volatiles and salt products (when present), sieving and other separation techniques, then progressing to high temperature, destructive processes. At any step, true waste products or overproduced intermediaries can be funneled into a "grab bag" category to be used for radiation shielding or bulk structures like berms.

For both lunar and martian soils, water as ice or hydrated minerals (Mars only) can be baked out in an oven or microwave heater. For Mars, it may actually be more energy efficient to extract water from soils rich in highly soluble sulfates *using dissolution and reverse osmosis rather than heating and distillation*. Ion-selective membranes could also remove dissolved perchlorates before reverse osmosis, making the solid salt residue safe for applications involving plants and humans. A side path here involves reacting lunar or martian soil with supercritical H_2O to form clays (for ceramics) and a residual ion-rich fluid that can form at least part of a hydroponic nutrient solution.

After these optional steps, simple sieving can separate fines, sand, and gravel/pebbles. The sand fraction is optimal for further magnetic separation to concentrate Fe/Ti-rich phases to be used in metal/O_2 production. The gravel fraction can be used as aggregate in concrete, and as a hydroponic medium for plant growth, amongst other applications. Fines can be used for additive manufacturing, as well as for batch melting to create spun basalt products (rebar, fabrics, insulation, etc.).

Demonstration: We tested some parts of the Fig. 1 diagram in the lab using high-fidelity regolith simulants.

Regolith Simulants: At UCF we have developed a line of simulants for the Moon, Mars and carbonaceous asteroids as part of the CLASS Exolith Lab. Our guiding principle has been to design *mineral-based simulants* that can do a better job of capturing regolith properties compared to past efforts. For this work, we used our LMS-1 Lunar Mare Simulant that contains 4.6 wt.% TiO_2 (mostly as ilmenite), and our MGS-1 Mars Global Simulant [9], a dusty basaltic soil (Fig. 2a,b).

Processing Methods: For the lunar case, we demonstrated sieving, magnetic separation of the sand fraction using an induced roll magnetic separator (Fig. 2c), and sintering of the fine fraction with a microwave kiln (Fig. 2d). For the martian case, we removed soluble salts (including perchlorates) by flushing with water (Fig. 2e), then sieved the remaining material and used the pebble size fraction as hydroponic media to grow microgreens (Fig. 2f). These experiments, while small in scale for now, demonstrate the feasibility of chaining together multiple ISRU processes for working with regolith.

Conclusions and Future Work: Instead of thinking of ISRU processes individually, we are extending the work of [1] to link them together in a logical sequence that maximizes the value of raw regolith. Future work will test more of the sequence, add new processes, and define creative uses for products that were previously considered waste.

References: [1] Mueller R. P. et al. (2016) *Earth & Space 2016*. [2] Taylor L. A. and Meek T. T. (2004) *J. Aero. Eng.*, *18*. [3] Gibson M. A. and Knudsen C. W. (1985) In: *Lunar Bases and Space Activities of the 21st Century*, 543. [4] Schwandt C. et al. (2012) *PSS*, *74*, 49. [5] Duke M. B. et al. (1998) *36th AIAA*. [6] Abbud-Madrid A.et al. (2016) *Report of the Mars ISRU Planning Study*. [7] Karl D. et al. (2018) *PLoS ONE*, *13*, e0204025. [8] Omar H. A. (1993) *NASA/CR-97-206028.* [9] Cannon K. M. et al. (2019) *Icarus*, *317*, 470.

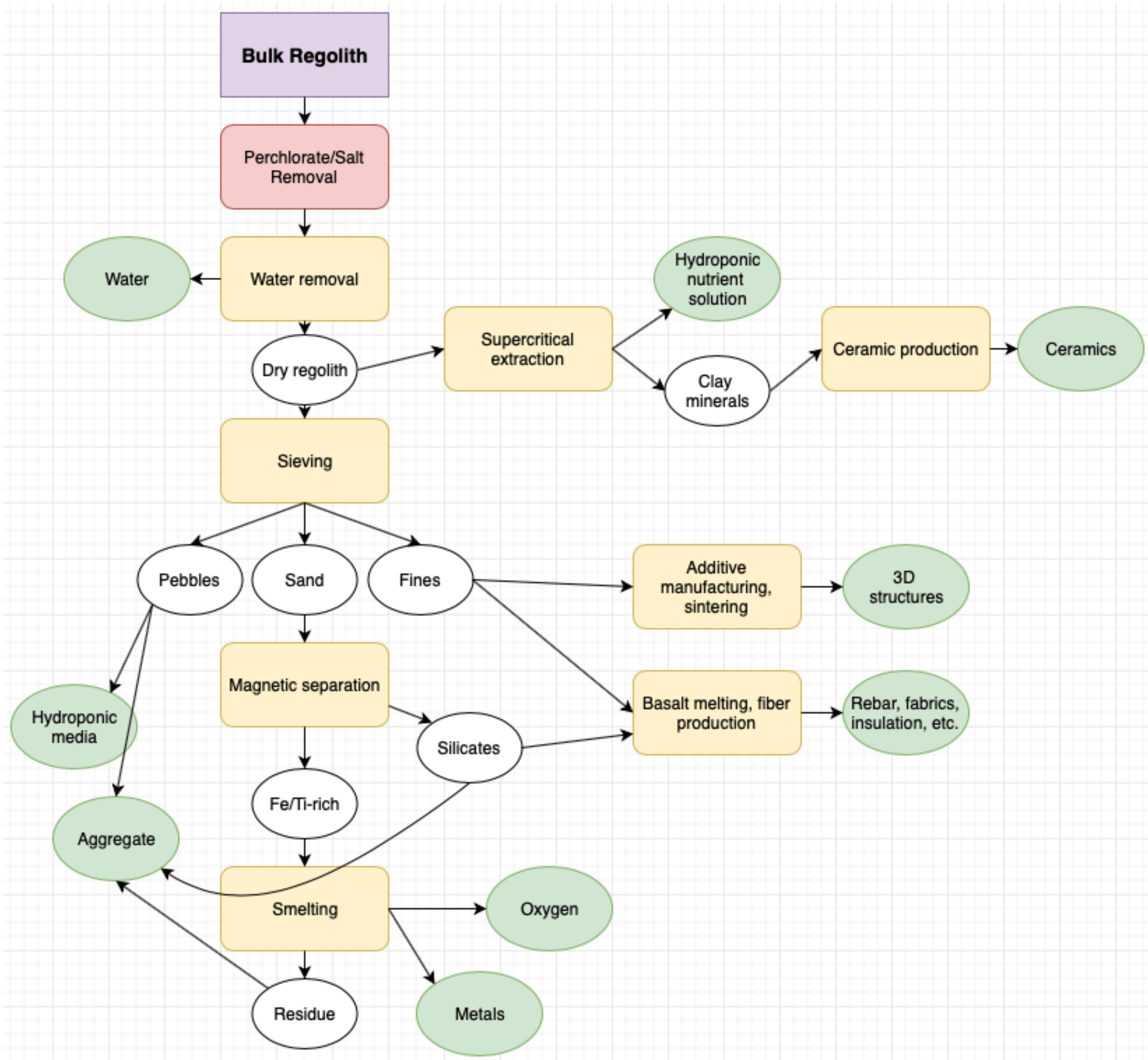

Figure 1. Regolith processing flow. Red = process (Mars); yellow = process (Moon or Mars); white = intermediary product; green = useful end product. All intermediaries can also be used as radiation shielding/berm material.

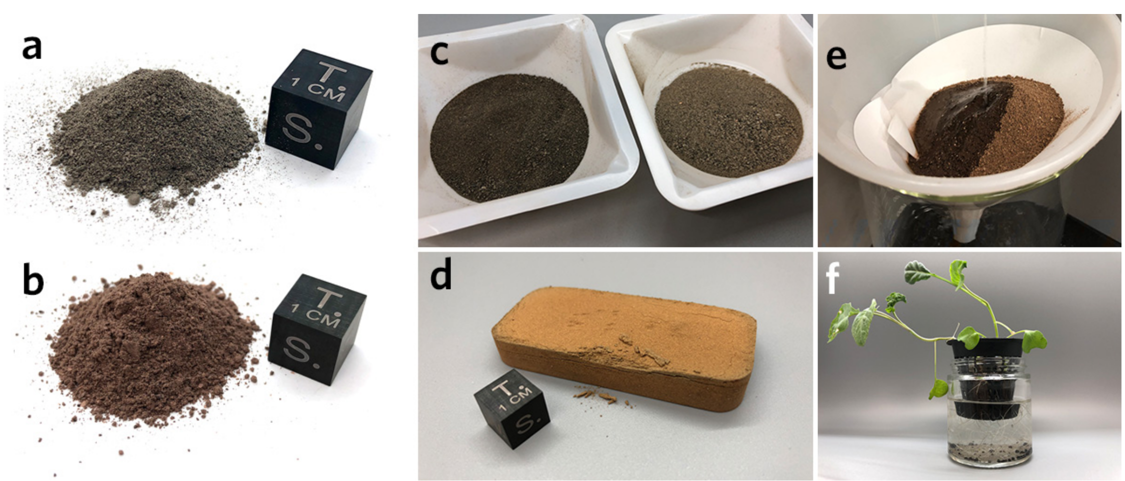

Figure 2. Process demonstration. a) LMS-1 simulant; b) MGS-1 simulant; c) LMS-1 magnetic separation; d) Sintered LMS-1 fines; e) Flushing MGS-1 to remove salts/perchlorates; f) Hydroponics using MGS-1 pebbles as media.