Planetary Resources

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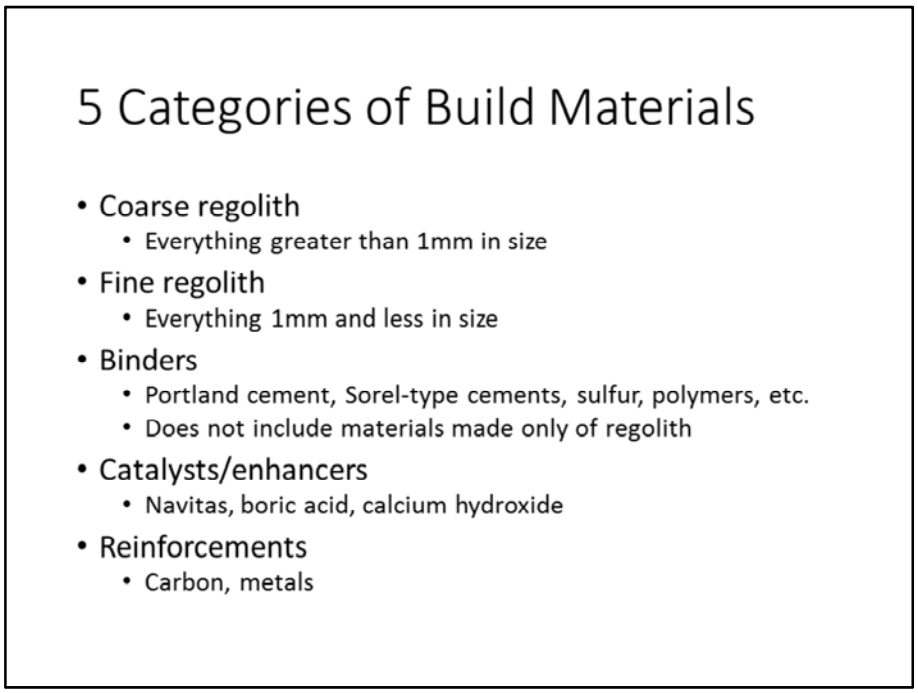
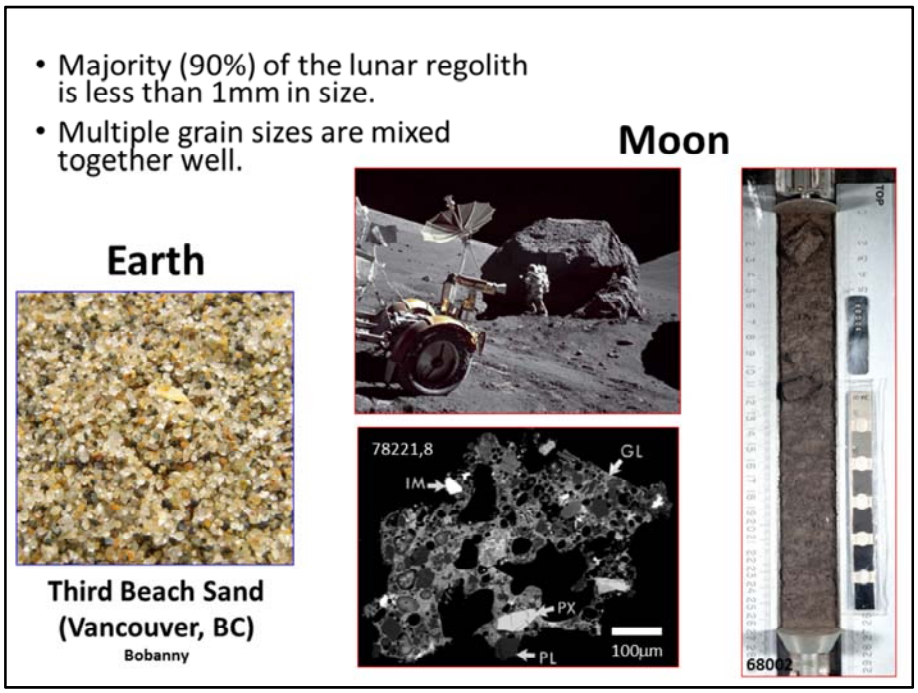
August 25, 2015

For the Keck Institute Additive Construction Workshop

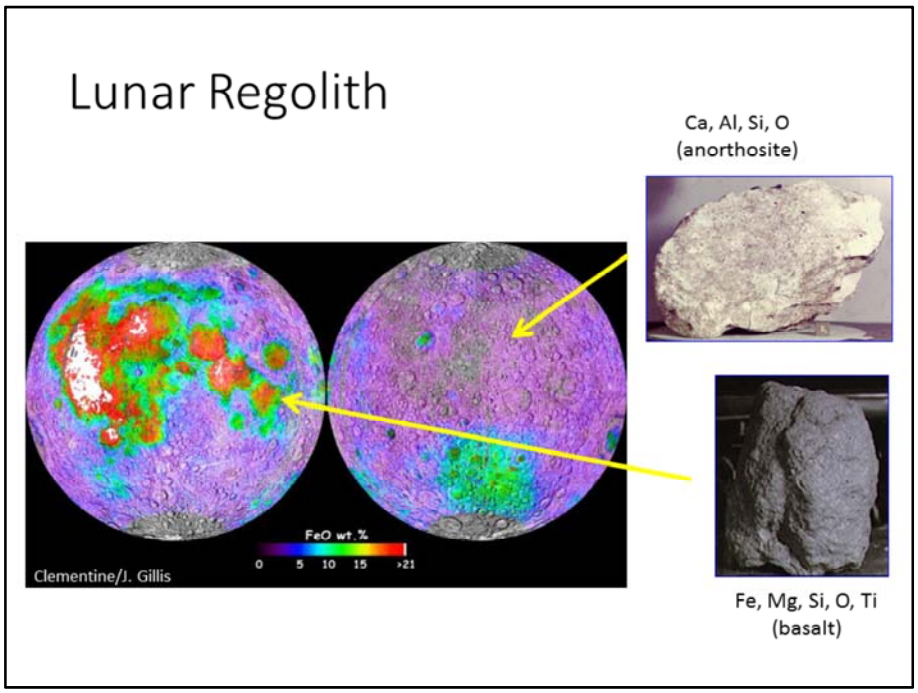
Papers cited within this presentation are only the ones I am most familiar with – there are plenty of other papers out there covering the same and related topics!



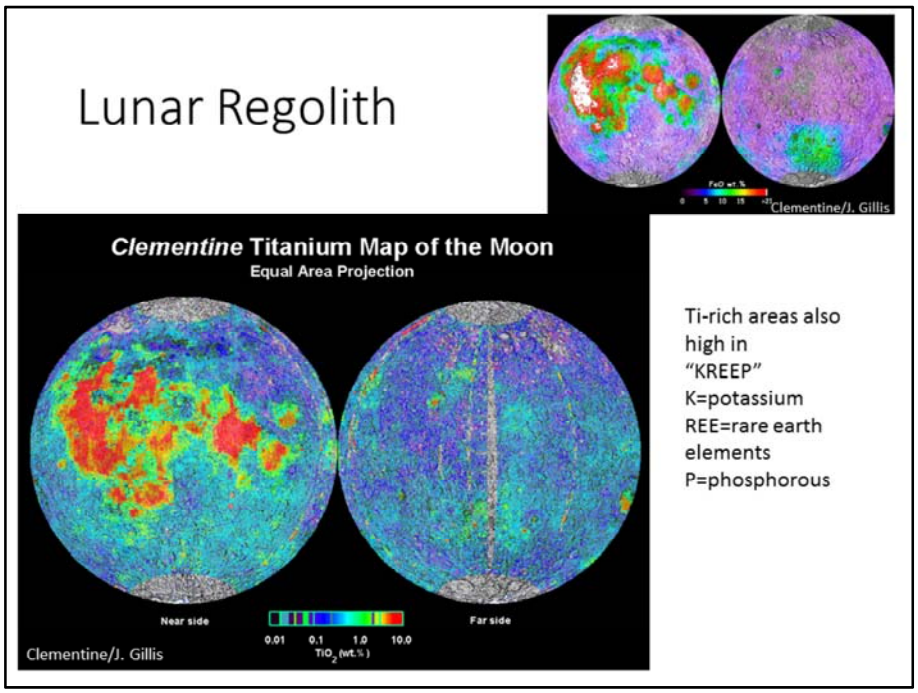
I defined coarse and fine regolith based on lunar material – 90% of lunar material is less than 1mm in size. Because of mining and processing techniques (e.g., ionic liquids), all resources from a planet's regolith are available to us. Navitas chemistry, if known, could likely be produced using planetary surface materials as well.



Note the poor size sorting on the lunar surface – dust grains can be found next to large pieces of rock. The sand on Earth image is provided as contrast to the lack of grain size sorting on the Moon.



FeO map – provides a glimpse of general rock types (the anorthositic, light colored highlands and the dark mare basalt regions). The South-Pole Aitken basin (on the far side of the Moon, right image in the map) is not like the basaltic mare on the near side of the Moon. The basin is one of the prime locations discussed for lunar sample return missions, since we only have remote sensing data to indicate what types of rocks can be found within this area.



The Ti map of the Moon shows areas rich in KREEP material as well as the mineral ilmenite (FeTiO3). The same (and other related) geologic processes that concentrate Ti concentrates the KREEP component (and uranium) as well.

Binders from Lunar Regolith

- Sulfur
  - Concentrations vary from a few tens of ppm in ferroan anorthosites (highlands rocks) to over 2000ppm in high Ti lavas (some mare rocks)
  - Veins of troilite in a few lunar breccias
- Magnesium
  - Basalts, Mg-suite highlands rocks
- KREEPy rocks
  - Apatites (primarily chlorine-bearing calcium phosphate)
  - Potassium-rich phases (K-feldspar)

More information on some cementitious binders can be found in the following two papers:
Werkheiser, N. J., Edmunson J. E., Fiske M. R., and Khoshnevis B. (2015) On the development of additive construction technologies for application to development of lunar/martian surface structures using in-situ materials. AIAA Space 2015 Conference, Pasadena CA, August 31-September 2 2015. Paper number AIAA-2015-4451.
Werkheiser N. J., Fiske M. R., Edmunson J. E., and Khoshnevis B. (2015) Development of additive construction technologies for application to development of lunar/martian surface structures using in-situ materials. Composites and Advanced Materials Exposition, Dallas TX, 26-29 October 2015. Paper number TP15-0352.
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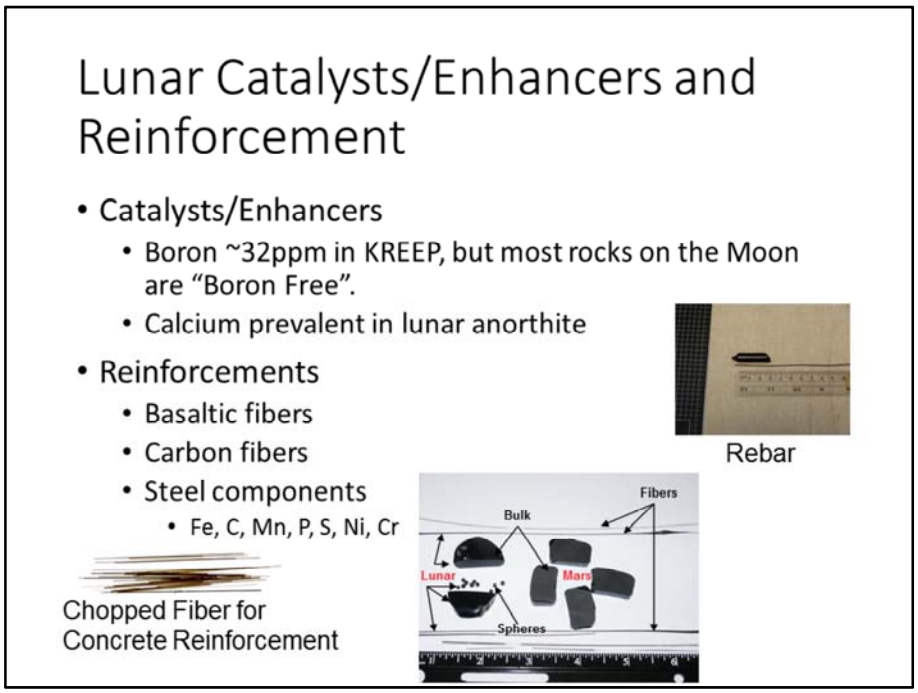
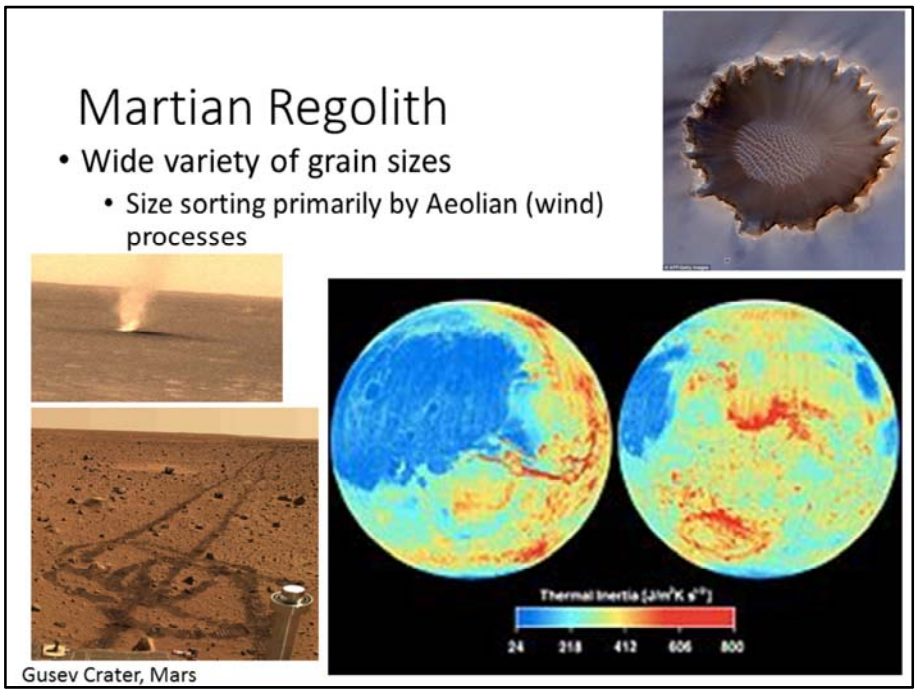


Materials needed to serve as catalysts/enhancers/reinforcements can also be found on planetary surfaces.

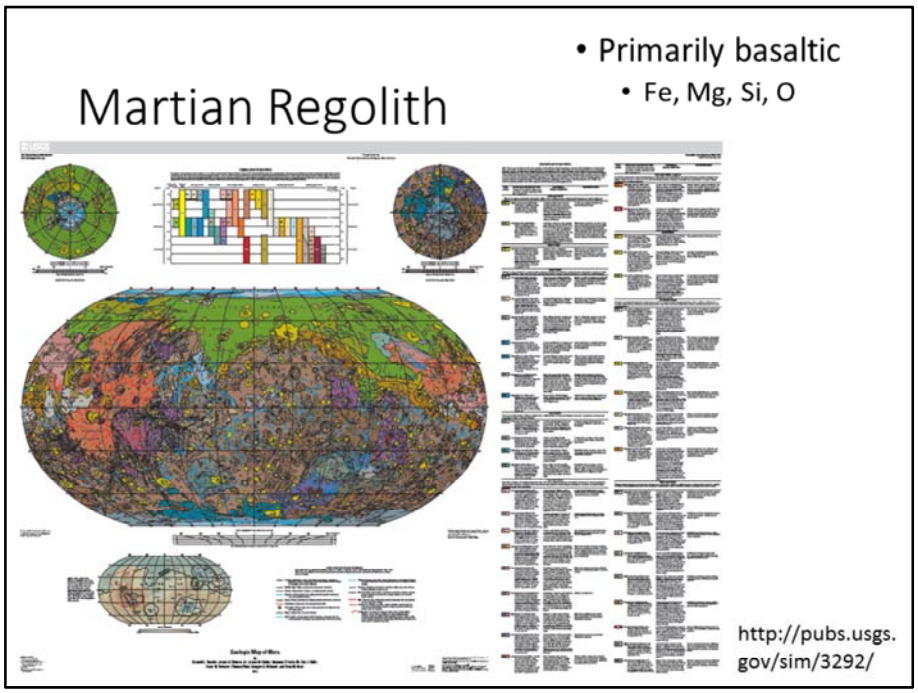
See:

Tucker D., Ethridge E., and Toutanji H. (2006) Production of glass fibers for reinforcement of lunar concrete. 44th AIAA Aerospace Sciences Meeting and Exhibit, Reno NV, 9-12 January 2001. AIAA-2006-523.

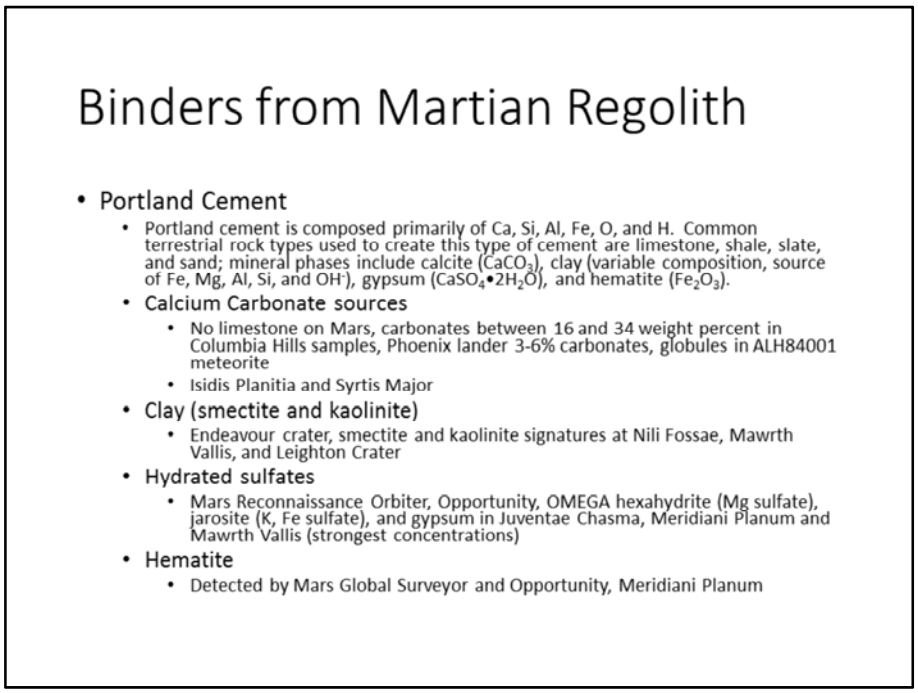
Khoshnevis B., Bodiford M. P., Burks K. H., Ethridge E., Tucker D., Kim W., and Toutanji H. (2005) Lunar contour crafting – a novel technique for ISRU-based habitat development. 43rd AIAA Aerospace Sciences Meeting and Exhibit, Reno NV, 10-13 January 2005. p7397-7409.



Thermal inertia – areas in blue indicate smaller (dust-sized) grains, the reddish areas are larger rocks/boulders.



The majority of the martian surface is basaltic.



See the same papers for lunar binders:

Werkheiser, N. J., Edmunson J. E., Fiske M. R., and Khoshnevis B. (2015) On the development of additive construction technologies for application to development of lunar/martian surface structures using in-situ materials. AIAA Space 2015 Conference, Pasadena CA, August 31-September 2 2015. Paper number AIAA-2015-4451.

Werkheiser N. J., Fiske M. R., Edmunson J. E., and Khoshnevis B. (2015) Development of additive construction technologies for application to development of lunar/martian surface structures using in-situ materials. Composites and Advanced Materials Exposition, Dallas TX, 26-29 October 2015. Paper number TP15-0352.

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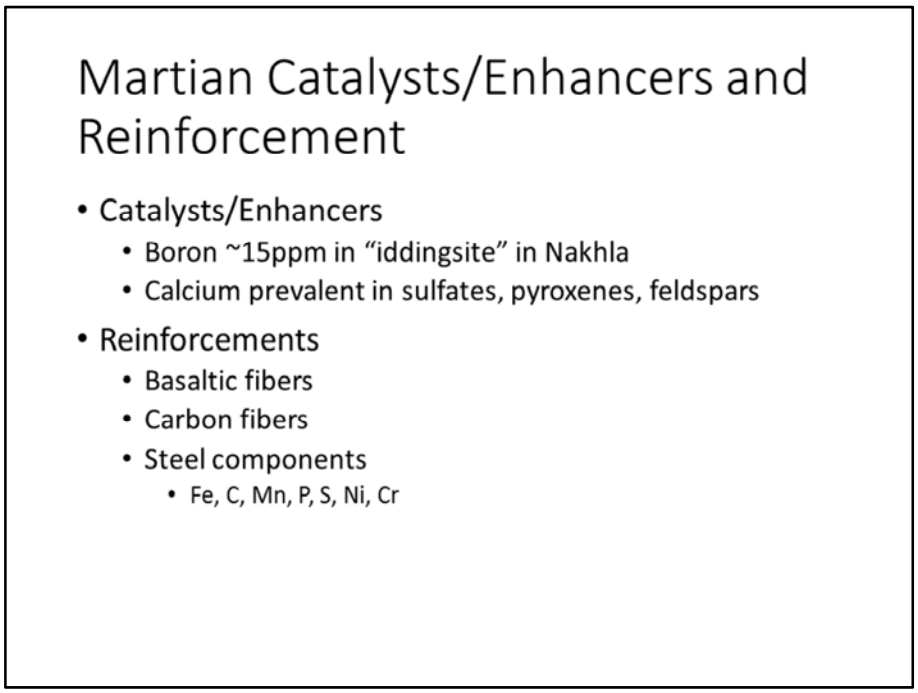
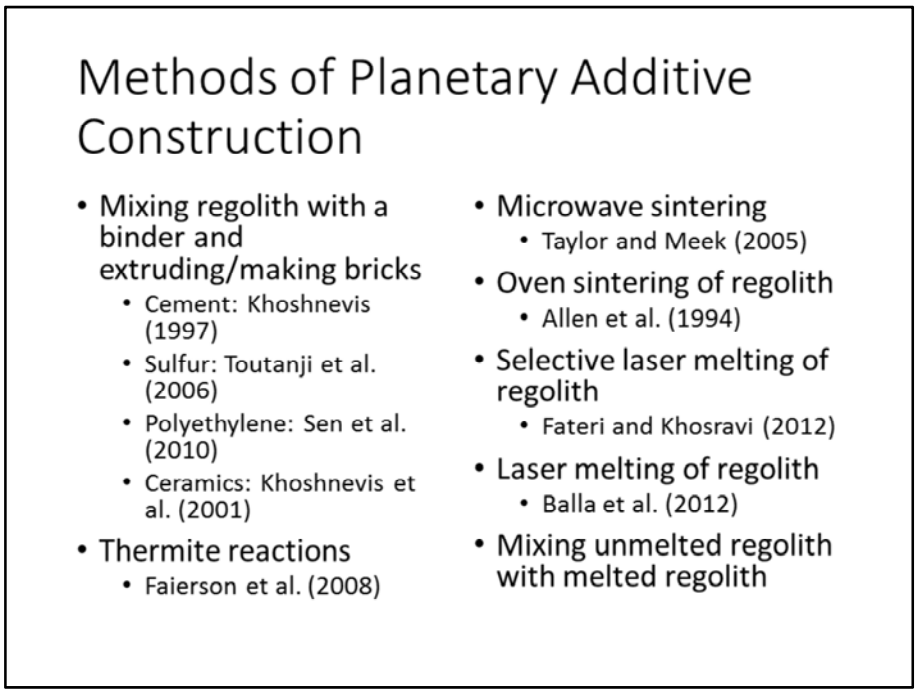
Binders from Martian Regolith

- Sorel Cement
  - Mg found in basaltic rocks
  - Chloride found in brines, brine deposits, apatite and amphibole. Detected at Endurance Crater.
  - Potassium in jarosite, some clays and micas in Meridiani Planum and near Nili Fossae.
- Sulfur Cement
  - Gypsum, jarosite, and hexahydrite sources.



Nakhla is a martian meteorite.

Additional Content



Note – these references are the ones I am most familiar with and are by no means the only references out there on these topics. I could not find one on mixing unmelted and melted regolith.

Allen C. C., Graf J. C., and McKay D. S. (1994) Sintering bricks on the Moon. ASCE Engineering, Construction, and Operations in Space IV. P1220-1229.

Balla V. K., Robertson L. B., O'Connor G. W., Trigwell S., Bose S., and Bandyopadhyay A. (2012) First demonstration on direct laser fabrication of lunar regolith parts. Rapid Prototyping Journal, Vol. 18 No. 6. p451-457.

Faierson E. J., Hunt M. P., Stewart B. K., Jefferies S. A., Okyen M. L., Hopkins S. D., Holt S. M., and Logan K. V. (2008) Lunar construction and resource extraction utilizing lunar regolith. Pacific International Space Center for Exploration Systems and Japan-U.S. Technology and Space Applications Program Conference.

Fateri M. and Khosravi M. (2012) On-site additive manufacturing by selective laser melting of composite objects. Concepts and approaches for Mars exploration. Abstract number 4368.

Khoshnevis B. (1997) Contour crafting – a new rapid prototyping process. Proceedings of the 7th International Conference on Rapid Prototyping. P13-22.

Khoshnevis B., Bukkapatnam S., Kwon H., and Saito J. (2001) Experimental investigation of contour crafting using ceramics materials. Rapid Prototyping Journal, Vol. 7, No. 1. p32-42.

Sen S., Carranza S., and Pillay S. (2010) Multifunctional martian habitat composite material

synthesized from in situ resources. Advances in Space Research, Vol. 46. p582-592.
Taylor L. A. and Meek T. T. (2005) Microwave sintering of lunar soil: properties, theory, and practice. Journal of Aerospace Engineering, Vol. 18 No. 3. DOI: 10.1061/(ASCE)0893-1321(2005)18:3(188).
Toutanji H., Fiske M., and Bodiford M. (2006) Development and application of lunar "concrete" for habitats. Earth and Space 2006, p1-8. DOI: 10.0161/40830(188)69.

Ionic Liquids

- Acids that can:
  - Digest materials
  - Be reused (with the addition of hydrogen – mined from solar wind collectors?)
  - Separate all elements
    - Metals can be electroplated out
    - Water can be distilled from the acid (oxygen source is the regolith minerals)
- Work by the following (specific to planetary): Laurel J. Karr, M. Steven Paley, Matthew Marone, and Robert J. Sharpe

Planetary Resource Resources of Interest

- Lunar Sourcebook: A User's Guide to the Moon (1991) Grant Heiken, David Vaniman, Bevan M. French, ed.'s. ISBN 0-521-33444-6
- Mars: Prospective Energy and Material Resources (2009) Viorel Badescu, ed. ISBN 3642036295
- Moon: Prospective Energy and Material Resources (2012) Viorel Badescu, ed. DOI: 10.1007/978-3-642-27969-0
- Uses of Extraterrestrial Resources for Human Space Missions to Moon or Mars (2013) Donald Rapp. DOI: 10.1007/978-3-642-32762-9