As the nation prepares to return to the moon and, later, to travel to Mars, the use of in situ materials for constructing long-term habitats makes eminent sense as a way of reducing the mass and volume of launch payloads. As a construction product, concrete is well characterized terrestrially but thus far has been only marginally evaluated for use on other planetary surfaces. In this study, it is assumed that water is not available on the moon as a construction product. This changes the classical definition of hydraulic cement concrete from that of a material made of cement, water, and aggregate to one made of cementitious materials and aggregate. “Waterless” concrete—for which lunar regolith would serve as an aggregate and an in situ material such as sulfur would serve as a binder—could be a good alternative to hydraulic concrete.


Sulfur holds promise as an alternative to portland cement as a binder in making concrete for use in lunar construction. Sulfur concrete offers the following advantages that are relevant to lunar construction:
A compressive, tensile, and flexural strength, as well as a fatigue life, that are greater than those obtained with conventional portland cement concrete;

• Rapid setting—a minimum of 70 to 80 percent of the ultimate compressive strength being attained within 24 hours of casting;

• Higher chemical resistance against acids and salts;

• Low water permeability.

A reinforced-concrete structure could be developed using any one of a number of techniques and then integrated with an inflatable internal liner or a liner that would be sprayed on to provide a hermetic seal. While most of these construction techniques require significant equipment as part of the payload from Earth, they also lend themselves quite well to automation and offer overall design flexibility. Reinforcement can be provided either by introducing chopped glass fiber into the concrete or by embedding glass or steel rebar in the concrete during fabrication.

The commercial use of sulfur concrete on Earth is well established, particularly in environments that are corrosive because of the presence of acid or salt. The finding of troilite on the moon raises the possibility of using extracted sulfur as a lunar construction material, an attractive alternative since such concrete does not require water. The accompanying table provides information about the amount of sulfur found on some of those missions.

### Sulfur Abundance in Apollo Soil Samples

<table>
<thead>
<tr>
<th>Mission</th>
<th>Abundance (µgS/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apollo 14</td>
<td>706–778</td>
</tr>
<tr>
<td>Apollo 15</td>
<td>517–712</td>
</tr>
<tr>
<td>Apollo 16</td>
<td>474–794</td>
</tr>
</tbody>
</table>


Sulfur can be extracted from lunar soil by heating the soil above 1,100°C in a vacuum environment, which will lead to a release of sulfur in the form of SO₂ and H₂S. Then, by using the Claus process, pure elemental sulfur and water are created:

Scientists and engineers at the National Aeronautics and Space Administration’s Marshall Space Flight Center, in Huntsville, Alabama, are developing technologies that will enable explorers from Earth to take full advantage of the resources they find on the lunar surface or on Mars. Do-it-yourself is being taken to a whole new level. By Melanie P. Bodiford, K.H. Burks, M.R. Perry, R.W. Cooper, and Michael R. Fiske

Habitat manufacturing and assembly technologies that incorporate in situ resources provide options for autonomous, affordable, prepositioned environments that can protect explorers from Earth from radiation, micrometeorites, exhaust plume debris, and other hazards. This is important because gamma and particle radiation constitute a serious but reducible threat to long-term survival in space environments.

Structures will constitute the primary mass element in the equipment launched for habitation on the moon or Mars. The ability to use in situ material to construct these structures will provide a benefit by reducing the mass of launch payloads. Without this benefit the cost of constructing long-term habitats would be prohibitive. The ability to fabricate structures in situ brings with it the ability to repair these structures, which creates the self-sufficiency necessary for long stays in outer space.
SO$_2$ + 2H$_2$S $\rightarrow$ 2H$_2$O + 3S

The Claus process takes the hydrogen sulfide and the sulfur dioxide and passes them through a heated catalyst bed at a temperature of 323°C. The catalyst that is usually used is bauxite (Al$_2$O$_3$), which has been found in the Apollo lunar soil samples (G.H. Heiken, D.T. Vaniman, and B.M. French, editors, *Lunar Sourcebook: A User’s Guide to the Moon* [New York: Cambridge University Press, 1991]).

Test results have shown that the compressive strength of sulfur concrete is higher than that of hydraulic cement concrete. A concrete specimen made with sulfur and a soil material similar to that found on the moon (“simulant”) was tested in compression. The simulant was developed and characterized under the auspices of the Johnson Space Center (jsc), part of the National Aeronautics and Space Administration (NASA), and is referred to as jsc–1. The addition of silica to sulfur concrete has been found to increase the compressive strength by as much as 26 percent (H. Toutanjii, B. Glen-Loper, and B. Schrayshuhen, “Strength and Durability Performance of Waterless Lunar Concrete,” in *Proceedings of 43rd American Institute of Aeronautics and Astronautics Aerospace Sciences Meeting and Exhibit* [2005]). Mechanically, silica is very similar to the silicate minerals in the lunar regolith. This addition of silica to the sulfur concrete decreases the amount of sulfur required and improves the mechanical properties of the system. Results have also shown that sulfur concrete exhibits no reduction in strength when subjected to severe freeze and thaw exposures or to prolonged freezing. The failure mechanism for the specimens is unchanged under these conditions, being similar to that at room temperature.

Temperature variations are a primary factor affecting the strength of sulfur concrete. The temperature should not exceed 119°C (the melting point of sulfur), and to prevent not only surface melting but also volume changes in the sulfur it should be below 96°C. Another critical concern is the effect of low pressure and very low temperature on the sublimation of sulfur. The performance of sulfur under such conditions as very low temperature and very low pressure is not fully known and is currently being investigated (R.N. Grugel and H. Toutanjii, “Viability of Sulfur ‘Concrete’ on the Moon: Environmental Consideration,” in *Proceedings of 44th American Institute of Aeronautics and Astronautics Aerospace Sciences Meeting and Exhibit* [2006]).

Glass fibers and glass rebar have provided reinforcement in a large number of terrestrial civil infrastructure applications. Glass fibers and glass rods are also ideal candidates for use in lunar construction.

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containing glass fibers (1 percent by weight) were then made. The plates made of concrete produced with sulfur and jsc-1 were strengthened with glass fibers. The glass fibers were placed in a horizontal plane two-thirds of the distance from the top surface. Initial results showed that both strength and ductility were significantly improved with the addition of glass fibers made from a lunar simulant.

Reinforced-concrete structures on the moon will most likely be fabricated using one of the following technologies:
- Precast, prestressed panels and forms;
- Extruded concrete;
- Inflatable concrete domes;
- Convergent spray technology.

As mentioned previously, a key assumption is that water does not exist on the lunar surface; therefore the team at NASA’s Marshall Space Flight Center (msfc), in Huntsville, Alabama, and the University of Alabama in Huntsville (UAH) dealing with in situ fabrication and repair as it relates to habitat structures is focusing on the development of waterless concrete. For precast, prestressed panels and forms, the concrete will be cast into different shapes using molds. These molds can be either brought from Earth or manufactured at the site using solid free-form fabrication techniques.

Extruded concrete is produced in a process developed at the University of Southern California whereby concrete issues from a nozzle attached to a robotic arm that can translate in three dimensions so as to “print” a layer of concrete, rise a predetermined distance, and print another layer of concrete (B. Khoshnevis, M.P. Bodiford, K.B. Burks, E. Ethridge, D. Tucker, W. Kim, H. Toutanji, and M.R. Fiske, “Lunar Contour Crafting—A Novel Technique for In-situ Based Habitat Development,” in Proceedings of 43rd American Institute of Aeronautics and Astronautics Aerospace Sciences Meeting and Exhibit, paper AIAA-2005-0538 [2005]). Flat-roofed or domed structures could be supported with this technology, which could be used for both internally based and externally based systems, and the process lends itself very well to automation.

The msfc and the uah are currently modifying a previously developed subscale concrete extrusion system. The modifications will make it possible to fabricate structures of greater complexity on a larger scale and to experiment with nozzle design and material as a function of required abrasion resistance, temperature, et cetera.

By sandwiching a layer of “wet” concrete and expandable metal coils between two liners that provide hermetic seals and then increasing the pressure underneath the lower liner, an inflatable concrete dome with metal reinforcement can be developed. After the concrete sets, the liners can, depending upon the application, be left in place or removed. Developed by the architect Dante Bini (“A New Pneumatic Technique for the Construction of Thin Shells,” in Proceedings of the First International Association for Shell Structures International Colloquium on Pneumatic Structures [1967]) more than 1,600 of

- Fabrication and testing of new extrusion nozzles and a nozzle “shutter” that will reduce waste material and allow cleaner starts and stops;
- Evaluation and incorporation of Y axis modifications to aid the quest for geometries of greater complexity.

The msfc has also been evaluating the use of inflatable concrete domes. The companion paper in this issue describes the structures devised by Dante Bini (“‘Binishells’”). As part of this effort, the msfc has developed a temperature–dependent pressure control system that has been demonstrated to control differential pressure during inflation to ±0.0276 kPa.

Bags filled with planetary regolith also can be used to support or build a habitat or structure wall (E.N. Khalili, “Lunar Structures Generated and Shielded with On-Site Materials, Journal of Aerospace Engineering 2 [1989]). The bags would be brought from Earth. Filled regolith bags are dense and durable, provide radiation shielding, and take advantage of readily available materials, but development work remains to be done to address sealing problems and contain the very fine, very abrasive lunar regolith. The msfc has been working to determine the optimal material for the bags and the most effective compositions of regolith and binder to develop techniques for automated filling and placement of the bags.

As part of an ongoing project for the automated handling and transport of regolith, the msfc has developed a subscale, remotely controlled tracked vehicle with a center dump bed and a front-end loading scoop. The vehicle can be operated from a handheld device or a computer screen. Its control is currently being refined, and the vehicle is also being used to develop ways of mitigating the effects of the dust generated during operation.

The msfc also investigated various fabrication techniques for blocks made of various combinations of regolith and binders, the latter to be brought from Earth. This effort began with the design and manufacture of a set of molds to make small (approximately 25 mm) cubes. The molds are being used to fabricate blocks with varying compositions of jsc-1 and such binders as polyethylene, polyurethane, or ethylene vinyl alcohol copolymer (evoh). To make the polyethylene blocks, polyethylene powder is mixed with jsc-1 in varying compositions (the polyethylene ranging from 10 to 50 percent by weight), manually compacted in the mold to varying pressures, and baked in the mold at 204.4°C for one hour. The polurethane blocks are made by mixing liquid polyurethane with jsc-1 in varying compositions (the polyurethane ranging from 10 to 30 percent by
these “Binishells” have been developed worldwide, and this technology also lends itself very well to automation. In all of these technologies, reinforcement of the concrete can be provided either by adding chopped fibers of glass derived from lunar regolith or by introducing metal or glass rebar (rods in tension) that would be either fabricated on the surface of the moon or Mars or brought from Earth.

Convergent Spray Technology, a method developed by Advanced Systems Technologies, Inc., that can be used to apply thermal protective coatings to aerospace and military launch vehicles (see www.wjs.com/cstdet.html), is being used by NASA on the solid rocket boosters of the space shuttle vehicles. This process uses a specially designed nozzle mounted on the end of a robotic arm that prevents the binder and particulate from mixing until after both materials have exited the nozzle. For construction on the moon or Mars, a low-volume binder could be sprayed and mixed with an aggregate based on planetary regolith and deposited on a fine wire mesh frame or on an inflatable shell. Curing would thus yield a hard, dense reinforced structure.

The data on lunar water are inconclusive, but even if water does turn out to be available on the moon it will be a precious commodity. Thus, waterless concrete made of sulfur, a by-product of the processes for extracting oxygen and carbon, may be an excellent alternative to hydraulic cement. Concrete made of sulfur and lunar regolith would be ideal for building structures on the moon. Its availability, high strength, and durability make it a very attractive candidate for use in the first lunar construction activities.

Construction technologies of the type discussed here are seen as very promising for those systems that will require automated deployment. The development of habitats for explorers from Earth poses tremendous challenges—challenges that will be met only by combining innovative design with cutting-edge technologies. But the benefits conferred by the technological solutions thereby obtained will by no means be confined to outer space.

Houssam A. Toutanji, Ph.D., P.E., F.ASCE, is a professor of civil engineering at the University of Alabama in Huntsville. Michael R. Fiske is a project chief technologist with Jacobs Sverdrup in Huntsville, Alabama. Melanie P. Bodiford is a project manager with the Marshall Space Flight Center (MSFC), part of the National Aeronautics and Space Administration (NASA), in Huntsville, Alabama. The authors wish to acknowledge the financial support provided by NASA grant NNM05AA22A. They would also like to thank Kevin Burks, Steve Kennamer, Shirley Abercrombie, Bill Seymour, and Eric Rogers of the MSFC for their efforts in developing prototypes of various construction methods and D.S. Tucker and E.C. Ethridge, also at the MSFC, for producing the glass fibers. This article is based on the paper “Development and Application of Lunar ‘Concrete’ for Habitats,” presented by the authors at Earth and Space 2006, a conference sponsored by ASCE and held in Houston in March.

Another ongoing development effort at the MSFC concerns the processing of thin films for use as liners in existing structures or as components of self-supporting inflatable structures. The efforts have focused on Soarnol—an epoxy manufactured by the Nippon Synthetic Chemical Industry Company, Ltd., of Japan—which is known for its low oxygen permeability. Purchased in the form of small pellets, the material has been successfully rolled and formed into sheets and disks through compression molding. Attention is now being given to its recyclability.

As discussed in the companion paper in this issue, the MSFC has been investigating the fabrication of glass fibers and rods made of in situ materials for potential applications as reinforcement for lunar concrete or for stand-alone applications. JSC-1 has been successfully melted and cast into molds with diameters ranging from 9.5 to 12.7 mm to demonstrate the feasibility of manufacturing rebar. Also, several hundred meters of glass fiber ranging in diameter from 0.25 to 0.75 mm have been successfully pulled from a bath of molten JSC-1, demonstrating the ability to manufacture glass fibers.

The surface of the moon offers a unique set of resources for developing structures, including habitats, based on in situ materials. As part of the MSFC’s ISER efforts, a number of these resources have been and continue to be evaluated. Lunar regolith, as represented by terrestrial simulants, can be used to provide all the materials necessary to make lunar concrete, can be a major component of block manufacturing on the lunar surface, and can easily be transformed into glass elements. Future efforts will continue to characterize the performance of these materials as new requirements emerge.

Melanie P. Bodiford is a project manager at the National Aeronautics and Space Administration’s Marshall Space Flight Center (MSFC), in Huntsville, Alabama. K.H. Burks, M.R. Perry, and R.W. Cooper are test engineers at the MSFC. Michael R. Fiske is the project chief technologist with Jacobs Sverdrup in Huntsville, Alabama, based on-site at the MSFC. This article is based on the paper “Lunar In Situ Materials–Based Habitat Technology Development Efforts at NASA/MSFC,” presented by the authors at Earth and Space 2006, a conference sponsored by ASCE and held in Houston in March.