In-Situ Resource Utilization (ISRU): The Basalt Economy.

Authors:

- Romo, Rodrigo. Pacific International Space Center for Exploration Systems. (rfvromo@gmail.com)
- Andersen, Christian. Pacific International Space Center for Exploration Systems. (canderse@hawaii.edu
- Mueller, Robert P. NASA Kennedy Space Center, Swamp Works. (rob.mueller@nasa.gov)

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Abstract

Mankind has been practicing In Situ Resource Utilization (ISRU) for several millennia. As a species, we have been able to use available local resources to provide shelter, tools, weapons and clothing. Whether on the Moon or Mars, habitat & infrastructure construction will require the development of multiple construction materials and processes sourced from local materials. Regolith seems to be the most logical choice given its abundance and easy access.

The Pacific International Space Center for Exploration Systems (PISCES) in Hawai'i and NASA's Swamp Works at Kennedy Space Center in Florida, have been working on the development of different sintered basalt regolith materials that can be utilized in various construction applications.

In this paper we will describe some of the properties from the sintered materials developed as well as some of the applications in which these materials could be utilized. Other terrestrial basalt fiber based products currently existing will be discussed along with their possible use in lunar and or Mars based construction.

Back to the Stone Age?

Until relatively recent times, mankind has been utilizing the available resources found in its vicinity to provide shelter, tools, clothing, and weapons in order to improve the quality of life and provide protection from the elements. Every place where human settlements have been found shows an ingenious level of ISRU activity. Whether the mud huts from Africa, grass shacks from tropical areas, adobe dwellings from the South West or stone buildings from around the globe we have been able to extract, collect, mine, hunt and transform those raw materials into useful materials. As we look into building settlements on the Moon, Mars, or other places outside of this planet, we need to take with us some of that ancient knowledge in order to find the best way to utilize the resources we will find in these new worlds.

We have many advantages over our ancestors, for one, we can do remote exploration through the use of satellites, rovers, and other types of unmanned prospecting systems and instrumentation. This allows us to know what resources we will find before we get there. Another great advantage we have is robotic technology. The advancement of robotics will allow mankind to begin some of the work ahead of time and before humans arrive at the new locations. Through robotic operations, resources can be mined or extracted and some infrastructure can be pre-built in preparation for human habitation.

We know that the most abundant material for us to use on the Moon or Mars is going to be regolith; there is plenty of it, it is accessible, it has been crushed and weathered into granular form, and it is readily available. We will not have trees, animals, or plants at our disposal, so we will have to learn how to make the most out of regolith to provide shelter, infrastructure, tools and perhaps even clothing.

Using the Proper Materials

Fortunately, there is data from space missions describing the chemical composition of the regolith on the Moon and Mars. With that information in hand, it is possible to find a material here on Earth that would allow us to do testing and experimentation on different methods or processes for using, manipulating or transforming the lunar or Mars regolith into useful materials. Crushed basalt obtained from a quarry on the Big Island of Hawai'i was found to have very similar composition to lunar and Mars regolith samples. Table 1 shows the chemical composition of different lunar and Mars samples, a lunar simulant and the Hawaiian basalt used by PISCES and NASA's Swamp Works in the construction of a Vertical Takeoff- Vertical Landing (VTVL) Pad in 2015/2016 [1,2].

Sample	MnO ppm	Fe %	Na_2O %	MgO %	Al_2O_3 %	SiO_2 %	K_2O %	CaO %	TiO_2 %
Hawaii Quarry[1]	1888	9.071	2.68	7.877	14.602	51.777	0.55	10.995	2.124
JSC-1A	1800	10.79	2.7	9.01	15.02	47.71	0.82	10.42	1.59
LS 14163	1000	10.5	0.7	9.6	17.8	47.3	0.6	11.4	1.6
Spirit	2500	17	3	8.7	10.2	45	0.3	6.1	1
Opportunity	3000	18	2.1	7.5	9.1	44	0.4	6.9	1.1
Curiosity	3000	21	2.1	6.5	9.5	43	0.5	7.2	1.5

Table 1: Chemical Composition of lunar, Mars and Hawaiian regolith samples.

Hawaiian Sintered Basalt, Properties and Potential Applications

The Hawaiian basalt was used by PISCES in collaboration with NASA's Swamp Works group in the development of sintered basalt tiles used for the construction of a full scale vertical takeoff – vertical landing (VTVL) pad. The project took place between the fall of 2015 and March 2016 when the landing pad tiles were tested under a static rocket motor test.

The interlocking pavers were initially sintered using Hawaiian basalt fines (<150µm) with no additives. Paver production was a complicated task, turning out to be more of an "Art" in defining the proper thermal profile, particle sizes, and mold design for thoroughly sintering the basalt without creating cracks/breakage in the pavers. The spring/summer 2015 timeframe saw a steep learning curve in designing a thermal profile that would create a suitable basalt paver. The resultant thermal profile was an approximately 30-hour run time in a high temperature kiln, with a maximum sintering temperature of over 1,100°C. Early paver prototypes consistently failed in the same manner and revealed lateral stress areas where the pavers were pulling against the molds upon thermal contraction of the paver. These failures were resolved by making part of the molds "float" such that the molds would slip upon paver contraction. Prior to making the molds float, only about 10% of the pavers were intact by the end of the run-time .

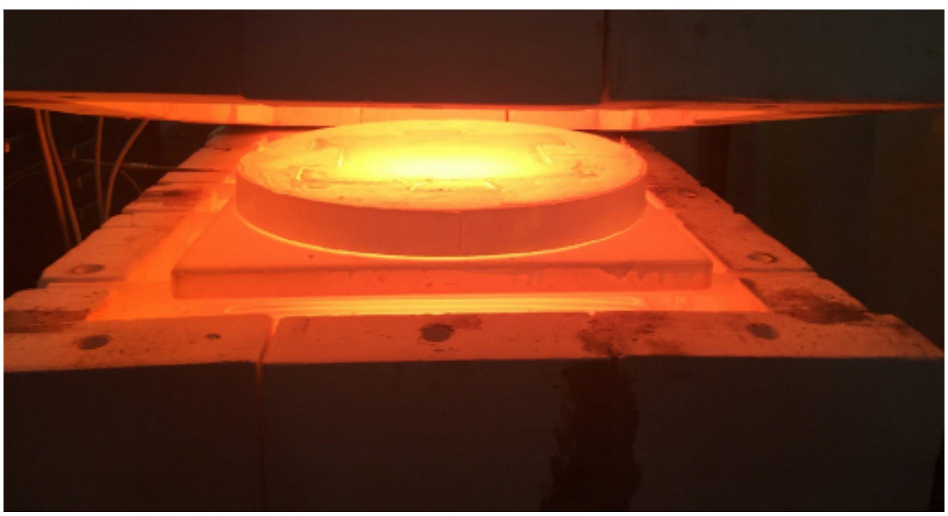

Figure 1: High temperature basalt paver fabrication kiln.

The post-modification intact rates improved to 50%, but revealed secondary stresses that accounted for the remaining failures. These secondary failures were due to vertical stress from the pavers contracting and pulling against the ledges of the mold. Due to the geometric constraints of the molds, additional floating modifications were not feasible. To reduce

[1] Analysis of the Hawaiian basalt was done by the University of Hawai'i in Hilo using an Energy Dispersive X-Ray Fluorescence (EDXRF) analyzer.

vertical contraction, a special mixture of particle sizes was found to offer the best performance with minimal shrinkage and overall failure rates dropped to less than 10%. The overall profile was finalized in September 2015 at which time paver production started in October 2015 and completed in December 2015.

NASA tests of the compressive and flexural strengths of the pavers yielded structural properties that exceeded residential concrete. Subsequently [3,4,5], PISCES modified the sintering temperature profile and was able to produce a material that surpassed specialty concrete with a compression strength of 35,000 pounds per square inch (psi).

Figure 2: PISCES Planetary Rover Helelani laying Sintered Basalt Pavers for the VTVL Pad Project in Hawaii, tele-operated from the Kennedy Space Center Swamp Works in Florida.

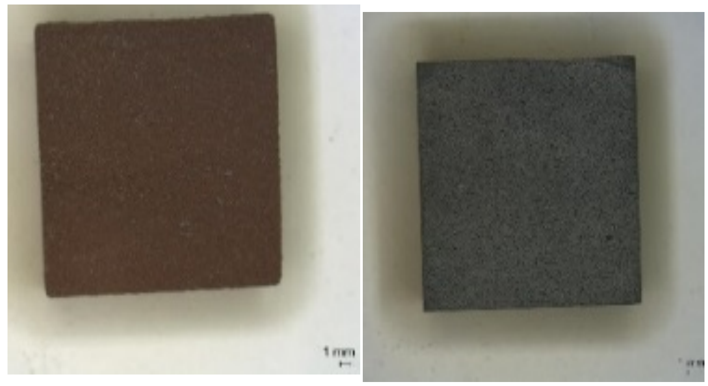

Figure 3: Hawaiian Sintered Basalt Samples: Left-Sample from paver used in VTVL construction (HHQ-Pad). Right HHQ+ sample

The two different samples were analyzed by NASA's Engineering Directorate, Material Science Division at Kennedy Space Center, FL. Table 2 shows the properties of the Hawaiian Sintered Basalt Samples compared with residential, commercial and specialty concrete. The samples analyzed were from one of the pavers used during the static rocket motor test (Hawaii Hilo Quarry (HHQ)) and from a sample from the modified thermal profile (HHQ+).

Test	Residential Portland Cement Concrete (typical)	Hawaii Hilo Quarry (HHQ)	Commercial Portland Cement Concrete (typical)	Specialty Portland Cement Concrete (typical)	HHQ+
Flexural Strength (psi)[2]	500	716	800	2,000	5,852
Compressive Strength (psi)[3]	2,500	3,116	4,000	10,000	30,825

Table 2: Flexural & Compressive Strength Properties of Hawaiian Sintered Basalt and Concrete[4]

Scanning Electron Microscope (SEM) analysis of the two crushed test samples showed many pores and voids and a few cracks present in the HHQ Paver sample. The HHQ+ sample contained a more even surface with few spherical pores on the surface (Fig 4). In addition density measurements were taken on the samples. The HHQ sample had a density of 1.699 g/cm^3 and the HHQ+ sample had a density of 2.64 g/cm^3.

[2] The flexural strength (Modulus of Rupture) test was conducted in accordance with ASTM C133, Standard Test Methods for Cold Crushing Strength and Modulus of Rupture of Refractories
[3] The cold crushing strength, or compressive strength, test was also conducted in accordance with ASTM C133.
[4] Theoretical values for concrete according to NRMCA.

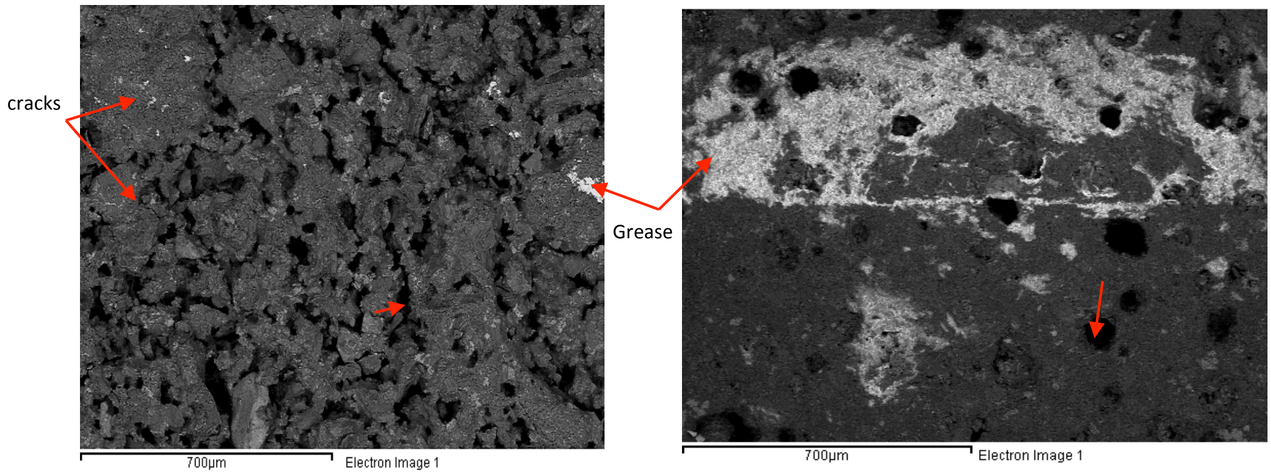

Figure 4: SEM Analysis of HHQ sample showing presence of cracks and many voids (left) and HHQ+ sample showing randomly distributed spherical voids (right). Magnification 75x.

The fact that these samples were produced without any additives or hydration, but rather just through the application of energy to indigenous crushed basalt rock, makes them ideal candidates for further research. The properties observed in the two sintered basalt samples offer a wide range of opportunities for lunar/Mars applications. Some of the potential applications for sintered basalt include but are not limited to:

- Paver manufacturing for Thermal Wadis
- Reentry Thermal Heat Shields
- Radiation Shields.
- Indoor/Outdoor Flooring Tiles
- Tools & Parts
- Flywheels for Kinetic Energy Storage Systems
- Construction Blocks
- Thermal insulation
- Paved surfaces for dust mitigation
- Pavers for landing and launch pads

Regolith Fiber Manufacturing

Basalt fibers are currently being used in the manufacturing of terrestrial products that include rebar, mesh, rope and fabric. These products have extraordinary properties with regards to strength, durability, chemical resistance, thermal insulation and radiation tolerance. Being able to manufacture basalt regolith fiber and associated derivative products locally on the Moon or Mars would significantly improve the level of sustainability of human settlements. Basalt fiber with the use of polymer thermoset or thermoplastic resins can be used in the same manner as carbon fiber or fiberglass polymer matrix composite materials. The fabric could also be utilized as part of the layers in EVA suits.

Not all basalt rocks are suitable for fiber manufacturing, table 3 shows the recommended range of various constituents in basalt rock that would be suitable to make continuous fibers (http://excelement.com/basalt-fibre-technology).

Component	Fe	Na_2O + K_20	MgO	Al_2O_3	SiO_2	CaO	TiO_2
Range (%)	9-14	3-5	3-5	14-19	50-60	5-10	0.5-3

Table 3: Desired chemical composition of Basalt for Fiber manufacturing.

From tables 1 & 2 it can be inferred that fiber manufacturing with lunar or Martian regolith may be possible. The next step will be to attempt to make basalt fiber with the Hawaiian regolith and test its structural characteristics. This will then open the door to research on the fiber extrusion process under space environment conditions.

Future Research

Results from sintering tests have produced promising basalt materials that could create a game changing situation with regard to habitat development, tool manufacturing and space infrastructure. Further research needs to be done in order to better characterize the following properties of the sintered materials:

- Tensile Strength
- Thermal conductivity
- Dielectric Properties
- Magnetic Properties or ability to magnetize
- Machining Operations for Precision Manufacturing

During the sintering process, there is a significant amount of shrinkage that takes place due to the nature of the process itself. Some of the biggest challenges foreseen involve machining of the sintered materials, especially materials such as the HHQ+. This means that molds will have to be made bigger than the final units need to be in order to account and compensate for the shrinkage, and once the part is removed from the mold, machining or grinding the piece to the design specifications may need to be done, depending on the required tolerances and applications.

Some of the ideas being considered for the first products to be made include abrasive grinding wheels which can be used to machine or grind the other pieces down to their desired dimensions and specifications.

Conclusions

Basalt regolith is abundant and readily available on both the Moon and Mars. The results produced by PISCES and NASA's Swamp Works using the compositionally similar Hawaiian basalt have opened the doors to numerous possibilities of ISRU applications that could rapidly advance the technologies, concepts and processes for human habitation on the Moon or Mars. However, further research is required in several areas in order to verify properties of the materials and feasibility of manufacturing.

Basalt has unique materials properties and basalt rock is commonly available in vast quantities on Earth at very reasonable prices. In fact, crushed basalt rock fines are a waste product in rock crushing operations for gravel commonly used in building roads. Using basalt in crushed rock form or in the form of drawn fibers, many products can be derived such as concrete reinforcements, cables, insulation, abrasives, woven cloth for polymer matrix composites, modular building blocks and 3D printed structures for metal forming molds or actual parts. By creating new basalt products for terrestrial applications, a new industrial sector can be developed which will create income and knowledge. This capital and expertise can then be used to create a "Basalt Economy" in outer space, where useful products will be created outside of Earth's gravity well, therefore avoiding substantial launch costs (>$5,000/kg) and creating the foundation for further economic activity in space, which will translate into a greater creation of wealth and prosperity for humans on Earth. The Hawaiian islands are a logical place for developing and incubating the "Basalt Economy" since indigenous basalt is ubiquitous and the local culture embraces its use to become world leaders in this new industrial sector.

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