Planetary Lego: Designing a construction block from a regolith derived feedstock for In-Situ Robotic Manufacturing

Rodrigo Romo[1] , Christian Andersen[1] , Kyla Defore[1] , Kris Zacny[2], Madhu Thangavelu[3], Thomas Lippitt[4]

[1]Pacific International Space Center for Exploration Systems, 99 Aupuni St. Ste 212-213, Hilo, HI 96720; PH (808) 935.8270; email: rfvromo@gmail.com, canderse@hawaii.edi
[2]Honeybee Robotics, 398 W. Washington Blvd., Ste. 200, Pasadena, CA 91103; PH (626) 421.7902; email: zacny@honeybeerobotics.com
[3]Department of Astronautics, Viterbi School of Engineering and School of Architecture, University of Southern California, Los Angeles, CA. PH ( ); email: thangavelu-girardey@cox.net
[4] Granular Mechanics and Regolith Operations Laboratory, NASA Kennedy Space Center FL 32899; PH (321) 867.1391; email: Thomas.lippitt@nasa.gov

ABSTRACT

Prior to human arrival to the Moon or Mars, some infrastructure will be required to ensure success of the goals of the mission. Such infrastructure may include landing pads, dust mitigation surfaces, thermal wadis, and shelter/habitats.

To reduce the mass of construction materials to be transported from Earth, it will be critical to utilize in-situ resources as the main construction material. Regolith seems to be the most logical choice given its abundance and easy access. There are two critical components to this task:

- **Materials:** The ideal material to exploit, given its abundance and accessibility is regolith. Regolith-derived feedstocks that can be used to manufacture parts, tools & construction materials to ensure a constant supply of raw materials for the success, maintenance and expansion of a mission.
- **Automation:** Some of this work is expected to be done before human arrival through robotic operations. Even after human arrival, resource extraction, collection, sorting, processing and construction should be done tele-robotically to reduce crews' Extra Vehicular Activity (EVA) time and radiation exposure. This will require equipment that can operate autonomously/semi-autonomously to perform all the tasks involved.

Honeybee Robotics, the Pacific International Space Center for Exploration Systems (PISCES) and USC's Viterbi School of Engineering and School of Architecture are working together under a NASA STTR Phase I contract to design and test a prototype building block using Hawaiian basalt that can be used for both horizontal and vertical construction projects. The final product should be able to meet construction standards, be manufactured without any additives, have a design that allows for robotic emplacement and have either an interlocking design or a mechanical joint.

BACKGROUND

It is evident from lander missions including Apollo and the recent 1Mt MSL, that energetic debris raised by lander propulsion impinging on pristine, unstabilized extraterrestrial surfaces can have lethal effect on both the lander components as well as high value assets in the vicinity of the lander. [Fig 1]

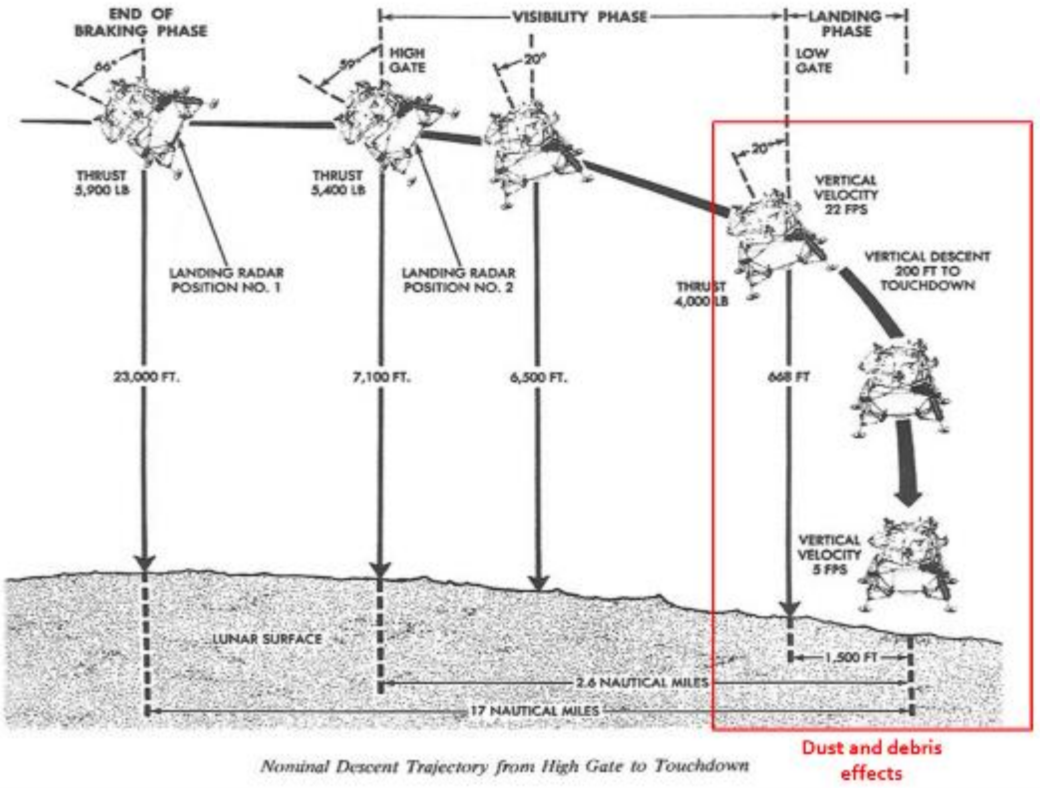

Figure 1 Hypersonic dust, a debris ejecta raised by the lander propulsion engines can have devastating effect on crew and high value assets several kilometers away from the landing site. Therefore, sturdy landing pads are essential for safe and repeated sorties missions in the vicinity of base of operations.

Solid, reliable, dust-free surfaces are needed for sortie missions to avoid hypersonic ejecta in ballistic trajectories from destroying spacecraft and high value assets. Landing pads are essential to safe and repeated landing operations.

Monolithic landing pads are proposed to be built up by sintering or other technologies. Measuring two to three times the footprint of the lander (30-45m dia), such structures may not be the most practical because the extreme diurnal thermal cycling presented by extraterrestrial surfaces will cause cracking of the built-up surface. The same problem arises for exposed extraterrestrial roads and allied platforms. Hence modular cellular tiled surfaces may be the most viable and promising option to test and certify.

Selective separation laser sintering(SLS) has been proposed to overcome part of this fragmentation and disintegration problem but does not completely solve it.[Figure 2]

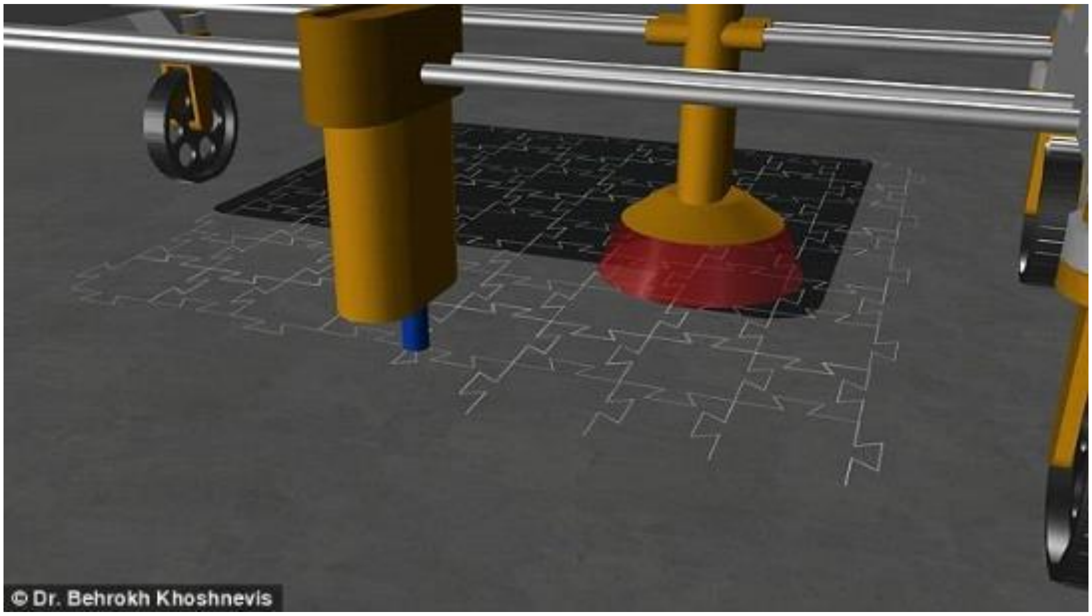

Figure 2 Selective Separation Sintering proposes to solve the monolithic fracturing problem by producing sintered, tessellated tiles in situ. It does not attempt to solve the 3D interlocking tiles design that is needed. [credit Khoshnevis]

Two-dimensional tessellation of the built-up landing pad surface may not be sufficient to withstand the propulsive forces since tiles can come loose and become effective high energy projectiles that can be lethal for crew or impact assets several kilometers away.

3-dimensional Interlocking tile design may hold the answer to stable and resilient paving that can withstand the forces involved on a repeated basis (100 landings as reference).

Interesting topological challenges exist in the design of such tiles. Three-dimensional folding morphology as seen in Nature like complex proteins, and cellular shapes and packing factors with minimal interstitial spaces and two dimensional footprints may offer clues to interlocking structures that may be useful. Origami techniques and smart bricks coupled with clever, modular pinning mechanisms may hold the key to developing paving systems that can resist multidimensional forces and hold their interlocking grip while still flexing and bending enough over several degrees of freedom. Such systems could be robotically deployed using techniques already being developed by Honeybee Robotics and PISCES.

PREVIOUS WORK

Between the summer of 2015 and the Spring of 2016 a team formed by the Pacific International Space Center for Exploration Systems (PISCES), NASA KSC's

SwampWorks group and Honeybee Robotics demonstrated the feasibility of robotically constructing a full-scale landing pad using only Hawaiian basalt for its construction [Figure 3]. Hawaiian basalt has similar properties to lunar and Mars regolith [Table 1], making it an ideal material for ISRU testing. [1]

Table 1: Chemical Composition of Hawaiian Basalt, Lunar Simulant, Lunar/Mars Regolith.

Sample	MnO ppm	Fe %	Na_2O %	MgO %	Al_2O_3 %	SiO_2 %	K_2O %	CaO %	TiO_2 %
Hawaii Quarry	1888	9.07	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

Figure 3: PISCES Rover Helelani (left) using Honeybee Robotics robotic arm during the construction of vertical landing pad using pavers made with Hawaiian basalt, and the completed pad & apron prior to rocket engine test (right).

The project produced the following results:

- Pavers made with sintered basalt [Figure 4] showed stronger flexural & compressive strength than residential Portland Concrete [Table 2]. During the manufacturing of the pavers, a modified sintering procedure was performed using a different thermal profile using the same basalt feedstock. The material (HHQ+) produced during this test had structural properties 10 times stronger than the material used for the pavers, and three times stronger than specialty Portland Concrete. [2]
- The sintered basalt pavers were capable of withstanding the high velocity and high temperature of a solid fuel rocket motor during a static test.
- The entire process of building the landing pad (which included leveling and grading the area, compacting the regolith, deploying the pavers for the bullseye

and spreading and leveling gravel for the apron) was done robotically through teleoperations.

- The interlocking design and manual process of making the pavers resulted in weak areas of the landing pad which led to cracking and separation during the rocket motor test.

Figure 4: Interlocking Pavers made with sintered basalt used in the construction of a landing pad in Hilo, Hawai'i.

Table 2: Flexural & Compressive Strength Properties of Hawaiian Sintered Basalt Pavers and Concrete.

Test	**Residential Portland Concrete**	**Hawaiian Sintered Basalt Paver**	**Commercial Portland Concrete**	**Specialty Portland Concrete**	**HHQ+**
Flexural Strength (ksi)	0.500	0.716	0.800	2.000	5.852
Compressive Strength (ksi)	2.500	3.116	4.000	10.000	30.825

MOVING FORWARD

The material produced under the HHQ+ sintering profile offers a variety of possibilities for planetary construction. In this proposal, design work will be done on 3-dimensional interlocking, modular, cellular tessellation systems for tiles that could be useful for a variety of applications besides landing pad design [Figure 5]. They include contoured micrometeoritic armor that can protect from micrometeoric showers and serve as radiation shielding for habitat overlays as well as for road paving, shade walls and other platforms. [Figure 6].

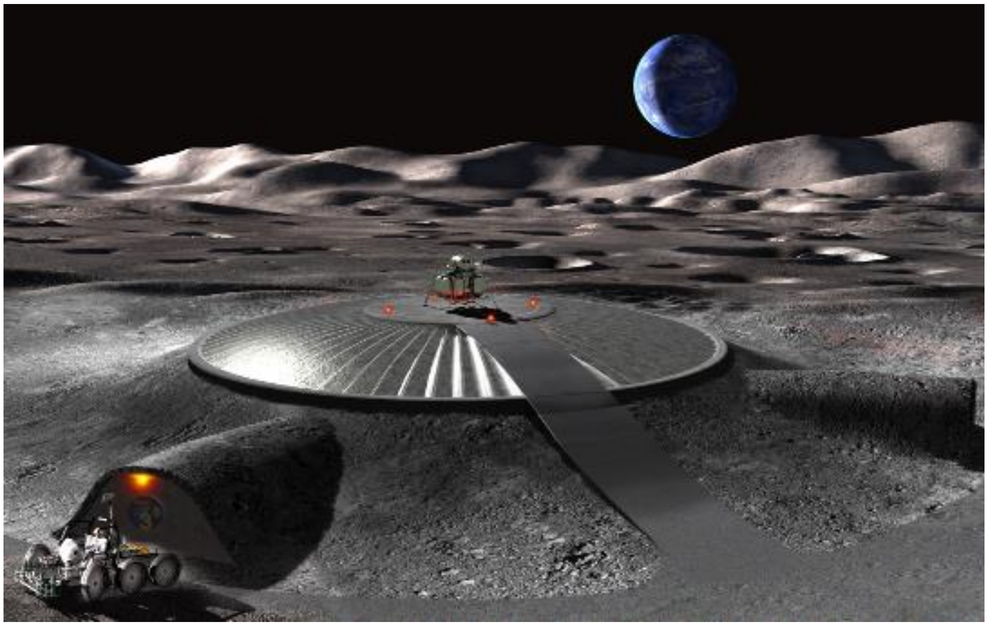

Figure 5: Three-Dimensional interlocking tiled surface assembled on site from prefabricated lunar regolith tiles as well as special refractory center core tiles tempered specially to handle the high temperature exhaust gases of the lander from repeated sortie missions may be viable using innovative technologies being studied by our group.

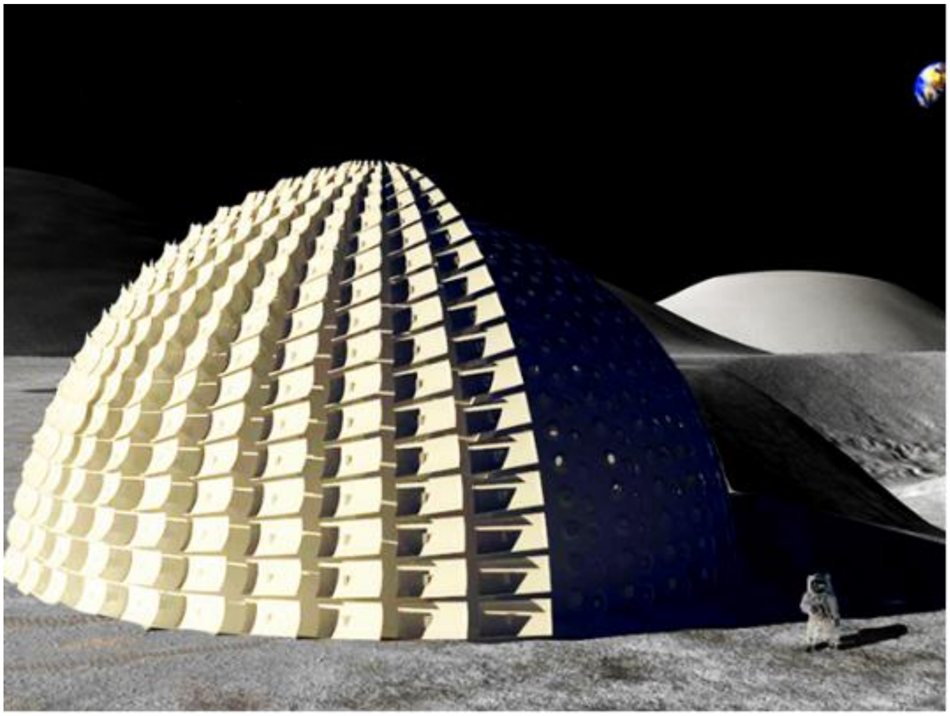

Figure 6: Three-dimensional interlocking tiles may have other applications including radiation shielding, thermal control and micrometeoritic armor overlays over habitats.

The structural properties of the material developed could allow the use of mechanical joints to hold the tiles, and by designing 2-3 basic structural interlocking modules (SIM) to enable robotic modular construction, without introducing the added complexity of additive manufacturing, structural "welds", or grouting. These modular tiles would facilitate the expansion of the previous work that allowed for horizontal construction only, into 3-dimensional structures. Figure and Figure 8 show two different conceptual designs of a combination of SIM's.

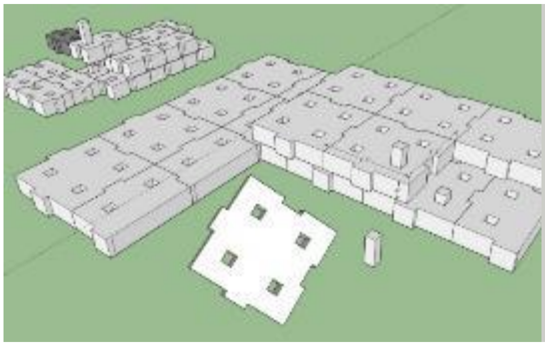

Figure 7: Sintered Basalt Structural Interlocking Modules (SIM) with vertical locking pins conceptual design.

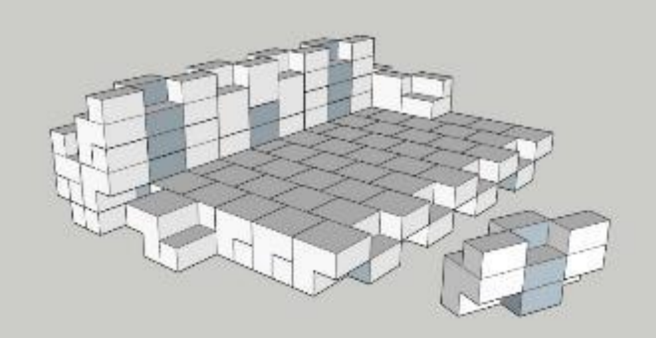

Figure 8: "Tetris" style Structural Interlocking Module Conceptual Design

HAWAIIAN BASALT

Hawaiian basalt in particular is of interest for regolith simulation due to its remarkable similarity in composition to those found on the moon and Mars. The composition of Hawaiian basalt may vary depending on several factors, such as: mountain of origin, age of flow/time of eruption, type of flow etc.

During the initial stages of the STTR Phase I grant, PISCES and Honeybee Robotics will be working on collecting samples from different quarries on the island of Hawai'i and perform chemical composition analyses. This will provide an idea of the variations of basalt throughout the island. Simultaneously, different designs for blocks and interlocking mechanisms will be worked on.

The samples collected will be sintered at different thermal profiles and structural and chemical analyses will be performed to determine what composition, mineral assemblage, and thermal profile yields the best material to work with.

Table 3 shows the composition from four samples collected through August 2017 from three different locations. As it can be seen from the table, the chemical composition of basalt can change even from samples collected from different locations within the same quarry.

Table 4 shows structural properties from sintered samples from Glover, PTA and W. Hawaii. Samples were sent to the University of Hawai'i Manoa and tested according to ASTMC133, Standard Test Methods for Cold Crushing Strength and Modulus of Rupture Refractories.

Table 3: Chemical Analyses through EDXRF of basalt collected from different quarries.

	MnO (ppm)	Fe (%)	Na_2O (%)	MgO (%)	Al_2O_3 (%)	SiO_2 (%)	K_20 (%)	CaO (%)	TiO_2 (%)
Puna Rock 4A Pisces	1677.425	8.54	2.392	9.109	12.552	50.69	0.347	9.838	1.755
Puna Rock 4B Pisces	1773.913	9.606	1.758	19.127	9.027	47.513	0.223	6.941	1.259
Glover Fines Pisces	1672.517	8.176	2.404	6.781	13.007	50.504	0.353	10.132	1.777
MK Ash Flow Pisces	2327.327	7.729	3.311	2.916	13.802	50.161	1.874	5.973	2.406
PTA Quarry	1639.78	8.23	2.45	5.574	13.664	52.119	0.411	10.808	1.977
W. Hawai'i Quarry	1712.953	9.41	2.284	14.067	11.804	50.152	0.293	8.304	1.577

Table 4: Structural test results from 3 different Hawai'i Quarries.

Test	W. Hawaii Sample	PTA Quarry	Glover Quarry
Flexural Strength (ksi)	0.15	1.04	1.24
Compressive Strength (ksi)	0.54	4.13	6.93

The samples from the West Hawai'i Quarry did not produce a sintered product of satisfactory properties, the other two samples did. The samples from Glover exceeded the strength from samples previously produced (Table 2).

The final objective for Phase I of the grant will be to produce and test a block design that will allow for horizontal and/or vertical construction through robotic teleoperations. Phase II will focus on the automation processes for the manufacturing of the blocks and the emplacement. Basalt from the Glover quarry will be utilized in the manufacturing of the blocks.

CONCLUSIONS

Preliminary work shows promising results yielding a material that is structurally adequate for construction purposes. The work is still in early stages. Further work needs to be done in evaluating how basalt sintering behaves under Lunar or Mars conditions (pressure and temperature wise). So far, the sintering work has been done under Earth atmosphere pressure and composition. However, if a reliable method to produce this regolith derived feedstock can be developed, without the use of any aggregates or additives, it would mean that an unlimited and readily available amount of construction material would be available for construction on the surface of the Moon or Mars.

A significant advantage of the processes suggested in this study relies on the simplicity of the concept. The raw material can go directly from the ground and into the production line without having to go through any separation, refinement or synthesis process.

Different grades of sintered basalt can be utilized for a variety of purposes including: tools, structural components, spare parts, VT/VL tiles, roads, indoor pavers, thermal re-entry tiles, radiation protection, thermal wadis, and shelter/habitat construction.

REFERENCES

[1] Romo, R., Kelso, R.M., Andersen, C., Mueller, Lippitt, T., Gelino, N.J., Smith, J.D., Townsend, I.I., Schuler, J.M., Nugent, M.W., Nick, A.J., Zacny, K., Hedlund, M. “Planetary Basalt Field Project: Construction of a Lunar Launch/Landing Pad, PISCES & NASA Kennedy Space Center Project Update” Presented at Earth & Space Conference, April 11-15, 2016, Orlando FL.

[2] Romo, R., Andersen, C., Mueller, R.P., “In-Situ Resource Utilization (ISRU): The Basalt Economy, Presented at New Worlds 2016 Conference, November 4-5, 2106, Austin, TX.

[3] Thangavelu, M., “Living on the Moon”, Encyclopedia of Aerospace Engineering, Online, John Wiley & Sons, 2010.