Dual-Use Research in Sustainable Construction on the Moon

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ABSTRACT

The performance of terrestrial materials, tools and equipment has synergized over thousands of years. As the prospect of mining and construction in space increases mining and construction engineers are challenged to design and test technologies that will perform under conditions totally different from those on Earth. The Space Mining and Construction Laboratory (SMCL) at the University of New South Wales has been working on several research projects experimenting with new building methods and materials for space. Of course, sustainability in these extreme environments is critical as the supply of material, machinery, etc. from Earth is cost-prohibitive. The goal of every project is to design solutions that rely to over 95% on In-Situ Resources (ISRUs). The paper will present the ongoing experimental work in: a) lunar and asteroid mining, b) waterless concrete, and c) in-situ thermal energy storage.

INTRODUCTION

In April 2013, Bechtel Engineers and Constructors joined the Planetary Resources Inc. to help it mine near-Earth asteroids for water, precious minerals and rocket fuel. Also this year, Deep Space Industries, a newly established space exploration company announced that it plans to create the world's first fleet of commercial asteroid-mining spacecraft. As the active participation of Bechtel demonstrates, space mining will require more than just hauling "dirt". It will require the design and construction of new structures in zero- or microgravity, activities that have never been necessary. On the other hand, the two new space companies believe that the Return-of-Investment from mining Moon and asteroids are extremely attractive. Naveen Jain, co-founder and chairman of Moon Express confidentially tells you that his company will start with lunar mining in 2016 to establish a secure source of "rare earth" minerals, the chemical properties of which are critically important for manufacturing high-tech products such as i-phones, electric and hybrid cars. Other possible "money-makers" abundant on the Moon are Helium-3 (He-3), Hydrogen (H) and Oxygen (O).

What will we use to construct such protections? Will each explorer take along his or her own shelter or will we build it using the resources available? Lessons from historical ventures may guide us. Bernold and Benaroya (2006) wrote: "… settlers in a new "land" depend on the effective use of In-Situ-Resources in order to ensure a sustainable presence. Even explorers who tried to traverse large spaces on Earth with plentiful provisions ended up being fed and saved by aborigines, natives of the land, who had learned to adapt to the environment within they lived."

Not surprisingly, the term In-Situ Resource Utilisation (ISRU) has become a focal point of research targeted to developing technologies in support of the long-term stay of humans in space. As the first phase of space exploration will most likely be based on robotic technology, the key for "survival of smart machines" will be the sustained production of energy which will also be essential for supporting human life in "hostile" environments.

Lunar soil, referred to as regolith, differs from soil on earth in several respects that are significant for construction. While the soil that establish the top layers (10-20 cm) is loose and "powdery", easily observable on Apollo movies, reaches the relative density of the regolith below 30 cm 90-100 percent. The grain size distribution of a common regolith as well as its high density below the top layers, hardly found in the terrestrial environment, create unique problems for excavating, trenching, backfilling, and compacting the soil (Benaroya and Bernold 2008).

LUNAR BASE FOR HUMANS AND ROBOTS

Even before Jules Verne's fantastic book published in 1865, "*From the Earth to the Moon*", concepts for lunar base structures have been proposed. One example offered by NASA some year ago is shown in Figure 1. Of course it resembles very much a terrestrial concept with a repair hanger, roads, towers and a bridge. While the travelled road lacks a hardened surface, something that the Romans learned to avoid, indicate the colour of the hardened structures the use of Portland cement concrete.

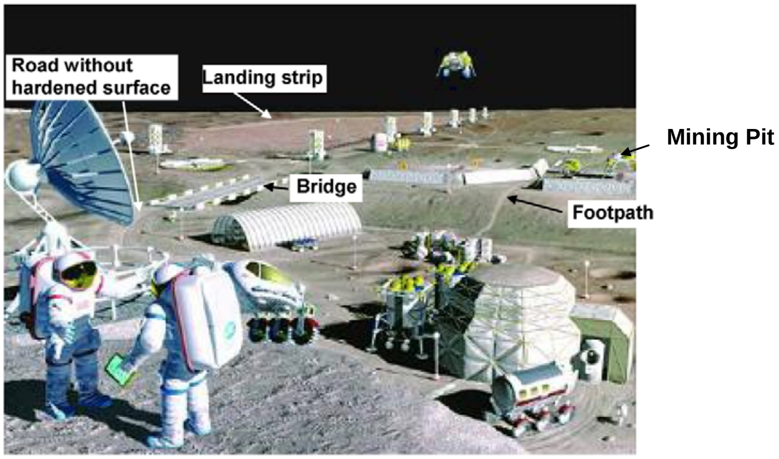


Figure 1. Example design of a populated lunar base (adapted from NASA, 2013)

The main purpose of the heavily populated base is not imminently clear. On Earth, one of the main drivers for exploration, with the exceptions of the poles, has been the mining of precious material, be it amber, flint, copper or gold. It is therefore no surprise that the potentials of mining the Moon and Asteroids has attracted private investments. Naturally, the need to install and maintain mining equipment will ask for supplemental technologies and facilities such as robots, soil processing/disposal machinery, and storage facilities. While the lunar environment does not lead to corrosion, the deep temperatures during the 17 day lunar nights, the fine dust, and the lethal radiation from solar flares require protections for both electronics and humans. The following section will discuss the critical issues of efficient excavation and mining the lunar soil with its unique characteristics.

TECHNOLOGIES FOR SPACE EXCAVATION AND MINING

All the common excavation technologies used on Earth depend on the effect of gravitational acceleration that turns mass into forces that are needed to cut, scoop, and move soil and rock. To study the related problems, large amount of lunar soil simulants were compacted to the necessary 90% density using a large hydraulic press. Subsequently a robot backhoe excavator was equipped with a bucket simulating a 6 times larger bucket on the Moon, (Bernold 1991), was unable to penetrate the dense soil-surface. Furthermore, a scaled clamshell bucket was equipped with a vibrator, as shown in Figure 2 b), but also was not able to load soil at all. It became apparent that a different approach to soil loosening was needed. A first approach was the use of explosives to loosen the dense soil so it can be excavated with a limited amount of force. Although the ejection of regolith would be hard to control possibly render it un-acceptable on the lunar surface, the research showed that explosives would loosen the dense soil very effectively. (Lin et al., 1994)

The developed technology being tested at UNSW is based on a closed pressurized system of pipes, filters and a blower/fan that transport the Australian Lunar Soil Simulant (ALSS) from the mining nozzle, inserted into a starter hole and plugged with a packer, to the separator above a future soil processing facility. Airflow is the result of a pressure difference in the pipe system. This is achieved by either creating high pressure at the intake side or low pressure at the output side. The fundamental physical principle of this operation is the ideal gas law:

$$p * V = n * T * R \qquad (1)$$

Where:

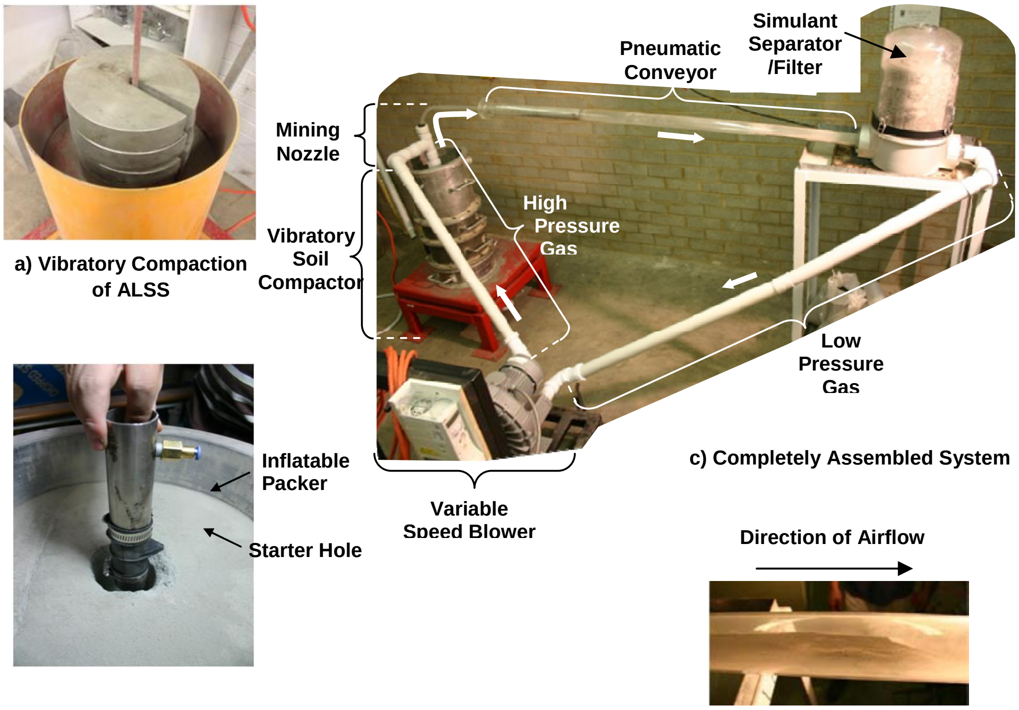
p = Pressure of the gas
V= Volume of the gas
n = Amount of substance of the gas (in moles)
R = Gas constant ($8.314\ J \cdot K^{-1} mol^{-1}$)
T = Absolute temperature in K

Boyle’s law refined the general law for a non-fluid condition where the temperature stays constant.

$$p_A * V_A = p_B * V_B \qquad (2)$$

Equation (2) indicates that the value of $p*V$ for condition A in a closed cycle is equal to that for condition B. In other words, if the pressure between A and B goes down, the volume must go up along a non-linear convex curve.

The presented system will also be useful in the production of waterless lunar concrete that will consist of mined regolith and glass fibers and pipes processed from the lunar regolith containing plenty of silicate.



a) Vibratory Compaction of ALSS

b) Insertion of Mining Nozzle

c) Completely Assembled System

d) Soil Accumulation Inside the Pipe

Figure 2. Pneumatic mining of Australian lunar soil simulant

Figure 2 displays the main components of the pneumatic mining system. The ALSS is filled into a steel cylinder mounted on a vibrator and loaded with a surcharge as depicted in Fig. 2 a). After 10 minutes of compaction a starter hole is drilled into the surface and the mining nozzle with the packer installed, shown in Fig. 2 b) done by hand during preliminary experiments. While Fig. 2 c) presents all the components of the prototype system comprising the blower, the compacted soil inside the steel cylinder, the closed cycle pneumatic pipes, and filter separator. Extensive experiments have been conducted to study the impact of pressure, gas velocity, pipe length and elevation changes.

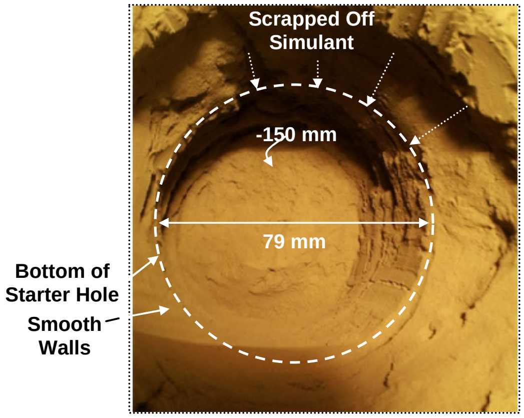


Figure 3. Mined vertical shaft using 73 mm inverted funnel nozzle

Figure 3 shows a view of the 150 mm deep mine shaft created by a 73 mm funnel nozzle creating a 79 mm diameter smooth cylinder. The air flowing from the high pressure to the low pressure-high speed riser pipe was forced through the 3 mm ring opening along the circumference of the funnel mouth. Because the created area is 970 mm^2 one can approximate the air velocity around the perimeter for a 40 km/hr air velocity created by the blower as 40 km/hr (1519 mm^2 /970mm^2) = 62 km/hr.

Present research efforts are directed at adding the capability of mining horizontally using a directional nozzle and extending the piping system.

WATERLESS AND CARBON-FREE CONCRETE

In the year 2000, General Portland Cement concrete accounted for 71% of the construction material in Europe (Gemert, 2005). As this cement requires lime water and lime, both hard to come by on the Moon, other binders have been sought for this ISRU heavy construction material. The research at UNSW focused on two that can be produced with material available on the Moon: a) Natural sulphur, and b) (carbon-based) polymer. When Portland cement is completely substituted it is referred to as sulphur or polymer concrete.

Thermoplastic polymer as binder

Thermoplastics melt at different temperatures and return to a solid state upon cooling. Most importantly, the melting point can be chosen and the melting-cooling process can be repeated. The process for creating the concrete on the lunar surface is relatively simple as the heating can be done with solar thermal energy that can be stored and recycled. Some polymers are particularly radiation resistant and they also provide extremely high strength properties. Still, the need for sufficient pressure and consistent temperature to bind the polymers evenly creates a challenge to create large concrete objects using the maximum amount of in-situ soil material. The first thermoplastic used had a melting point of 160 ºC but was replaced one that has a melting temperature of 110ºC and an amorphous density of 0.9g/cm^3. The ratio of polymer used for a sample mix was based on mass. The first mixes contained 10% polymer. Compressive strength was measured using cubes as shown in Figure 4 a) and its tensile strength a 3-point flexural method in accordance with the Australian Standards (AS1012.11 2000) was used. Figure 4 b) presents the set-up for a hollow hollow-core beam.

a) Sample Cube After Failure **b) Hollow Beam Before Flexure Test** **c) New Polymer Concrete Sample**

Figure 4. Strength testing of polymer concrete samples

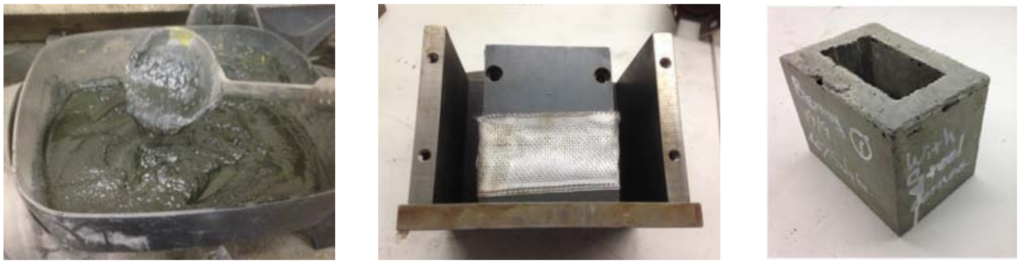
The first samples produced low compressive strengths with an average of 4.0 MPa and the flexure tests resulted in a tensile strength of 1.4 MPa. A new set of experiments with the second polymer focuses on studying the effect of pressure during “curing” on the compressive and tensile strength. The first results are promising indicated by a drastically improved surface smoothness shown by the sample in Fig. 4 c).

The hypothesis of the second set of experiments predicts a strong correlation of pressure and compressive as well as tensile strength.

Elemental sulphur as binder

The key goal of sustainable construction is to increase the use of natural material that does not destroy the environment. Sulphur concrete received significant attention from the scientific community during the early 1990’s as a potential material to safely contain hazardous material (Kalb et al., 1991, Vroom 1991, Lin et al., 1995) and more recently as a sustainable alternative to cement (Sandrolini et al., 2006). Sulfur is not only readily available on Earth but also on the Moon. Thus, to achieve a good understand of how to cast and its achievable strength will help in studying its use in both spaces.

The production of sulphur concrete begins with the preheating of the aggregates and formwork prior to the mixing step to a temperature of 90 ^{o}C. The premeasured sulphur powder is heated to the same temperature in a container to an oily state inside a contained and ventilated area. Finally, the aggregates are added into the pan to create the completed mix shown in Fig. 5 a).



a) Heated Sulphur Concrete Mix **b) Hollow Beam Form with Glass Fibre Reinforcement** **c) Deformed Beam Section**

Figure 5. Casting sulfur concrete to create hollow beam elements

The temperature is critical at this point as the mix will change its consistency very quickly. The pouring of the mix into the preheated forms, as the hollow beam segment, can be done in using various techniques. Steel reinforcement can be used similar to the Portland Cement concrete. Fig. 5 b) presents the use of glass fibre fabric that was tested. The deforming can be done 20 minutes after casting as the strengths increases rapidly with the cooling. Figure 6 shows a deformed cube and a beam sample that were both tested using standard compression and flexure test procedures.

a) Deformed Cube Sample b) Compression Test c) 3-Point Flexure Test

Figure 6. Compression and flexure tests of sulphur concrete mixes

After a steep learning curve, the resulting strengths have become expectedly high. While normal concrete reaches a 20 MPa the sulphur concrete reached significantly higher values. The values of two samples are shown in Table 1.

Table 1. Results of compressive strength tests

	Sample A	Sample B	
Volume	306.6	309.5	cm^3
Weight	0.7677	0.7327	kg
Density	2504	2368	kg/m^3
Compr. Strength	76.09	64.66	MPa

The results confirm a hypothesis of this research as it was predicted that the loading of the still liquid mix inside the form with different weights will result in different densities and, as a result, in related strengths. The 64.66 MPa of sample B and the 76.09 MPa of sample A correlate with 2,368 kg/m3 and 2,504 kg/m3.

Present work focuses on studying the effect of different mixes and reinforcements on the strengths of beams.

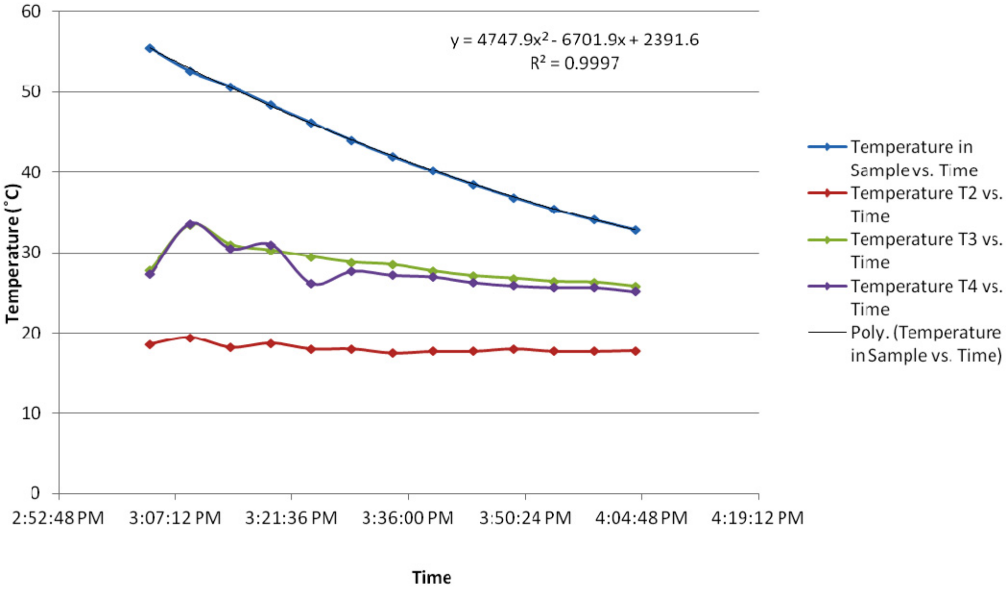


Figure 7. Changing of temperature during natural convection through center opening

STORAGE OF SOLAR HEAT ENERGY

The mean solar energy reaching the Earth’s atmosphere and the surface can be “harvested” from a given area via a variety of solar collectors with different shapes and materials have been developed over time. The goal of each design is to concentrate the incoming energy. Because of the cycles of day and nights, solar energy needs to be stored in order to be used during the nights. Ongoing work intents to measure the heat capacity of sulphur and polymer concrete to serve as a “solar energy” battery. For this purpose samples have been cast with a tubular opening in the center. After a sample is reheated it is wrapped with heavy insulation and equipped with sensors to measure the natural convection on depleting the stored heat energy. Figure 7 presents the result of such a test. Work is ongoing to identify the maximum energy that can be stored and retrieved for a given volume.

SUMMARY AND CONCLUSION

This paper presents ongoing work in experimenting with new technologies to mine and construct in space. It is demonstrated that there are many opportunities to conduct dual-purpose research that could also benefit terrestrial construction.

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