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Extraterrestrial Constructions in Lunar and Martian Environments

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ABSTRACT

Space exploration and terraforming nearby planets have been fascinating concepts for the longest time. Nowadays, that technological advancements in manufacturing, robotics and propellants are thriving, it is only a matter of time before humans can start colonizing nearby moons and planets. In recognition of the 50th anniversary of the first manned lunar landing, the National Aeronautics and Space Administration (NASA), together with the European Space Agency (ESA), revealed plans to establish a permanent human presence (habitats) on the Moon and Mars by 2040. In order to facilitate feasible and sustainable space exploration, such habitats are envisioned to be primarily built from lunar and Martian in-situ resources. To date, our understanding of indigenous resources continues to be lacking and in order to bridge this knowledge gap, this paper explores the suitability of construction materials derived from lunar and Martian regolith, along with terrestrial derivatives, for interplanetary construction. This paper also identifies key processing techniques suitable to produce extraterrestrial construction materials under alien environments (i.e., vacuum, low gravity, etc.) and showcases prominent design concepts for "space-resilient" habitats and colonies.

Keywords: Space exploration; Lunar and Martian habitats; Space construction materials.

INTRODUCTION

We are explorers by nature. Our curiosity continues to grow towards finding an Earth-like destination that would be suitable for colonization. This pursuit has allowed us to land manned missions to the Moon in 1969 and inspired current efforts to launch manned missions to Mars within the next 10 years. While it is true that the Moon is much closer to Earth than Mars, a number of studies have pointed out the possibility of sustaining human life on Mars due to the attractiveness of its surface environment (i.e. improved gravity and atmosphere, lower radiation levels etc.) (Banin et al. 1992; Lim et al. 2017).

Whether we pursue lunar or Martian colonization first, space explorers are to be housed in habitats that not only need to withstand extreme environments, but also preferably fabricated from in-situ resources. This emphasis is triggered by the fact that transporting one pound to the Moon can cost up to $10,000, a cost that can exponentially scale in the case of Mars (Johnson-Freese 2017). Fortunately, remote sensing missions have reported the abundant substances and elements that could potentially be used to produce lunar and Martian construction materials (Alexiadis et al. 2017; Lim and Anand 2015). While utilizing in-situ resources promotes the development of independent and sustainable space habitats, one should note that characterization and processing such materials under microgravity as well as radiation and vacuum is challenging (Naser 2019b; Toutanji and Grugel 2008). This is the first motivation behind this work.

The design functionalities of a space habitat resemble that of a terrestrial structure in which such a habitat is expected to provide a "safe" environment. This notion implies that the design of space habitats should accommodate the extreme nature of lunar and Martian environments, while also providing higher degrees of redundancy and sustainability (Franklin 1991; Land 1971). Despite recent advancements in structural and construction engineering, there is virtually no design or construction precedent for lunar or Martian habitats. As such, the design of safe space-resilient habitats seems to be a unique challenge that requires in-depth investigation and interdisciplinary efforts. This is the second motivation behind this work.

In support of NASA's and ESA's exploration efforts, this paper presents past and most recent research findings, as well as identifies current limitations and technological needs associated with space colonization. More specifically, the present review explores the feasibility of using indigenous space resources and space-native fabrication processes to allow the development of extraterrestrial construction materials and load-bearing components. This paper also showcases a number of structural/construction–related design concepts for lunar and Martian habitats.

LUNAR AND MARTIAN ENVIRONMENTS

Both lunar and Martian surfaces hold a multitude of harsh environments that are quite different from those on Earth. Some of these include weak/lack of atmosphere, vacuum, space debris (micrometeorites), high radiation and rapid temperature fluctuation. The magnitude and intensity of such environments stem from fundamental differences in the characteristics of Earth, Moon, and Mars. For instance, the Moon and Mars have a smaller mass than our Earth. Thus, the gravity on the Moon and Mars is about 17 and 38%, respectively, of that on Earth. This low level of gravity has also led to the existence of a weak atmosphere on the Moon and Mars, and hence, they have higher radiation levels. When compared to Earth, the Moon does not have an atmosphere, and hence, its surface experiences hard vacuum (equivalent to 3×10^{-13} kPa) (Allen 1998). It is worth noting that the Martian atmosphere is about 100 times thinner than that on Earth (~0.7 kPa).

LUNAR AND MARTIAN IN-SITU RESOURCES

A number of exploration missions have successfully studied the surfaces and sub-surfaces of the Moon and Mars (Tsuji et al. 2012). The outcome of these missions allowed a proper assessment of lunar and Martian in-situ resources and started a movement towards in-situ resource utilization (ISRU) which is defined as an operation that harnesses 'in-situ' resources to produce products (or create services) that allow robotic and human explorations (Cesaretti et al. 2014).

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A comprehensive analysis led by NASA on collected lunar soil and rocks showed the presence of substantial amounts of alumina, calcium oxide and silicate (Morris et al. 1983). Although soil samples have not been brought back from Mars yet, remote sensing carried out using Viking and Mariner-9 orbiters has confirmed the availability of similar compounds (Pettengill 1978). Table 1 compares chemical contents between lunar basalt, Martian soil, Martian lava, and cement. As can be seen in the table, all samples have high amounts of SiO_2, as well as FeO, ranging from approximately 37-45% and 11-21%, respectively, of the total sample weight. It is worth noting that a more comprehensive review on the properties of lunar and Martian resources can be found elsewhere (Benaroya, 2018).

Table 1 Chemical content of lunar and Martian samples (by percentage of total weight).

Constituent	Lunar Basalt[1]	Lunar Basalt[2]	Martian Sample[3]	Martian Lava[4]	Cement
SiO_2	45.03	37.79	44.7	44.48	20.13
Al_2O_3	7.27	8.85	5.7	11.25	5.98
FeO	21.09	19.66	-	11.38	-
Fe_2O_3	-	-	18.2	3	2.35
MgO	16.45	8.44	8.3	17.32	1.19
CaO	8.01	10.74	5.6	9.54	64.01
K_2O	0.06	0.05	<0.3	0.4	0.77
TiO_2	2.54	12.97	0.9	-	0.37
SO_3	-	-	7.7	-	-
Cl	-	-	0.7	-	-

[1]Apollo 12 and [2]Apollo 17; [3]Chryse Planitia; [4]calculated composition

EXTRATERRESTRIAL CONSTRUCTION MATERIALS

A closer look into the composition of lunar and Martian regolith samples by Heiken (1975) and Happel (1993) shows the potential for fabricating a number of construction materials that are suitable for space construction. Some of these materials include derivatives of concrete, metals and advanced materials.

Concrete-like derivatives

Concrete is inherently resilient and has durable characteristics. The suitability of concrete material, together with various concrete derivatives, including sulfur concrete, geopolymer concrete, polymer concrete and waterless concrete, was examined throughout the past years (Osio-Norgaard and Ferraro 2016; Wan et al. 2016). These research programs investigated properties of concrete under simulated lunar and Martian environments and noted how concrete derivatives have a high potential for use in space habitats due to the abundance of raw materials. In parallel, the wealth of regolith also implies the possibility of in-situ repair and fabrication (ISRF), which becomes handy for needed repairs and future colonial expansion. Current efforts aim at optimizing mixture design and components and possibly eliminate the need for water/curing.

Metals
While metals are not readily available on the Moon nor Mars, regolith can be procced to produce metals and/or alloys. Both Happel (1993) and Fairen et al. (2009) analyzed samples of lunar regolith, as well as imagery from Martian surface and reported the availability of high amounts of aluminum (Al), magnesium (Mg), iron (Fe), and titanium (Ti), etc. The use of metals in space habitats can be beneficial for radiation and vibration/impact resistance. One should keep in mind that processing metals in large quantities can be challenging in lunar or Martian environments. As such, efforts are being carried out to develop space-friendly fabrication/processing technologies.

Advanced materials
Due to the harsh nature of lunar and Martian environments, traditional materials may not satisfy some of requirements relating to strength, serviceability, or safety criteria. To overcome such limitations, a number of researchers started investigating the use of advanced materials (Krenkel and Berndt 2005; Shukla et al. 2018). Currently developed advanced materials have superior properties and, most importantly, multi-functionalities. As such, the umbrella of advanced materials covers composites, as well as materials with memory shape effect, and self-sensing/self-healing capabilities. A common denominator between currently available advanced materials is the lack of verification tests in space environments as well as the uncertainty of fabrication with in-situ resources (Naser 2019a).

PROCESSING OF EXTRATERRESTRIAL CONSTRUCTION MATERIALS
The ability to process and fabricate large quantities of extraterrestrial materials in space conditions is of high importance to enable scalable, feasible and sustainable lunar and Martian habitats. This section highlights some of the space-native processing/fabrication processes suitable for future space exploration programs.

Sintering
Heating a porous material, often in the form of powder, up to a temperature below its melting point is referred to as sintering (Bell et al. 2007). Sintering can be carried out by focusing solar, microwave or laser energy onto bedded granular material to heat it. The grains are then embedded by crystallization of the whole melted grain or by using micro melt grain welding. This enables the particles of the porous material to bond together to form a solid with reduced porosity. Typical heat sintering methods available allows sintering 0.1 mm successive layers at 1000°C. The application of microwave sintering enables electromagnetic energy using ultra-high frequency microwaves (2.45 GHz) and/or extra-high frequency microwaves (in the range of 100 and 500 GHz). Low-energy laser sintering, of about 2.12 J/mm^2, has been successfully reported in the literature (Balla et al. 2012).

Cold-pressing
A more convenient and energy preserving method of processing in-situ resources is through cold-pressing. This processing technique leverages the existence of adhesive forces within regolith particles, especially smectite-like clay mineral and water moisture. Smectite-like clay has high amounts of montmorillonite mineral with a large

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cation exchange capacity, and has the ability to absorb a tremendous amount of water within soil/regolith layers. As a result, when regolith is pressed, the viscosity of montmorillonite turns into a binding force between the particles, transforming the pressed material into a solid (Altemir 1993).

Biocementation

Biocementation, also known as microbially induced calcite precipitation (MICP), involves the use of microorganisms to precipitate calcium carbonate ($CaCO_3$) as a binding agent for a novel eco-friendly alternative to conventional construction materials (Ariyanti and Handayani 2011). A recent effort by Gleaton et al. (2019) explored a novel MICP technology for space exploration applications. The key technical challenge is to create a bioprocess that is potentially Mars-compatible. In particular, photosynthetic microalgae (e.g., *Haematococcus pluvialis* and *Chlorella protothecoids*) were used as potential biocementation microorganisms because they can use CO_2 (from Martian atmosphere) and/or urea (from organic waste) as carbon and nitrogen sources to generate inorganic carbon (e.g., $CO3^{2-}$) for $CaCO_3$ precipitation in the presence of calcium (from Martian regolith). Preliminary results confirmed the formation of biocement and the significant improvement in the mechanical (compressive) strength of Martian regolith-based bioconcrete.

DESIGN AND CONSTRUCTION CONSIDERATIONS FOR HABITATS

Considering the harsh surrounding environment, space habitats are required to implement higher levels of intelligence, redundancy, and resiliency. Overall, structural systems in space habitats would be similar to that used on Earth, but with modifications to allow for easier and quicker installation as well as high quality-control. Since gravity levels on the Moon and Mars are approximately 1/6 and 1/3 that of Earth, space habitats will be able to resist dead loads that are three to six times smaller than that on Earth (despite the need for radiation and micrometeorite shields). There is practically little-to-no wind or earthquake actives on the Moon and Mars, and hence, the lesser amounts of loadings would lead to having larger spans and allowing structural members to be much slender and/or made of relatively low strength materials (Indyk and Benaroya 2017). Space structural systems may utilize self-healing/sensing materials, which can be essential to monitor structural "health" performance and need for maintenance/upgrades.

CONCEPTS FOR HABITATS

Since the early days of space exploration, several researchers started to outline concepts for habitats (McKay 1985; Naser and Chehab 2018). Although these concepts span over five decades of research, they seem to recognize a number of commonalities with regard to the extreme nature of the Moon and Martian surfaces and need for internally-pressurized conditions for comfort. In general, space habitats can be grouped under rigid, inflatables, underground and mobile.

Rigid habitats

These are "rigid" structures that can are designed to accommodate the majority of load actions without the need for a secondary (or supplementary) load-bearing system. Rigid

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structures have high redundancy but require complex construction and design process, which is associated with higher mass, larger material utilization and transportation volume (Okumura et al. 1994).

Inflatables habitats
In lieu of rigid habitats, inflatables promote a practical solution while reducing the construction process and associated costs. These habitats will be shipped from Earth (while preassembled/folded) due to their high packing coefficient. These habitats will then be unfolded and inflated via a mechanical or automated process. Inflatable habitats are expected to be made of high-strength composite fabrics (Darooka et al. 2001).

Underground habitats
Due to the low gravity on the Moon and Mars, lava tubes could grow to a few kilometers (Orlandi et al. 2017). Thus, space habitats could be easily installed within underground lunar or Martian "lava tubes". Constructing a habitat inside of a lava tube can be accomplished by employing light inflatable systems as they do not have to support shielding systems. This option can be favorable given the weak/lack of seismic activities on the Moon and Mars.

Mobile habitats
Traditional concepts of habitats revolve around scenarios where bases form a stationary habitat. In a different view, operating a mobile habitat could improve the exploration range as compared to stationary bases. The concept of a mobile base can be superior for short-to-medium duration reconnaissance missions. Weaver and Duke (1993) proposed a mobile habitat concept formed by a group of independent rovers. Since each rover is an independent unit, this habitat has high redundancy and mobility.

CONCLUSIONS

This paper presents a collection of past and recent research findings associated with lunar and Martian colonization efforts. This paper also highlights the most prominent concepts for the design and construction of lunar and Martian habitats. The following summarizes other key findings:

- The harsh and unique lunar and Martian environments can adversely affect construction materials, as well as on structural systems. Such effects are to be taken into consideration when designing habitats.
- While a number of space-based processing and fabrication techniques is available, emphasis should be applied to improve their efficiency and minimize associated energy needs and/or equipment.
- Space habitats can be grouped under four main types: rigid, inflatables, underground and mobile. These habitats could be built on-surface, or within lave tubes, or left to roam the surface.

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