Acta Astronautica 140 (2017) 517–536

Contents lists available at ScienceDirect

Acta Astronautica

journal homepage: www.elsevier.com/locate/actaastro

A structural assessment of unrefined sintered lunar regolith simulant

Stephen J. Indyk [a,*], Haym Benaroya [b]

[a] Honeybee Robotics, 398 W. Washington Blvd. Suite 200., Pasadena, CA 91101, USA
[b] Department of Mechanical and Aerospace Engineering, Rutgers University, 98 Brett Rd, Piscataway, NJ 08854, USA

ARTICLE INFO

Keywords:
Lunar in-situ-resource utilization
Structural in-situ-resource utilization
Lunar regolith
In-situ resource utilization (ISRU)

ABSTRACT

The potential of utilizing lunar regolith as the raw material for manufacturing structural members is very appealing for future exploration and settlement of the Moon. Future lunar missions will depend on in-situ resource utilization (ISRU) for structural components, among other things. Sintered lunar regolith has been proposed as a structural material. In general, it has been assumed that the regolith would be at least minimally processed before use. We propose the possibility of manufacturing structural components directly using unrefined sintered lunar regolith with the advantage of requiring fewer specialized material processing equipment.

Our purpose in this study was the quantification of the material properties of unrefined sintered lunar regolith simulant. Two batches of sintered lunar regolith simulant JSC-1A samples, with porosities of 1.44% and 11.78%, underwent compression testing using an Instron series 4500 Universal Test System machine. Material properties were evaluated from the acquired load vs. deflection data. Stress vs. strain, modulus of elasticity, toughness, bulk modulus and compressive strength were evaluated as a function of porosity. The average compressive strength of the 1.44% porosity material was 218.8 MPa, and 84.6 MPa for the 11.78% porosity material. Our tests show that even unrefined sintered 11.78% porosity lunar regolith holds the possibility of being a useful structural material for lunar construction. Comparing our experimental results with those of other ISRU derived structural materials, unrefined sintered lunar regolith is expected to be one of the strongest material derived from lunar sources.

1. Introduction

From the log cabins built from trees felled by settlers of the American Pacific Northwest to the reinforced concrete, steel and glass skyscrapers towering over Manhattan and other modern cities, humans have been constructing progressively more complex structures. The lime and clay processed into cement and the iron ore forged into steel share the same humble beginnings as the timber harvested by logging - they originated from Earth. Making use of indigenous materials to construct dwellings has been a human activity for millennia. Of course, human-inhabited structures are simply a convenient example of what has and can be constructed from indigenous materials. Structural materials comprise a majority of man-made objects, such as underground pipes, smart phone housings, aircraft fuselages and many more. They all share a thread of being constructed from indigenous, processed and, of course, refined materials. Determining the strength and capabilities of structures depends heavily on the material used to create the structure, as well as the application envisioned. Through testing and statistical analysis, the strength of materials has become a fundamental field. With information available about common materials only a click away on the Internet, and with finite element analysis (FEA) software readily available, the real difficulty in assessing structural materials becomes apparent when investigating new materials.

Colonizing the Moon has been a human dream since mankind first looked up at the night sky. Before any such dream can become a long-term reality, it is necessary to first learn how to use existing lunar resources. However, the difficult environment of the Moon does not afford its first settlers the luxury of simply chopping down trees to construct shelter. Instead, these intrepid settlers will have to rely on constructed habitats transported from Earth for a considerable period of time. These domiciles will be well thought out, having exact placements on the lunar surface decided well in advance by Moon surveying satellites in order to maximize, or minimize, the effects of the Sun, ensure constant communication with Earth and allow spacecraft to ferry goods to and from this home away from home. Later, second or third generation lunar structures will be constructed mostly, if not entirely, out of indigenous materials.

The potential utilization of lunar regolith as a raw material for manufacturing structural members is very promising for future

---

Abbreviation: SLS, Sintered lunar simulant.

[*] Corresponding author.

E-mail addresses: indyk@honeybeerobotics.com (S.J. Indyk), benaroya@soe.rutgers.edu (H. Benaroya).

https://doi.org/10.1016/j.actaastro.2017.09.018
Received 14 April 2017; Received in revised form 2 August 2017; Accepted 18 September 2017

exploration and settlement. For economic and practical reasons, future lunar missions will eventually depend on in-situ resource utilization (ISRU) for lunar structural components. Manufacturing structural components directly from unrefined lunar regolith would advantageously require less specialized terrestrial equipment. One method to forge structural material from unrefined lunar regolith is a process known as sintering. A possible issue with sintering from a structural perspective is the pores created in the sintering process. 'The more vacuum a thing contains within it, the more readily it yields …,' words written in the first century B.C. by the Roman philosopher Lucretius in his work entitled, *On the Nature of the Universe*. That porosity affects material strength is not a new concept.

We address the question of how processed does the lunar regolith have to be in order to consider it of structural quality.

1.1. Research goals

In order to further explore and develop the Moon, long-duration surface missions will increasingly depend on ISRU. Otherwise, everything necessary for building habitable structures on the Moon would have to be transported from Earth, which is economically unsustainable. Fortunately, the Moon itself provides a promising and easily accessible raw material via its regolith that may be used to construct habitats and other structures. Lunar regolith is a granular substance that is not only plentiful on the Moon, but can also be easily extracted and sintered for use in large load bearing structures.

From a structural perspective, it is expected that lunar settlement would take place in three phases: the first phase would require prefabricated structures to be transported from Earth to the Moon. Phase two would comprise of hybrid structures, partially terrestrially built, and finalized on the lunar surface. Finally, the third phase would see structures that are primarily composed of lunar-derived structural material. Thus, it is important to develop a path to increase the maturity of the technologies needed to manufacture, inspect and construct these indigenous lunar structures.

Several types of lunar regolith-derived structural materials have been previously proposed and studied, some more thoroughly than others. Each depends on various methods for working with the lunar regolith. Some methods refine the lunar regolith into raw ore, where others form more conventional construction materials by combining regolith with additives to produce lunar concrete. The practicality of these materials have been extensively evaluated to the point that elastic material constants are understood, see works such as Lin [1] and Toutanji et al. [2]. Oppositely, qualitative evaluations of the structural potential of sintered lunar regolith have been studied to a lesser extent. Sintering, the process of applying heat to a powder compact to increase strength and integrity, has previously been shown by researchers such as Taylor and Meek [3] to be a possible method of converting raw lunar regolith to solid components. However, the sintering process itself contains many variables to control, the foremost being porosity. Porosity significantly affects strength as well as other properties of sintered materials.

A central aspect of this work is to determine whether unrefined sintered lunar regolith is a viable lunar ISRU structural material, and which parameters are of most impact. Developing an understanding of how porosity affects the elastic material constants of unrefined sintered lunar regolith is our goal. To this end, we investigate the properties of high and 1.44% porosity lunar simulant.

The effects of porosity on basic material properties, such as bulk modulus, Young's modulus, toughness and compressive strength, were investigated. Compression testing of the sintered lunar simulant was performed, and then stress and strain values were computed from recorded load and deflection data. These collected material properties were also compared with similar terrestrial materials. The data were also compared to other potential lunar ISRU derived materials.

Our overarching motivation has been whether structures can be constructed on the Moon using unrefined sintered lunar regolith. Our primary contribution is the examination of sintered lunar regolith properties via experiments and our assessment of that data. The short answer is: yes, it will be possible to erect surface lunar structures using unrefined sintered lunar regolith.

1.2. The lunar environment

An understanding of the lunar environment is prerequisite to the design of any system that is expected to operate on the Moon. Based on the *Lunar Sourcebook* by Heiken et al. [4] we summarize some key lunar environmental parameters. The Moon is Earth's nearest celestial body at an average distance of 284,400 km. The lunar gravitational constant is 1.622 m/s^2 whereas Earth's gravitational constant is 9.81 m/s^2, making lunar gravity approximately 1/6th that of the Earth. Lunar regolith is abundant and coats the surface of the Moon. Median depths of the lunar regolith have been estimated to be 2–4 m in the mare regions and 6–8 m on the far side and non-mare nearside areas. The increase in density with depth leads to significant difficulties in excavation. The dust environment is another engineering concern.

Regolith is very fine grained, and its mean grain size ranges from 40 to 900 μm with most mean values being between 45 and 100 μm. Particles below 20 μm in size have also been found. Materially, regolith contains heavy metals with many minerals common to those on Earth. This includes hard rocks and minerals such as basalt, anorthosite and olivine. Once disturbed, the regolith is electrostatically charged and can remain suspended 1–2 m above the surface for long periods of time. All of these properties make the regolith a serious threat to any mechanical system, leading to accelerated wear due to the regolith's abrasiveness. It is also considered to be a carcinogenic threat.

The lunar surface has low thermal capacity and very low thermal conductivity, making heat retention difficult. Surface temperatures between 374 and 92 K have been measured at the Apollo 15 landing site. Intense solar radiation exists at the lunar surface with intensities of between 1316 W/m^2 and 1421 W/m^2, depending on the position of the Earth relative to the Sun. For comparison, radiation at the Earth's surface is about 0.095 W/m^2. The lunar surface has a high vacuum with a pressure of 2.667e-13 kPa (2e-12 Torr) at night. For comparison, average sea-level pressure on the Earth's surface is 101.325 kPa (760 Torr).

1.3. Literature review

There are four main reasons why sintering lunar regolith is an efficient and viable option for use as a structural material. First, there is a need for ISRU. Secondly, there are limited alternative materials that could be made from ISRU without extensive refinement. Third, the current state of manufacturing process technology available would allow for effective sintering manufacturing. And finally, there are a multitude of useful structures that could be produced with sintered lunar regolith. Relevant research work is listed below and evaluated on these four criteria. Our research is focused on sintering of unprocessed lunar regolith.

Our review of the literature is organized based on relevance to this research effort. Special attention is given to experiments that estimate material properties. Relevance is based on four fundamental classifications; the need for ISRU, alternative ISRU materials, manufacturing processes, and what could be constructed.

1.3.1. The need for ISRU

Duke et al. [5] developed a strategy for exploration and development of the Moon. A main focus was the economics of going to the Moon. The cost of transporting material from the Earth into orbit was cited as a main problem with commercializing space. Development of the Moon would allow for natural resource access and a space transportation infrastructure. ISRU was discussed as a key factor in the development of the Moon. Resources that could come directly from the Moon included power, propellants, life support consumables and structural materials. Sintering