ESTIMATION OF ENERGY AND MATERIAL USE OF SINTERING-BASED CONSTRUCTION FOR A LUNAR OUTPOST – WITH THE EXAMPLE OF SINTERHAB MODULE DESIGN.

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Introduction: Various space agencies including NASA and ESA are currently engaged in preliminary studies for alternative space habitat systems for deep-space exploration, harnessing advanced technologies for planetary surface use, including mobility, deployment and the use of local resources [1]. Thus, plans are being considered for launching a series of lunar missions over the next decade ranging from orbiters, landers and rovers for extended stays on the lunar surface. One of the main reasons for focusing on the Moon is its pivotal role as a first stepping-stone for setting up human outposts, laboratories and observatories beyond the Earth and low-Earth orbit [2], and thereafter to Mars, eventually leading to exploration beyond the solar system.

Over the last decade, Space Architecture – the theory and practice of designing and building an environment for humans in outer space [3] – has become an emerging issue in the context of future space exploration, and is increasingly seen as a fundamental requirement for supporting long-term space settlement and exploration on other planetary bodies. Additive Manufacturing (AM, a.k.a. 3D Printing) is a layered process joining materials to make objects from 3D model data. Recently, a few researchers [4-6] successfully demonstrated the potential of AM in a construction process, thus Space Architecture researchers regard automated AM as a key technology for construction of In-Situ Resource Utilisation (ISRU)-derived human habitation and infrastructure, including radiation protection cover, surface paving, bridges, dust-shield walls and spacecraft landing-fields on extraterrestrial surfaces [1-7]. The groundbreaking research in this area will help to address important challenges of alternative construction processes and materials in extreterrestrial environments particularly on the Moon.

Sintering of Lunar Simulant: Lunar regolith contains various chemical and mineralogical resources – an area of lunar science of considerable importance for ISRU investigations [8]. For example, the native Fe (elemental Fe^0) abundance in the regolith is at least ten times greater than in the rocks from which it is formed [9]. Recently, the interest in exploiting the lunar regolith as a construction material [10, 11] has been increased, including previous investigations into setting up lunar outposts have focused on developing conventional cement [12-14], concrete [15, 16], brick [17] and sulphur-based concrete [18, 19] using lunar regolith simulants.

Some researchers have investigated the potential of lunar regolith sintering using a high-powered laser and/or microwave, as the natural lunar regolith is potentially an excellent construction material, as it mostly consists of soil (≤ 1 cm) and dust (≤ 20 µm) particles which require only mechanical sieving, without crushing. Kingery [20] proposed that the complex morphology of raw lunar regolith might be more suitable for sintering because its glass portion could assist in densification during sintering. Similarly, Taylor [21] proposed that raw lunar regolith is a strong microwave absorber due to the presence of nanophase iron (np-Fe^0), indicating its suitability for microwave sintering. He observed that microwave energy is easily deposited into a regolith depth of around 65 cm at low temperature, while the half-power depth of penetration decreases as temperature increases. Recent studies involving sintering of lunar simulant found that microwaves could melt the lunar simulant up to 13.4 mm depth [22] while a solar-concentrator could melt up to 6 mm depth [23].

Lunar outpost Design - SinterHab: One of the most recent conceptual designs for lunar outpost is SinterHab. SinterHab is a design concept of a habitat module at the lunar south pole in the Shackleton Crater, which can be constructed using a sintering-based AM process and partial ISRU [1]. The module was designed as a hybrid concept for 4 to 8 mission crews by combining inflatable membrane and rigid structures with a sintered regolith cover for enhanced radiation and micrometeorite protection (Fig 1). In this module concept, counter-pressure ribs are constructed by sintering around inflatable core module before inflation of membranes. Then the protection cover is sintered using lunar regolith over the ribs and deployed membrane strucrture (Fig. 2). The floor area per person (34 m^2) and the volume of the core module (1,220 m^3) was estimated according to an average requirement of long-term living in confined habitats including a biogenerative life-support for the crew members from other modules, i.e. 120 m^3 [24]. The protection cover was designed with variable thickness ranging from 0.7 to 2.6 m with the total volume of 1,580 m^3. The main drivers for the cover form of the module are the properties of microwave sintering and the robotic construction process.

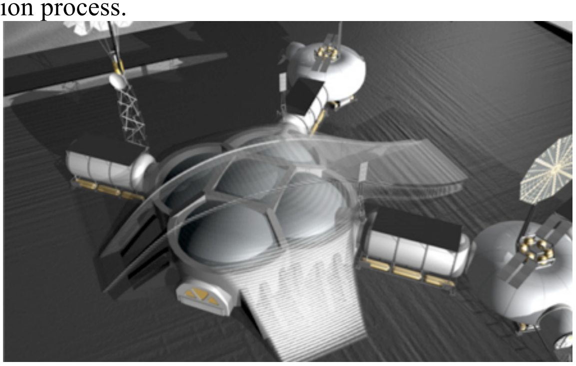

Fig 1. 3D rendered image of SinterHab visualizing the inflated compartments and counter-pressure ribs. [1]

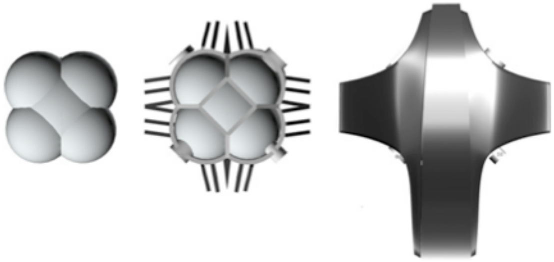

Fig 2. Assembly order of the core module, counter-pressure ribs and regolith cover from left. [1]

The bulk density of lunar regoligh near the surface is around 900 to 1100 kg/m^3 while it reaches a maximum value of 1900 kg/m^3 [25] at a couple of meters depth, which is similar to lightweight concrete (1440 to 1840 kg/m^3). The total weight of the protection cover after sintering would depend on fabrication methods, e.g. bone-inspired celluar structure (Fig 3) or rigid structure, etc. Recent study from ESA [11] revealed a potential biomimicry design concept of closed form structure from human bones (Fig. 3), which traps bulk lunar regolith into the sintered cells for increasing shielding properties from cosmic rays and micrometeoroids. This design would promise less weight of the protection cover while sustain its high strengths.

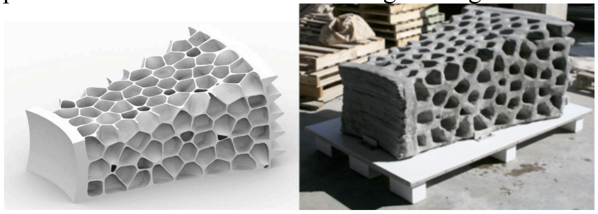

Fig 3. Closed form structure. Left – Rendered image of the concept; Right – Printed block (1 by 2 m footprint) using a lunar simulant developed by D-Shape. [11]

Discussion: In this contribution, we would revisit the usability of microwave for lunar regolith sintering through an in-depth experiment, and examine the minimum materials and energy required for sintering based on the SinterHab design. This will include the minimum layers to print, estimated printing time, minimum energy required for the sintering process and the potential energy sources.

Due to the current upsurge of interest in Space Architecture, we are embarking on a multi-disciplinary research project to integrate our existing expertise in 3D Concrete Printing [6] and knowledge of ISRU potential on the Moon [8] to perform a series of experiments using lunar simulants to optimize 3D printing process and its potential application to building structures and components on the Moon in the context of future habitation of the Moon.

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