Foam structures for encapsulating regolith in additive manufacturing applications G.D.M Morris[1]
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Introduction: Taking anything to space is expensive, somewhere between $5,000 to $10,000 per kilogram for LEO and $35,000-70,000 per kilogram to get to the Moon's surface [1]. In addition, the lunar environment is harsh and exposed to solar flares, cosmic radiation and constant bombardment from micrometeorites. Any kind of structure built on the Moon to protect humans or sensitive equipment will need to protect them from this. One way to do this is to make the walls thick, and that requires a lot of mass, at $35,000 per kilo, this swiftly becomes uneconomically expensive. By using the resources at the site chosen to establish a base of operations we can reduce the cost of developing our lunar economy. This is initially achieved through cheaper habitats, labs and processing facilities, but eventually all the way through to reduced logistic concerns and developing new technology that takes account of the materials available [2]. Initially the most obvious resource is Lunar regolith, the fine dusty rock particles that cover the Moon's surface and the most obvious use is for the radiation shield, however bonding it all together require energy or binder, both of which require additional mass to be transported to site.

Habitat designs and considerations: There are several proposed methods of creating structures using lunar regolith including cementitious extrusion, microwave or thermal sintering or binder addition, however all of them use some form of layer by layer deposition to build up the volume required.

Liquid binders: A paper [3] investigates the use of regolith with D-shape printing technology. D-shape uses a technology similar to conventional selective laser sintering (SLS), except instead of fusing the powder with heat, they inject a liquid binder (saturated $MgCl_2$ solution) into a thin layer of powder at the locations that are to be fused. By repeating this process many times the 3D structure can be built up within the powder bed. The granular mix is seeded with 15% MgO which reacts with the $MgCl_2$ solution to form an artificial stone comparable to dolomitic sandstone. The paper [3] also investigates the effect of printing a cellular foam structure that encapsulates unconstrained regolith to minimize the amount of binder required. They briefly cover the effect of cell size on structural properties for the printed foam and inspired the focus of this paper which is on optimizing the foam structure.

Cementitious extrusion: Another method of manufacturing on the Moon is proposed by Contour Crafting based in California [4]. They propose a technology that lays down concrete as a continuous extruded length, similar to fused deposition modeling (FDM) used in desktop 3D printing. Khoshnevis *et al.* [4] also discuss the use of waterless sulfur/regolith mix, however, as a cement this is highly susceptible to high temperatures (sulfur sublimes above 96°C) and thermal cycling.

Microwave sintering: Srivastava *et al*. [5] built upon Taylor and Meek's 2005 [6] analysis of microwave sintering of regolith to investigate its use as a method of creating a Lunar base. They reference a design laid out by [6] for a Lunar observatory, which also briefly discusses the use of microwave sintered regolith.

Discussion: All of these proposed methods for early stage ISRU on the Moon, assume the use of regolith, they assume that it is granular or powdered and comprises the necessary properties to be applicable to the range of technologies discussed. However few look at the actual details of the structure to be formed. [3] do however propose an outer and inner skin of regolith that covers a core of printed foam that encapsulates unbound regolith as a method of reducing the amount of binder required to build the structure. This is an interesting concept but they do not look in detail at the optimization of the foam like structure in the interior. It is also worth noting that as the foam like interior of the shell is cellular by nature, if any part of it is breached regolith shield only leaks out of the cells that are ruptured. Were the interior optimized solely for structural support as has been done with terrestrial additive manufacturing one often ends up with non-cellular structures. If these were ruptured due to impact or long-term degradation, large amounts of unsintered regolith could flow out relatively quickly, raising the danger posed to the structure and crew within. This paper presents a high level analysis of possible methods to do this and introduces some basic foam characteristics that can be taken into account when conducting more in-depth analysis.

Liquid Foam Structure: When individual bubbles are packed next to each other into a foam the structure they form is governed by a set of simple rules arising from the physical forces of the system.

Plateau borders: These are formed at the junction where three bubble films (lamellae) meet and contain most of the liquid in the foam. The three lamellae form angle of 120° with each other at all times. This can be obfuscated when the lamellae themselves are curved, but at the point of contact with the Plateau border, the angle is 120°.

Nodes: Plateau borders run throughout the entire structure of a foam, allowing liquid to drain from it over time. They only ever meet at nodes where four, and only four, individual Plateau borders link at an angle of 109.5° to each other.

Structure: The above two rules apply to all liquid foam structures, regardless of the polydispersity of the bubble volumes or the liquid content of the foam. Liquid foams are dynamic structures and will constantly rearrange themselves to maintain the above to rules as bubble within them burst or are absorbed into each other. However the entire system is driven by surface energy and is also constantly moving towards a minimum surface energy arrangement. The random foams that are generated through a frit are at a local minima but there are certain structures that have been identified that have much lower surface energies and still encapsulate bubbles of equal volume.

Low energy foam systems: There are two foam structures of interest here. Both have the constraint that they must represent the structure that consists of only one bubble size but use the minimum total surface area to encapsulate it in a tessellating pattern. If it were only one bubble the answer is a sphere.

Kelvin foam structure: The Kelvin [8] foam was identified by Lord Kelvin in 1887 and for over one hundred years represented the lowest energy foam that for a monodisperse bubble foam. It is made from a single tetrakaidecahedron that can be tessellated and has a surface area 9.7% larger than a sphere of equivalent volume [9].

Weire-Phelan Foam structure: The Weire-Phelan [10] foam structure was identified in 1994 and has a surface area 0.3% less than Kelvin's, but consists of two types of polyhedron in an eight cell tessellating unit. Two of the cells are dodecahedra and the remaining six are tetrakaidecahedron.

Comparison of cells cubic versus Kelvin and Weire Phelan: We will assume that a volume of shell needs to be constructed and it is divided into a series of tessellating cells that will each comprise a wall containing a volume of regolith. The cells are assumed to be of a volume much smaller than the construction volume so that boundary effects may be ignored. In reality a more thorough analysis will need to investigate smoothing the cellular structure into the skin of the construction. For simplicity we will assume non-dimensionalised units and a cell volume of 1. Taking the most simple of tessellating the structures, a cube we can see that for a unit cell volume the surface area will be 6. In comparison the single unit of a Kelvin foam would have a surface area of 5.31, based upon the assumption that it has 1.097 the surface area of an equivalent sphere and that this is 4.84 for a sphere encapsulating a volume of 1. Conversely the Weire-Phelan structure will have (an understandably very similar value) of 5.29. Assuming that the printed wall thickness is much smaller than the unit cell equivalent radius an additive manufacturing process that utilized one of the low surface area foam structures could reduce the volume of binder material required by roughly 12%. For a sintering based process this would reduce the energy required by 12%. There are however a large number of assumptions that have been necessary to reach these values. They are discussed in the summary below.

Summary: A basic investigation of the saving in mass or energy required to sinter regolith here shows that the large body of work in foam structures could be a rich source of process optimization. There is clearly much more to be investigated including optimizing the foam structure further and taking into account the effect of wall thickness in more depth. In addition a true comparison of the saving to be made for sintering based approaches would require a more in-depth analysis of the power system design and whether savings were best realized as a smaller power plant or a reduced time to completion. Time to print has not been included in this analysis but additive manufacturing can be a time consuming process, by reducing the amount of material that needs to be bonded time savings can also be realized.

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