ADVANCED CONCEPTS FOR ISRU-BASED ADDITIVE MANUFACTURING OF PLANETARY HABITATS

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ABSTRACT

In-Situ Resource Utilization (ISRU) is a key enabler for the expansion of space activities beyond low Earth orbit. While early ISRU developments have focused primarily on mission consumables, the last decade has seen an exponential increase in research on ISRU for manufacturing. In particular, it has been shown that many resources available in space can be successfully utilised with various Additive Manufacturing (AM) techniques. In the Advanced Concepts Team (ACT) at the European Space Agency, novel ideas are being studied in the field of space architecture and infrastructure. This paper give an overview of early concept feasibility studies conducted in the ACT, in conjunction with European research partners, related to in-situ manufacturing of habitats using local resources and various automated manufacturing technologies. The projects investigate growing biocomposite materials in space, AM of regolith-ceramic functionally graded materials, fabrication of fibre-reinforced geopolymer for radiation protection applications and basalt-fibre coreless winding process of a shell structure.

1. INTRODUCTION

1.1. The drive for in-situ resource utilisation

The return of humankind to the Moon is imminent, with multi-agency collaborations such as the Orion spacecraft and the Lunar Gateway underway to increase lunar access, and NASA's Artemis program targeting the first woman and next man to land on the Moon by 2024 [1]. In parallel, ESA's Moon Village proposal sets out to develop a permanent lunar settlement through international and public-private partnership [2]. These programs can be considered as a stepping stone toward landing, for the first time, humans on Mars. In all these cases, development and construction of extra-terrestrial habitats is vital for mission success, both in terms of human wellbeing and scientific capacity.

In the short term, such habitats are likely to be Class I, defined by NASA's Habitats Development Roadmap to be pre-integrated, hard-shell capsules delivered from Earth [3]. However, this short-term strategy is inefficient and a long-term sustained extra-terrestrial presence will necessitate development of Class II (prefabricated and assembled in-situ) and eventually Class III (fully derived in-situ) habitats. Class III habitats are particularly efficient in terms of reducing launch costs and exploiting the unique resources and manufacturing environment offered in space. Developing these technologies for use with in-situ resources not only enables construction of habitats, but also offers up greater potential for in-situ maintenance and expansion. Thus In-Situ Resource Utilization (ISRU) is a key driver for sustained human presence on the Moon, Mars and beyond.

Current ISRU research is widespread, and focuses on derivation of mission consumables, such as water, oxygen, energy, and propellant, as well as materials for manufacturing and infrastructure. Research in ISRU for construction covers a number of architectural and materials engineering concepts. From a resource standpoint, the primary material available for ISRU is regolith, the loose layer of unconsolidated granular material that covers the surface of a rocky planetary body such as the Moon or Mars. Lunar regolith characteristics have been determined from lunar samples retrieved by in Apollo programme [4]; Martian regolith has been characterized by Mars orbiter and surface missions [5]. While the mineralogical content of extra-terrestrial soils varies based on location, both lunar and Martian regoliths are globally abundant in silicates and metal oxides, which can be used in a variety of manufacturing methods to produce useful in-situ products.

1.2. Current ISRU developments in additive manufacturing

A range of techniques can be considered for space habitat construction. However, developments in off-Earth construction must consider the uniquely hostile extra-terrestrial environments, which can be characterised by:

- Weak atmosphere or vacuum
- Ionising radiation (including primary radiation

from galactic cosmic radiation and solar particle events, and secondary radiation from energetic particles interacting with matter)
- UV radiation
- Extreme temperature changes
- Partial gravity
- Micrometeorites
- Regolith dust

Habitats should withstand these conditions in the long term while also mitigating their effects on scientific equipment and human inhabitants. ISRU development should also consider the technology requirements for resource extraction, relocation, processing, and storage, as well as the limitations presented by large-scale manufacturing in adverse conditions.

The unique set of challenges and opportunities provided by the space environment necessitate, as well as enable, development of novel architectural techniques beyond those used routinely on Earth. This has led to the emergence of Additive Manufacturing (AM) as a salient ISRU method. AM offers benefits such as capacity for handling complex geometries including convex, concave or hollow cavity structures, and high suitability for automation and computer-aided design, which reduces the requirement for human intervention in the construction process and thus prevents unnecessary human exposure to the extra-terrestrial environment.

Many advances in ISRU for construction propose the AM of regolith as a minimally-processed feedstock. These include powder bed fusion techniques such as solar sintering [6]–[8], microwave sintering [9]–[12] and laser powder bed fusion [13]–[16], which can manufacture with regolith after a simple crushing/sieving step or even in the as-received state. Other AM techniques require polymer or chemical additions to assist with the binding of AM material: these include photo-polymerisation methods such as stereolithography [17] and digital light processing [18]; and extrusion methods such as D-shape processing [19], geopolymer extrusion [20], [21] and contour crafting of sulphur concrete [22], [23]. Many studies also explore the potential for extracting silicon and metallic elements for more tailored and advanced applications, with oxygen often being a useful by-product. Possible techniques to refine regolith in this way include microbial extraction [24], fluorine processing [25] and molten salt electrolysis [26].

1.3. The drive for future concepts research

While a broad range of ISRU technologies have already been demonstrated terrestrially, the first demonstration of ISRU in a lunar environment will likely be focused on volatiles extraction and the production of fuel [27], [28]. ISRU for construction, on the other hand, has far greater obstacles to overcome before manufacture of Class III habitats and other infrastructure becomes a reality. It thus becomes relevant to identify advances in terrestrial technologies that have the potential to inform and impact in-space manufacturing over the next several decades.

Recent studies conducted by ESA's Advanced Concepts Team (ACT) have identified a number of future technology concepts which could be successfully applied to a lunar or Martian habitat. The ACT is a group of multi-disciplinary researchers focused on monitoring advances and performing novel research in a variety of space technology domains, including space architecture and infrastructure. These activities often draw on innovations from outside the field of space research to inform new approaches to future challenges. Many studies undertaken by the ACT are conducted through the Ariadna mechanism [29], a framework for collaborative investigation with centres of expertise outside ESA. The remainder of this paper will provide a review of Ariadna studies undertaken in the ACT on the topic of space habitats, each of which has been conducted on the level of concept validation and demonstration, or Technology Readiness Level (TRL) 1-2. Many of the studies discussed draw on approaches to ISRU construction that can be considered 'advanced': these include strategies for manufacturing composites through fibre-reinforcement or multi-material AM; autonomous robotic manufacturing; and use of biologically-sourced materials such as urea and fungi-derived mycelium.

2. MYCELIUM-BASED BIOCOMPOSITES

Mycelium is the term given to the interconnected network of filaments, or hyphae, which make up the vegetative part of a fungal colony. The mycelium is responsible for absorbing nutrients from its surroundings, and in many species of fungi it does so by the simultaneous degradation and infiltration of a nutrient-rich substrate, expanding its network of hyphae as it does so. Such substrates are often organic plant waste, for example wood sawdust, litterfall or straw. The mycelium network functions as a binder, forming a compact biomass in combination with the substrate it grows in. This principle can be applied in a controlled process of biocomposite manufacturing where different combinations of substrates and fungi can be used in a development of fungi-based materials with different material properties that are renewable, biodegradable, low mass and relatively cheap.

Pure mycelium materials can be fabricated by letting the hyphae network fully consume the growth substrate to produce rubber-, paper-, textile-, and leather-like materials. However, this can be a lengthy and low-yield process. In order to fabricate structural materials the mycelium needs to be combined with a substrate after which the growth of the fungus will be stopped by using high heat before the substrate is fully consumed. With this method, biocomposites resembling cardboard, softboard, hardboard or brick can be produced by varying raw materials, growth conditions and post-treatments [30]. A number of studies [31], [32] have evaluated the properties of mycelium-based biocomposites and found them to be highly thermally insulating and non-flammable. While compressive strength values observed to-date are typically lower than conventional structural materials, biocomposites could still be used in load-bearing applications [33]–[37] when combined with geometry optimisation (Fig. 1). This possibility becomes even more feasible when considered for structures in reduced gravity environments, such as the Moon or Mars.

Figure 1 - MycoTree by F. Heisel et al. (2017), load-bearing biocomposite structure with geometry optimisation [37].

Läkk, Krijgsheld, Montalti and Wösten explored the application of biocomposites to space infrastructure by using additive manufacturing production technology, in a joint study between the ACT, Utrecht University and Officina Corpuscoli [38], [39]. Their investigation proposed a method for producing a mycelium-based printing paste in-situ, using the following workflow:

1. An organic substrate medium is cultivated in a controlled environment, then sterilised.
2. Mycelium culture inoculant is added to the sterilized biomass substrate.
3. The mycelium is allowed to colonise the biomass in a controlled environment for a 10-21 day incubation period.
4. The cultivated mycelium is combined into a paste with water, thickening agents and more powdered biomass substrate.
5. Structures are 3D-printed from this paste before undergoing further incubation in a controlled environment, to allow the mycelium to grow through the biocomposite.
6. Mycelium growth is stopped by exposure to extreme temperature, leaving behind the finished structure.

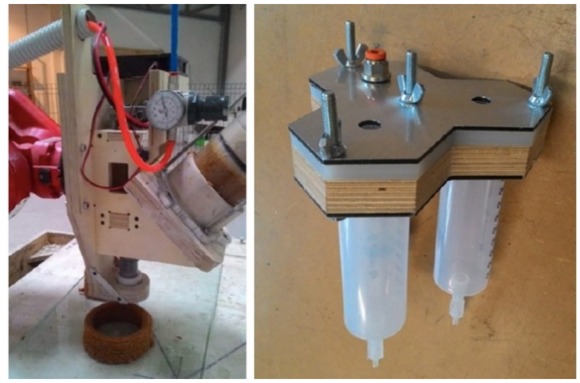

Figure 2 - Bio-material deposition using the paste material extruder, Officina Corpuscoli, Co-de-iT, digifabTURINg, 2017.

The mycelium paste would then be used with a 6-axis robotic arm for printing structures (Fig. 2). In order to validate the process for space application, the study addressed two major factors: availability of biomass; and effects of the space environment on mycelium growth.

Since extra-terrestrial space environments are lacking in organic material, the study addressed the requirement for organic substrate by prescribing in-situ cultivation of a fast-growing lower plant. In this case, *Azolla filiculoides* (AF) was chosen: a fern that grows in water bodies and therefore does not need soil. AF able to absorb its nitrogen from air and therefore grow on nitrogen-deficient matter, making its cultivation in space less complex. Another benefit is a high distribution rate, with ability to double its area in only 7-10 days under suitable conditions [40] AF can also be used as food and feed due to its protein content, as fertilizer for plants and for the biofuel production. In space, it can be grown in a CO_2 and N_2 containing atmosphere under controlled environmental conditions. The released O_2, as a byproduct of photosynthesis, can be utilised in life support systems. In the study various fungi were grown on AF substrate. It was found that *Schizophyllum commune* 227 (SC 227) showed the strongest growth.

To further examine the effect of space environment conditions on mycelium production, the investigators considered both radiation and reduced gravity conditions of strains 227 (natural) and 439x440 (treated) of SC. Previous evidence has found that certain species of melanised fungi exhibit enhanced growth under exposure to ionising radiation. To this end, the melanin production in mycelium was induced by adding the precursor L-dopa to multiple different strains. The modified inoculants were cultivated in minimal medium and irradiated using Co-60 (gamma radiation) with 0, 20, or 200 Gy for 72 hours. It was observed that both strains survived 200 Gy (60 x the lethal dose for humans) although viability of 439x440 was 3-fold lower when compared to untreated mycelium (Tab. 1). However, the results showed no differences between non-irradiated and irradiated cultures in melanin content, showing that melanin production is not induced by gamma radiation.

The study also explored the effect of reduced gravity on two strains of mycelium, by placing pre-grown samples into a Random Positioning Machine (RPM) for 72 hours. The RPM was set to simulate microgravity conditions. The difference in biomass was measured to assess growth; no hindrance in mycelium growth was displayed due to microgravity conditions. Further, for one particular strain (SC 227.1 co-inoculated with 227.2) the study found that mycelium growth is accelerated under microgravity (Fig. 3).

Table 1 - Colony Forming Units (CFU) resulting from 0.04 and 0.004 g SC *mycelial macerate after irradiation.*

Strain	Irradiation (Gy)	CFU (0,04 gr inoculum)	CFU (0,004 gr inoculum)
439x440	0	606-800	30-119
439x440	20	504	32-56
439x440	200	130-323	15-47
227	20	10	2-4
227	200	52	2

The in-situ biocomposite construction process suggested by Läkk et al. [38] presents several benefits over other current in-situ proposals. Primarily, it eliminates the cost associated with locating, validating, extracting, and processing indigenous material. For many regolith-based ISRU technologies, the cost of these crucial first steps is overlooked. In contrast, sustainable biocomposite production would require just 1 mg of mycelium from Earth, along with the capability to produce in-situ organic substrate, which would be compatible with any mission that has capacity for off-Earth crop cultivation. A cradle-to-cradle approach is also possible, whereby waste plant matter from other botanical experiments is used as substrate, or a combination of the two.

A major limitation of the proposed method is the complex environmental conditions required at multiple steps in the process. Temperature, atmosphere, humidity and light intensity must be controlled for steps 1, 3 and 5 of the workflow, as well as water pH and nutrient composition for AF growth in step 1. These requirements are likely to be energy intensive. The construction capability from this method is also entirely dependent on the AF yield; in this study, a 3 m^3 growth pool yielded 3 kg of dry material per week. While it is not stated how much mass of biocomposite this can yield, it is reasonable to assume that harvesting sufficient substrate for a large habitat-type structure would take many weeks or months. Furthermore, due to the largely uncontrollable nature of biological growth, there is a degree of uncertainty in the final biocomposite material properties, which would be complex to account for.

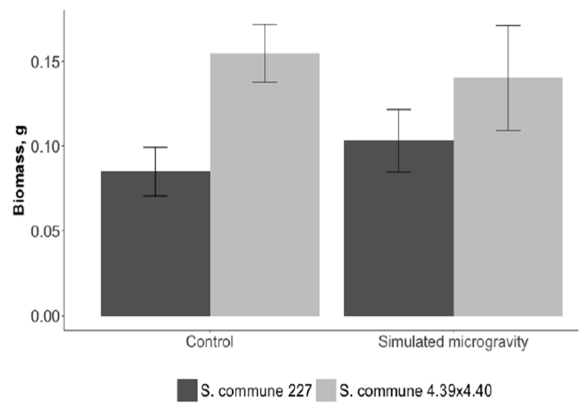

Figure 3 - Effect of simulated microgravity on the biomass of SC strains 4.39x4.40 and 227

Figure 4 - 3D-printed biocomposite samples in different stages of colonization: after 3 days (above) and after 1 week (below) of growth, Officina Corpuscoli, Co-de-iT, digifabTURINg, 2017.

One major consideration for this process is the autonomous nature of much of the workflow. While the growth process would take several weeks, the number of person-hours required is comparatively low. The construction process itself can be autonomous, as robotic extrusion-based AM is possible, and the controlled environment requirements could be fulfilled by a temporary inflatable structure. A custom-made algorithm developed as part of the investigation was able to simulate the deposition process, and from this biocomposites were printed and colonised (Fig. 4). These biocomposites were printed with sawdust as the organic substrate.

Further investigation required to validate this process should address the following:

- Printing of biocomposite prototypes using AF substrate instead of sawdust, to validate the use of in-situ cultivated substrates.
- Assessment of mechanical properties of the biocomposite, in particular investigating the effect of growth conditions and substrate on the final product.
- Undertaking mycelium growth experiments under partial gravity conditions instead of simulated microgravity. It is reasonable to expect accelerated growth to occur under partial gravity as well as microgravity, however the extent of this is currently unknown.
- To validate for larger applications such as habitat construction, manufacture of large-scale prototype structures should be considered.
- In the study, the authors note the possibility of applying basalt fibre-reinforcement to biocomposites. Since basalt fibres can be manufactured in-situ, as will be discussed in the fibre winding section of this paper, the effects of fibre-reinforcement could be explored to improve mechanical properties.

3. FUNCTIONALLY-GRADED METALLIC-REGOLITH COMPOSITES

Class III space habitats require automated in-situ fabrication with local resources. For this scope, many previous researchers propose multi-layered shell designs to achieve high structural performance, and to mitigate the multitude of space environment requirements [41]. A common trend is to have an interior pressurized metallic cabin, and an exterior regolith structure that protects from radiation [42]. However, state of the art solutions use mono-material AM approaches to manufacture these layers, typically proposing independent techniques for each layer of the structure [7], [19], [22], [43]. These methods can contribute to challenges regarding mismatch between materials, in terms of fatigue, fracture, corrosion, and stress corrosion cracking [44]. Functionally Graded Materials (FGMs) can serve as an optimal transition between two incompatible materials. They are designed with specific performances or functions in a gradient structure or composition to achieve tailored features [45]–[47]. For example, a buffer layer included between the lunar regolith and metal can improve compatibility by creating a firm bonding interface between them (Fig. 5). Moreover, thermal properties can be enhanced by tailoring the sequence of graded layers [48], [49].

Popovich, Laot, Cheibas and Rich investigated the feasibility of functionally graded metallic-regolith in a collaborative study between the ACT and TU Delft [50]. FGM manufacturing methods were selected based on their compatibility with metallic-ceramic processing in a space environment. These are Digital Light Processing (DLP), a stereolithography-based AM method, and Spark Plasma Sintering (SPS) [17], [18], [51]. The study initially assessed the capability of the techniques to consolidate regolith alone, before demonstrating consolidation of a metallic-regolith substrate.

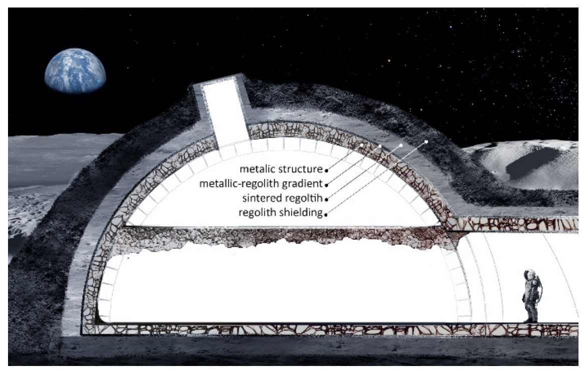

Figure 5 – Schematic example of a multi-layered lunar habitat.

Three regolith simulants, EAC-1A, LHS-1, LMS-1, were characterised to assess their suitability for FGMs and the optimum processing conditions. [52]. These simulants were investigated in a gradient with two metal powders, Ti_6Al_4V and stainless steel 316L. For the DLP method, EAC-1A powder was sieved through a 30-µm aperture and incorporated into a slurry with 41% solid content. The mixture was additively manufactured in rectangular bars with a layer thickness of 50 µm and a depth of cure of 100 µm. Water debinding was performed on the samples for 24 hours to remove the resin and reduce residual carbon. Then, the bars were sintered for 1 hour in a standard furnace in an air atmosphere at 1050 °C. An additional sintering run at 1075 °C was carried out to improve sintering of the bars.

SPS was conducted under vacuum using a 20 mm graphite die with graphite punches to produce 4mm height samples. A two-step experiment was employed to obtain FGMs consisting of lunar simulants and Ti_6Al_4V / 316L: initially the powders were sintered separately, then they were positioned in a metallic-regolith gradient. The optimal conditions for sintering regolith with stainless steel were found to be 1100°C, 50 MPa and hold of 20 min, and for regolith with Ti_6Al_4V were found to be 1050°C, 50 MPa, with holding time of 10 min. Density of the samples was measured before and after sintering, and micro-hardness measurements were completed on the sintered FGMs at the metallic, regolith and interface regions.

The study presented a successful technique for AM of functionally graded metallic-regolith, with combination of DLP and SPS. Densification and micro-hardness were increased with rising temperature and reduced particle size (Fig. 6) [50]. Furthermore, FGMs were made using the optimal SPS parameters, while metallic powders can be fully densified with SPS at relatively low temperature and 50 MPa pressure. The most promising FGM was proven to be the combination of lunar regolith and Ti_6Al_4V. The hardness profile showed a gradual transition between the two layers and the interface is strong enough to avoid cracking.

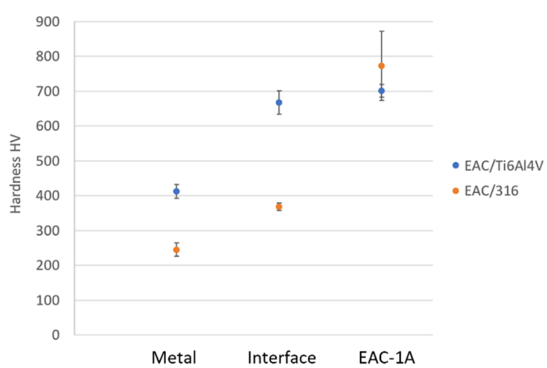

Figure 6. Vickers hardness profile of two FGMs.

To conclude, highly optimized materials are essential for space habitat and engineering tools manufacturing. FGMs are high-performance composite materials that can improve interfacial boundary compatibility, and enhance thermomechanical behaviour. These materials are able to overcome the multitude of space environment requirements by securing localized tailored mechanical properties. This study successfully demonstrated the proof of concept for a lunar metallic-regolith gradient. The concept can be further expanded to other off-Earth or terrestrial applications.

However, due to the feasibility nature of this research, further investigation can be considered for follow-up study as follows:

- Investigation of mechanical properties for regolith-metallic FGMs, including compressive strength, fracture toughness and thermal fatigue behaviour as well as wear resistance for coating applications.
- Manufacture of FGMs with pure metals, such as aluminium, iron, and titanium powders to better resemble a lunar scenario.
- Investigation of DLP resins that would have greater compatibility with a lunar environment.
- Investigation into scaling up the SPS and DLP techniques for large-scale production.
- Investigation of hardware possibilities for FGM gradients. Customizable nozzles and mechatronics are required to manufacture larger products.

4. FIBRE-REINFORCED GEOPOLYMERS FOR RADIATION SHIELDING

Geopolymers are inorganic alumino-silicate polymers with outstanding resistance against fire and extreme temperature fluctuations, and good radiation shielding properties [53], [54]. On Earth, they serve as an environmentally friendly alternative to Portland cement [55]. The chemical composition of fly ash, which is used as precursor for geopolymers on Earth, bears close resemblance to lunar regolith (Tab. 2) [56]. Consequently, geopolymer presents a promising ISRU construction material for lunar surface structures that could provide protection against ionizing radiation and micrometeorites. The use of basalt fibres produced in-situ on the lunar surface might be an advantageous way to reinforce potential structures built from geopolymer to enhance their mechanical strength.

Table 2 - Main oxides in DNA-1, typical Class F fly ash, and lunar regolith soil samples [57].

Oxide	Lunar regolith simulant DNA-1 (wt. %)	Fly ash class F (wt. %)	Lunar regolith soil samples range (wt. %)
SiO_2	47.79 ± 0.05	50.83 ± 0.04	40.6–48.1
Al_2O_3	19.16 ± 0.07	23.15 ± 0.06	12.0–28.0
Fe_2O_3	8.75 ± 0.01	6.82 ± 0.01	4.7–19.8
CaO	8.28 ± 0.03	6.87 ± 0.02	10.3–15.8
K2O	3.52 ± 0.02	2.14 ± 0.01	0.04–0.55
Na_2O	4.38 ± 0.03	1.29 ± 0.01	0.31–0.70
MgO	1.86 ± 0.01	1.70 ± 0.01	5.6–13.0
TiO_2	1.00 ± 0.01	1.01 ± 0.01	0.47–8.4

Pilehvar, Arnhof, and Kjøniksen undertook a joint ACT study with Østfold University College to investigate the AM of geopolymers with superplasticizer additions and fibre reinforcement for habitat applications. The first part of the study [58] explored the possibility of using urea as a superplasticizer for lunar geopolymers. Samples produced without superplasticizer were compared to samples with the addition of urea, and polycarboxylate and naphthalene based superplasticizers. All geopolymer mixtures were prepared with DNA-1 lunar regolith simulant and 12M sodium hydroxide solution 12 M. Initial tests showed that a sodium hydroxide solution to regolith ratio of 0.35 in the geopolymer recipe was ideal and a chemical admixture dosage corresponding to 3% of the lunar regolith mass was used for the polycarboxylate and naphthalene based superplasticizers, and urea respectively. The samples were prepared in 3x3x3 cm moulds and pre-cured at 80 °C for 6 hours, before being de-moulded and submitted to 0, 2, 4, and 8 freeze-thaw cycles (-80 ± 2 °C and 80 ± 2 °C for 48 hours respectively). Tests were conducted on shape deformation and layer-by-layer buildability (Fig. 7 and Fig. 8) setting time and compressive strength of the specimen. Fourier-Transform Infrared Spectroscopy (FTIR) was performed on the geopolymer samples subjected to freeze-thaw cycles and sample drill cores were analysed via X-ray microtomography (XCT).

Figure 7 - Shape deformation experiment, loading 1 kg over a) sample without superplasticizer, b) sample with 3% urea, c) sample containing 3% polycarboxylate-based superplasticizer, and d) sample with 3% naphthalene-based superplasticizer. Fractures are indicated by arrows.

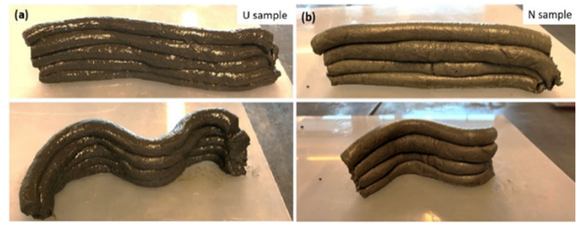

Figure 8- Layer-wise buildability of a) sample containing 3% urea and b) sample containing 3% naphthalene-based superplasticizer.

The second part of the study [59] investigated the effect of adding different amounts of urea (0 wt. %, 3 wt. %, and 5 wt. % respectively) as a geopolymer superplasticizer. Moreover, the effect of vacuum and extreme temperature oscillations of the lunar environment on the geopolymer properties were examined. Again, DNA-1 lunar regolith simulant and a 12 M sodium hydroxide solution were used to produce the samples. The specimens were cast in 4x4x4 cm moulds and pre-cured in a thermal chamber at 80 °C for 3 hours, half of them at 0.01 mbar, and the other half at ambient atmospheric pressure. The samples were then de-moulded, put in an exicator (for maintaining a vacuum environment) and subjected to temperature oscillations of a simulated lunar day-and-night cycle (114 °C to −80 °C). Lunar night-time temperatures get as low as −171 °C [60], however, due to equipment limitations, the temperature low was limited to −80 °C.

Mini slump tests were conducted to investigate the reduced water demand when using urea as a superplasticizer. Furthermore, extrudability, buildability, setting time and compressive strength and mass loss of the different mixtures were analysed and XCT scans were performed.

Early studies have shown the promising properties of urea to be used as a superplasticizer in geopolymer for 3D-printing applications on the lunar surface. The addition of small amounts of urea can significantly reduce the water and alkaline solution demand in geopolymer recipes and increase the workability for additive manufacturing [58]. This finding in particular is valuable for terrestrial, sustainable construction applications as well. The results of a subsequent investigation, comparing recipes with varying urea contents and investigating the effects of vacuum and extreme lunar temperature oscillations to simulate the lunar surface environment on the material, allow the following conclusions [59]:

- The use of urea as a superplasticizer minimizes the necessary amount of water in the geopolymer. The same workability that is necessary for extrusion-based 3D-printing can be achieved with a water reduction of up to

32%.

- Urea additions of 3% were found to offer the optimal viscosity for extrusion-based AM. Urea additions also delayed setting time of the geopolymer, which is beneficial to avoid clogging in the AM assembly [58], [59].
- Exposure to the simulated lunar day-and-night cycle increased the material's compressive strength. Both the addition of urea and curing in vacuum increased the porosity and decreased the compressive strength of the material.
- Negligible mass loss has been observed in vacuum-cured samples that have been subjected to the lunar temperature cycle.

Ongoing research examines enhancement of the already good compressive strength results of the earlier investigation by adding basalt fibres as reinforcement.

Geopolymer is highly efficient in its use of in-situ resources compared to other ISRU materials suggested for extrusion AM of lunar radiation protection structures. All ingredients for the lunar geopolymer proposed in the current study can be sourced on the Moon: lunar regolith makes up the largest part of the recipe (ca. 73 wt. %), water (ca. 16 wt. %) and urea (ca. 2 wt. %) can be extracted from astronaut urine (additional water could be sourced from water ice in cold, permanently shadowed lunar craters), and sodium hydroxide (ca. 9 wt. %) can be sourced from beneficiated lunar alkaline metals. Basalt fibres for reinforcement can also be sourced and manufactured entirely in-situ. Furthermore, lunar geopolymer shows superior compressive strength when compared to other ISRU materials suggested for additive manufacturing (all values for samples not subjected to vacuum). It exhibits 16-32 MPa after 8 freeze-thaw cycles [58]. Due to the lower gravity on the Moon, this is well above the limit for structural safety (>7 MPa).

However, to produce lunar geopolymer entirely from in-situ resources, beneficiation methods and equipment to produce water and alkaline activator on the Moon need to be developed further. In addition, to improve scalability of the developed geopolymer recipe - particularly in early stages of lunar construction activities and if larger structures would need to be built - some urea might need to be brought along on missions to be available in sufficient amounts until more people live on the Moon. However, urea has manifold uses (e.g. as fertilizer) and bringing small amounts would potentially make sense for other purposes (e.g. greenhouses) as well.

The project is ongoing. The activities/experiments currently in progress include:

- Assessment of the suitability of basalt fibres as geopolymer reinforcement
- Testing the geopolymer radiation shielding capacity and comparison to the results of Monte Carlo simulations
- Building a 3D-printer capable of operating in vacuum, to test geopolymer printing capabilities in a vacuum environment, and the effect of vacuum on the extruded material.

In addition, the following necessary investigations steps have been identified for further study:

- Conducting larger-scale 3D-printing of a prototype habitat structure, to investigate the AM capability of geopolymer for a variety of geometries at larger scale.
- Perform long-term vacuum and extreme temperature cycle exposure tests on printed geopolymer to assess longevity, both with and without reinforcement.

5. AUTONOMOUS ROBOTIC WINDING OF BASALT FIBRE STRUCTURES

As discussed, AM techniques offer many benefits for construction within the space environment, including high capacity for autonomy and geometric versatility. However, with all AM technologies, there exists a key challenge for habitat technologies: low tensile properties. This is a direct result of the layer-wise additive structure of powder-based materials, which yield moderate compressive strength but low tensile performance. Thus, AM structures are ill-equipped for non-compressive loads such as those produced in a pressure vessel, making them highly unsuitable for housing a pressurised habitat without an internal envelope or other support structure capable of sustaining the tensile loads. Other challenges relate to printing in vacuum or low atmosphere, under reduced or zero gravity and extreme temperature environments.

To bypass many of these issues a robotic fibre-based winding process could offer an alternative for manufacturing structures in space. Läkk, Schleppi, Cowley, Vasey, Yablonina and Menges investigated the process of using in-situ produced basalt fibres in robotic multi-stage coreless filament winding for space habitat applications [61]. In comparison to the majority of AM techniques, fibre winding can be considered a more accurate process with a higher degree of fidelity, due to the level of material property control afforded from fibre placement, and the use of continuous, homogeneous fibres as opposed to liquid- or powder-based feedstock. In addition, they can be used in both tensile structures, thanks to high tensile capacity of the fibres, as well as compressive structures when suitably reinforced with additives, and in elastic bending-active structures. Unlike AM, fibre-winding can also be utilized in partial gravity situations with minimal effect on the final product, without sacrificing formability afforded by AM. These features position fibre-wound composites as a viable advanced manufacturing product for extra-terrestrial environments, especially for non-compressive applications.

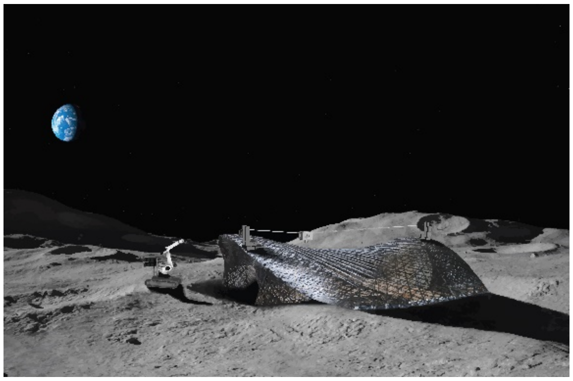

Figure 9 - Concept image of manufacturing on the Moon.

Vasey, Menges and Läkk put forward a potential method for autonomous robotic manufacturing of large-scale fibrous structures (Fig. 9) in a joint study between the ACT and the Institute of Computational Design, University of Stuttgart [62]. Their method proposes the winding of resin-infused basalt fibre rovings around a preplaced boundary framework, which could also be constructed from basalt, using various bespoke robots. Such structures could contribute to functional ISRU habitats when used in combination with regolith AM or accumulation methods, whereby the fibre-wound structure provides the pressurized envelope and the regolith layer provides thermal and radiation shielding. The two-part study initially investigated ISRU manufacture of basalt fibres before going on to develop a design concept for a hyperbolic fibre-wound structure.

Investigations into fibre manufacture were undertaken with a monofilament method. Molten JSC-2A regolith simulant was poured from a crucible into a graphite mould until the temperature decrease and pour level was sufficient to form an 'anchor' within the mould. The crucible was then manually drawn away from the mould at velocities from 0.5 ms^{-1} to 2 ms^{-1}, forming a drawn fibre between the molten regolith and the graphite anchor with diameter averaging 150 µm. This is up to 10 times greater than diameters achieved in previous literature, which range from 16.7 µm to 45 µm. [63]–[65]. It was found that increasing draw velocity led to a decrease in fibre diameter. The temperature of the molten regolith at time of draw also had an effect on the fibre diameter. The given monofilament method would be inefficient and unsuitable for ISRU applications, however it provides insight into optimal drawing parameters for basalt fibre.

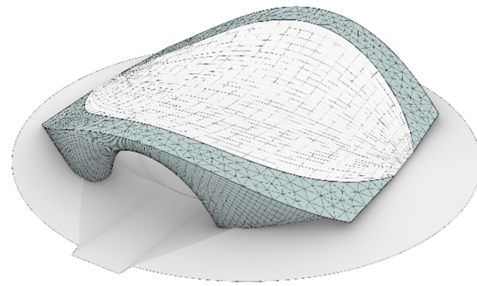

Figure 10 - Bending-active hyperbolic shell structure over a crater.

In the second part of the study, the investigators employed computational design and physics-based simulation tools to derive valid tensile windable geometries for bending-active hyperbolic shell construction. In defining boundary conditions for developed shell geometry, the habitat location was first considered; the optimal build site was selected to be over an existing lunar crater, to reduce need for support structures and regolith-moving technology, with the extra benefit of added thermal regulation from the surrounding regolith. These conditions led the design to a hyperbolic surface, composed of two boundary elastically-shaped bending-active arches with an interwoven surface connecting them (Fig. 10)

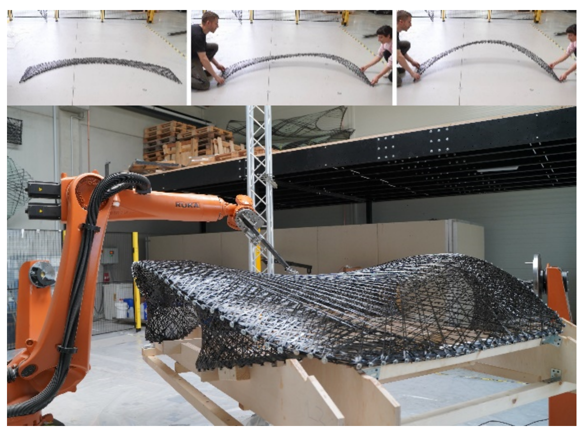

Figure 11 - Large scale demonstrator of the whole structure during fabrication at a scale of 1:10.

Using a 6-axis robotic arm, a prototype was manufactured from commercially-produced basalt fibres and epoxy resin at a scale of 1:10, representing a crater diameter between 30m – 35m. Two-dimensional strips were wound before being anchored in the required elastic bending-active shape. Then, reinforcement layers were applied with the robotic arm to form the final structure. (Fig. 11).

In a lunar context, the authors propose use of dissimilar robots for different stages of the manufacturing process: first, high payload robot or crane mounted on a mobile platform equipped with winding arms would produce the bending-active arch structures, then smaller locomotion robots would move along these structures, working in conjunction with a cable bot that moves between the arches to perform winding. In combination with an autonomous fibre production method, this workflow was proposed to be completed fully autonomously without human intervention; habitats constructed autonomously in this way could thus potentially be produced in advance of human arrival on the Moon or Mars, as long as the required equipment could be delivered safely. Other benefits include the light-weight nature of these structures versus metallic or regolith AM structures, which could be useful for mobility in producing modular or fully-mobile habitats, and the ability to tailor the (an)isotropy of composite properties for specific applications by altering fibre lay-up.

The major drawback of this method is the requirement for resin matrix. Fibre rovings must be pre-saturated in the matrix before winding takes place, which limits the choice of matrix to viscous polymer resin. Organic resins cannot be procured on the lunar or Martian surface and must be brought from Earth, which is costly for the large quantities required to support a full habitat structure. A solution could be a use of inorganic or bio-based resin systems produced in-situ [66]. The investigation into application of that type of resins in combination with basalt fibre was, however, out of the scope of the study and should be studied separately. Another drawback is the porous nature of the wound structure, which requires sealing to contain a pressurised environment. The team proposed a solution to add sealing layers of chopped fibres and resin in between the wound layers. A viable fabrication option for automating chopped fibre application could be achieved through a process of extrusion and cutting, similar to composite tape laying, where fibres are pulled off a bobbin through motorized extrusion, and simultaneously cut and rolled onto the pre-existing layers of fibre with a pressure sensitive application process.

In order to fully confirm the feasibility of this method, the following steps could be undertaken for follow-up study:

On a fibre level:

- Development of an automated filament drawing process for in-situ production of continuous fibre. This is the subject of a follow-up study currently being undertaken by the ACT in conjunction with RWTH Aachen Institute of Textile Technology (ITA). Influence of the space environment on fibre properties must be fully understood in order to optimise the properties of the fibre product. This will also increase feasibility of fibre-reinforcement in conjunction with other ISRU techniques, such as geopolymer and biocomposite materials discussed earlier in this review.

On a composite level:

- Examination of tensile, elastic and compressive behaviour of basalt-fibre composite, including influence of fibre orientation, to develop an optimal fabrication strategy.
- Investigation of in-situ resin systems to reduce requirement of Earth materials, for example bio-based or inorganic resins. Matrix additives could also be investigated to improve compressive performance.

On a structural level:

- Prototype production with simulant-derived basalt-fibre, to account for differences with commercially-produced fibre used in this study.
- Investigation of long-span filament winding with small scale mobile cable robots, at a similar 1:10 scale, to test the feasibility of using a cable driven bots to robotically wind long spans, including the necessary machine vision and behavioural, decentralized control strategies that will enable them to successfully achieve these tasks.
- Further refine structural details, such as anchoring to the lunar surface, airlock connections and overall structural performance.

6. CONCLUSION

Recent studies conducted by the ACT, in conjunction with Ariadna research partners, have assessed the feasibility of various innovative ISRU manufacturing techniques including mycelium biocomposites, functionally graded materials, fibre-reinforced geopolymers and robotically-wound structures. In these studies, advanced approaches to Class III habitat manufacture are presented which go beyond typical mono-material AM techniques, such as application of composite or multi-material solutions, or utilisation of biological resources. The discussed approaches were determined to be feasible for application in lunar or Martian environment, and the next steps have been outlined. These studies highlight the ISRU innovations that can be gained through investigation of novel and less-established off-Earth manufacturing concepts, especially by drawing on technologies and knowledge bases outside of the space sector. However, extensive development of these methods is still required to raise technology readiness beyond the level of concept validation.

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