IAC-25,A3,2B,9

FFLD Everyday Hardware Fabrication To Support Lunar Activities: Advancing Sustainable Lunar Exploration Through Fused Fiber Layer Deposition 3D Printing Using Lunar Regolith

Monika Brandić Lipińska[a], Anna Barbara Imhof[a]*, René Waclavicek[a], Denis Schreider[b], Miranda Fateri[b], Advenit Makaya[c]

[a] *LIQUIFER Systems Group, Obere Donaustraße 97/1/6, 1020 Vienna, Austria,* barbara.imhof@liquifer.com
[b] *Faculty of Mechanical Engineering and Material Science, Aalen University of Applied Sciences, Germany*
[c] *European Space Agency (ESA), The Netherlands*
* Corresponding Author

Abstract

In-Situ Resource Utilisation (ISRU) remains central to achieving sustainability in lunar exploration, reducing reliance on Earth-based resources. This paper examines the utilisation of lunar regolith in Additive Manufacturing (AM), with a particular focus on fibre-based strategies developed through the Fused Fiber Layer Deposition (FFLD) project, within the broader context of Fused Layer Deposition (FLD). FFLD is a novel approach that involves not only extruded regolith layers but also embedded fibres within the molten regolith matrix material. The approach was explored as a method to enhance the mechanical performance of glassy regolith structures, promising increased autonomy for Moon missions and reducing reliance on Earth's resources. While processes exist for the integration of fibres and extraterrestrial concrete blocks, there are no proposals for additively manufacturing fibre-reinforced glassy products from regolith feedstock to date. Building upon the successful FLD project under the ESA OSIP OFF-EARTH MANUFACTURING AND CONSTRUCTION CAMPAIGN-STUDY SCHEME, this study centred on the optimisation of the existing FLD 3D printer application through the introduction of FFLD.

While conceptually promising, the approach was limited by the thermal incompatibility of lunar fibres with molten regolith and the brittle behaviour of annealed glassy deposits. Building on these insights, the study investigated other pathways for fiber-based manufacturing: casting onto single or woven fibres to create mechanically stabilized composites; fibre-imprinted casting, where fibres act as sacrificial templates to guide surface texture and functional performance; hybrid strategies combining reinforcement and imprinting; and the reuse of fractured composites through sintering or binder jetting. These methods provide a range of practical pathways for producing multifunctional, structurally coherent lunar components, enabling scalable and resource-efficient production of infrastructure, habitat elements, and surface systems. By situating these approaches within a technology roadmap, the paper outlines strategies for integrating fibres in regolith-based AM, highlighting their potential to enhance durability, multifunctionality, and autonomy for a sustainable lunar presence.

Keywords: (maximum 6 keywords)

Acronyms/Abbreviations

AM - Additive Manufacturing
FFLD - Fused Fiber Layer Deposition
FLD - Fused Layer Deposition
ISRU - In-Situ Resource Utilisation

1. Introduction

A sustainable human presence on the Moon requires the ability to manufacture infrastructure, tools, and consumables directly from local resources. In-Situ Resource Utilization (ISRU) is central to this vision, reducing dependence on costly supply chains from Earth and enabling more autonomous and resilient mission architectures. Among available resources, lunar regolith is the most abundant and accessible, making it a primary candidate for construction and manufacturing processes. Among candidate ISRU technologies, Additive Manufacturing (AM) offers distinct advantages for ISRU: material efficiency, design flexibility, and the capacity to fabricate complex geometries on demand. Several regolith-based AM approaches, such as laser sintering [1-2], solar sintering [3], and microwave melting [4] have demonstrated feasibility, yet challenges in material performance, scalability, process control, and remain. Parts manufactured using these technologies exhibited cracks and porosity with limited tensile, compressive and flexural strength. These limitations constrain applications to low-stress components unless additional reinforcement strategies are employed, and achieving consistent resolution and mechanical reliability is critical to expanding the range of industrial and off-Earth applications.

In this context, Fused Layer Deposition (FLD) represents a particularly promising approach for lunar manufacturing, involving the layer-by-layer extrusion of molten regolith to produce glass structures inside an annealing chamber.

Annealing during printing has been demonstrated in glass printing approaches such as Molten Glass Extrusion (Klein et al.) and GLASS II (Inamura et al.), which enabled digitally controlled fabrication of strong, optically transparent components. Building on this, FLD has been applied to molten regolith extrusion, aiming to produce defect-free, in-situ annealed products. As a further step, fibre reinforcement has been introduced to improve the tensile and bending properties of the parts, leading to the concept of Fibre Fused Layer Deposition (FFLD) of lunar regolith.

FLD combined with fiber reinforcement – fibers can be incorporated as continuous strands aligned within the extruded material – has emerged as a promising approach, combining the versatility of AM with the potential to enhance material performance. Recent work on fiber-reinforced and natural-filler composites demonstrated that mechanical properties can be tuned through controlled reinforcement, though challenges remain in bonding and post-processing [5-7].

2. Fused Fiber Layer Deposition

2.1 Concept

FFLD was proposed as a novel method in which continuous fibers are embedded directly within molten regolith during extrusion. Unlike conventional FLD, which fabricates components solely from extruded molten regolith, FFLD integrates continuous fibers directly into the extrusion path, creating an in-situ composite material [see Fig. 1].

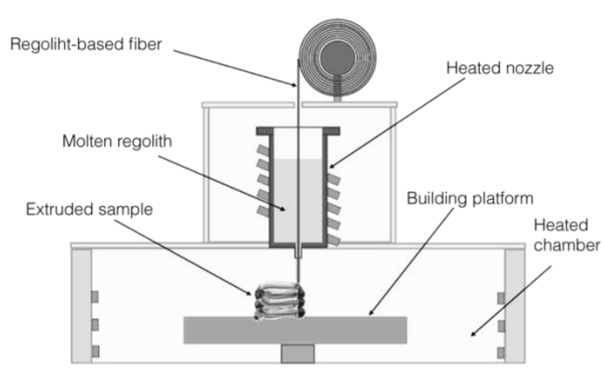

Fig. 1. Design of the FFLD 3d printer.

The rationale behind the concept drew from well-established principles of composite engineering: fibres act to bridge microcracks, redistribute stresses, and mitigate brittle failure. By embedding fibres into regolith-based structures, it was anticipated that the material would exhibit enhanced strength, toughness, and durability, overcoming one of the central limitations of glassy regolith-based products. The goal was to leverage the local availability of regolith while exploiting the mechanical advantages of fibers, enhancing toughness, crack resistance, and overall durability of lunar additive manufacturing components, to fabricate mechanically robust tools, structural components, or even habitat elements without relying on Earth-supplied reinforcements.

2.2 System Development, Annealing Process, and Fiber Compatibility

Initial work on FFLD focused on modifying the existing FLD system to accommodate fibre handling and embedding. This required adaptations to the extrusion system, thermal management, and fibre unwinding. Test campaigns were carried out to explore whether continuous fibres could withstand the high-temperature environment of molten regolith extrusion and whether embedding them into the matrix could be achieved under controlled conditions. Candidate fibres were produced from lunar regolith simulant (LHS-1), and extrusion trials explored a range of geometries to test feasibility. The campaigns revealed both the promise and the difficulty of FFLD. While embedding fibers aligns conceptually with terrestrial composite manufacturing, the combination of molten regolith's high temperatures, viscosity control requirements, and fiber degradation presented fundamental obstacles. Stable integration of fibers within printed regolith layers proved far more challenging than initially anticipated. This effect was primarily attributed to the narrow difference between the processing temperatures of the matrix material and the fibre, which led to partial melting of the fibre during molten regolith extrusion. Consequently, interlayer fibre reinforcement was selected for further study, as the limited contact time between the melt and the fibre material was expected to mitigate fibre degradation. However, a central factor limiting this approach was the annealing process, which is essential for stress relief in glass matrix material. Annealing allows molten regolith to cool gradually, relieving internal stresses and producing cohesive, glassy structures. However, this process also exposed embedded fibers to prolonged, relatively high processing temperatures, causing degradation, eliminating the fiber-reinforcing effect within the matrix. In Figure 2, the colour change associated with fibre degradation is visible after processing with the FFLD 3D printer.

Fig. 2. Lunar fibre before (left) and after FLD annealing process (right)

The results of the conducted printing campaigns indicated a trade-off:

- With annealing → Samples that underwent annealing produced cohesive, glassy structures, but the process destroyed any embedded fibers, eliminating their reinforcing function.
- Without annealing, → Non-annealed samples preserved the fibers to some extent, yet the surrounding regolith remained brittle and prone to cracking, resulting in mechanically unstable components.

Thus, the experiments demonstrated that fiber reinforcement is incompatible with high-temperature FLD under current conditions.

The challenges encountered during FFLD development served both as a technical experiment and a conceptual springboard: they clarified the limitations of direct fiber embedding and motivated the exploration of alternative fiber-based strategies for lunar manufacturing. These approaches open new directions in fiber–regolith composite fabrication, offering more practical pathways to resilient, multifunctional lunar infrastructure. Consequently, the project focus shifted in two directions: (1) optimizing FLD as a stand-alone process, refining extrusion and annealing parameters to produce mechanically stable, glassy components; and (2) exploring alternative fiber-based strategies, where fibers function as templates, surface imprints, or hybrid reinforcement rather than being embedded directly in molten regolith.

3. Fiber-based manufacturing

Given the limitations of embedding fibers directly into molten regolith, particularly the incompatibility with the crucial annealing process, the project shifted toward indirect fiber-based approaches. Rather than acting as continuous reinforcements within the melt, fibers are now explored as templates, reinforcement mats, or precursors for secondary processing, enabling composites to be produced through casting, imprinting, or hybrid methods [see Fig. 3]. These approaches can be broadly classified into three categories:

1. Integrated fiber composites, where fibers remain part of the final matrix, contribute to structural reinforcement.
2. Template-based or imprinted composites, where fibers do not form part of the matrix but instead guide surface texture, patterning, or functional structuring.
3. Hybrid strategies, which combine elements of both approaches, may serve as templates for surface design while also reinforcing localized regions.

By avoiding prolonged thermal exposure, these strategies allow the production of mechanically and functionally enhanced composites without the constraints of full annealing. Fibers can also be incorporated into non-thermal processes, such as powder-based methods like binder jetting, where they interact with chemical binders rather than being destroyed by heat. This framework establishes a versatile set of pathways for lunar fiber–regolith composites, balancing mechanical performance, surface functionality, and process feasibility.

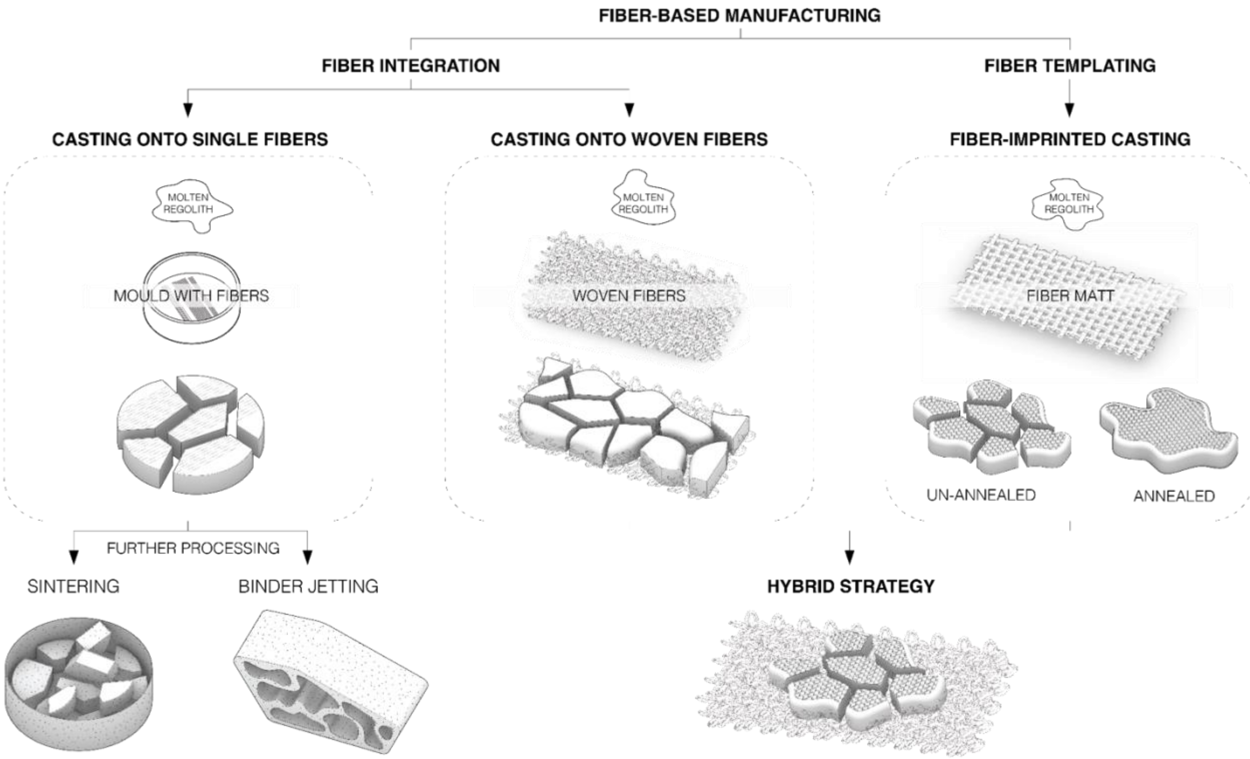

Fig. 3. Fiber-based manufacturing strategies.

3.1 Fibre Integration: Casting onto Single Fibers

One of the most direct approaches to creating regolith-based composites with the inclusion of fibers is the casting of molten regolith onto individual regolith-derived fibers. In this method, fibres are partially integrated into the solidifying matrix, often remaining exposed at the surface. However, the thermal mismatch during cooling and the inevitable pyrolysis of the fibres during annealing cause the composites to fracture extensively [see Fig. 4, 5]. The result is a brittle material with limited structural performance, yet valuable as a baseline for studying fibre–regolith interactions at the microscale [see Fig. 5, 6].

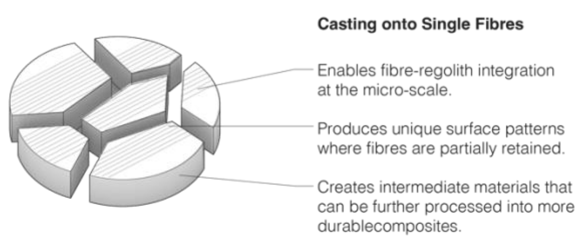

Fig. 4. Casting onto single fibers strategy.

Fig. 5. Casting onto single fibers strategy. Samples produced during the printing campaign.

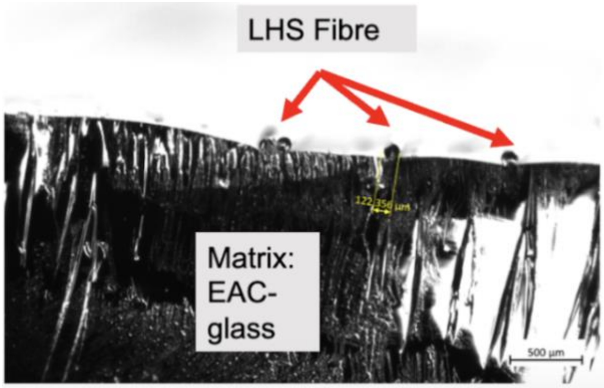

Fig. 6. Side view of a sample presented in Figure 5

Although composites created by casting onto single fibres cannot retain their initial mould shape and tend to shatter after the cooling process, they remain valuable for material research and as feedstock for secondary processing. In a lunar context, this pathway provides a low-threshold entry point into fibre-regolith integration, enabling testing of manufacturing infrastructure under real conditions. Such trials are essential for validating regolith melting, fibre handling, and casting equipment before committing to large-scale production.

While the initial castings suffer from cracking and limited structural use, their fragmented nature provides a valuable intermediate product that can be repurposed for further processing, either by re-sintering into heterogeneous, terrazzo-like composites or by crushing them into feedstock for binder jetting.

3.1.1. Sintering

To overcome the fragmentation of single-fibre castings, fractured composites can be reintroduced into moulds, overlaid with regolith powder, and subsequently sintered. This secondary treatment could create a heterogeneous, terrazzo-like composite, in which cracked fragments act as inclusions within a consolidated regolith matrix [see Fig. 7]. The aim is that the resulting material would demonstrate improved toughness through crack deflection and energy dissipation mechanisms. This strategy also illustrates how potential waste material from AM processes can be reintegrated into the fabrication cycle, enabling closed-loop resource utilization on the lunar surface.

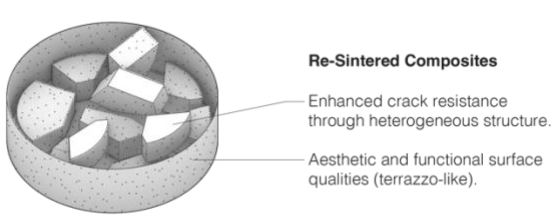

Fig. 7. Re-sintered composites strategy.

Terrazzo-like regolith composites may be particularly suited for architectural and infrastructural applications where durability and surface heterogeneity are advantageous. In lunar habitats, such components could function as flooring, wall cladding, or interior tiling, providing both structural resilience and an aesthetically distinct finish. Their inclusion-rich structure also makes them suitable for protective shielding elements, enhancing energy absorption against micrometeoroid impacts.

3.1.2 Crusing and Binder Jetting

An alternative reuse pathway for fractured composites containing fibers involves crushing them into granular feedstock, which is subsequently processed through binder jetting. This approach transforms brittle material into a versatile input, enabling the fabrication of geometrically complex components [see Fig. 8]. The binder-jetted structures benefit from the heterogeneous nature of the crushed inclusions, potentially enhancing fracture resistance and surface functionality, while allowing precise control over surface morphology. While this direction remains largely conceptual, it highlights promising synergies between fibrous reinforcements and non-thermal ISRU fabrication methods. Techniques such as binder jetting or chemically bound regolith composites could exploit fibers as reinforcement without exposing them to destructive heat, providing a practical pathway to incorporate fiber functionality in lunar manufacturing.

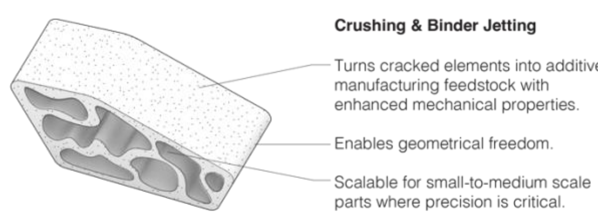

Fig. 8. Crushing & binder jetting strategy.

Binder jetting enables the on-demand fabrication of complex geometries from locally sourced regolith, supporting high-precision components for habitat maintenance, logistics, or modular systems [8]. The process allows integration of functional textures for dust mitigation, thermal management, or light control, while improving the strength-to-weight ratio of small parts. Binder jetting thus provides a versatile and rapid-response pathway for lunar manufacturing needs.

3.2 Fibre Integration: Casting onto woven fibers

Although fibers cannot survive prolonged immersion in molten regolith at high temperature, they can serve effectively as stabilizing substrates during casting. Woven silica or regolith-derived fibers placed beneath or around molten regolith provide mechanical support, reducing cracking in larger glassy parts. Casting molten regolith onto woven fiber mats thus represents a more integrated reinforcement strategy: while the solidified regolith still develops cracks due to the absence of annealing, the woven network holds the fragments in place, maintaining sufficient structural integrity [see Fig. 9]. The resulting material resembles a flexible mosaic mat, where fractured regolith fragments are mechanically interlocked by the fibrous scaffold. This configuration mitigates complete structural failure, enabling the creation of coherent, sheet-like composites. Experiments using woven "regolith wool" demonstrated that, although cracks formed during cooling, the fiber mesh prevented catastrophic failure by holding the fractured sections together [see Fig. 10, 11]. These findings suggest that woven fibers could serve as build platforms or stabilizing interlayers in FLD or other direct melt processes, such as laser melting processes [9], offering a practical strategy to mitigate the inherent brittleness of glassy regolith structures while enabling larger, structurally coherent components.

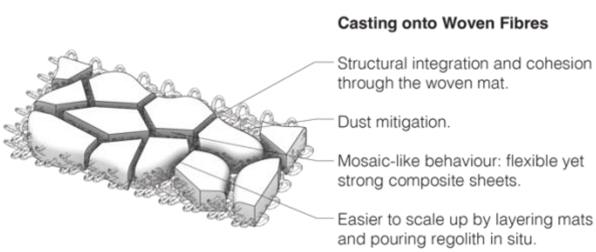

Fig. 9. Casting onto woven fibers strategy.

Fig. 10. Casting onto woven fibers. Sample produced during the printing campaign.

Fig. 11. Casting onto woven fibers. Close-up of a sample produced during the printing campaign: Fibre-cast part: top view (left) and bottom view (right).

Woven-fiber-reinforced regolith composites offer significant potential for large-area, low-precision lunar applications. These mosaic-like mats provide structural stabilization, making them suitable for paving elements, road surfaces, and dust-mitigation mats. Such surfaces could support rover mobility, cargo handling, landing pads, and general logistics operations, improving safety and operational efficiency on the lunar surface.

The scalability of this approach, achievable through layering and casting onto large rolls of woven fiber matting, makes it a promising candidate for civil engineering applications on the Moon. Beyond surface stabilization, woven mats could serve as reinforcing platforms for in-situ printing, stabilizing substrates for FLD structures or walkways, and embedding meshes in tiles and panels to delay fracture propagation.

3.3 Fiber-Imprinted Casting

A fundamentally different approach uses fibers not as reinforcement but as temporary templates. In fiber-imprinted casting, molten regolith is poured over fiber mats, such as silica fabric, leaving behind patterned surface imprints [see Fig. 12, 13]. Because the final composite consists solely of consolidated regolith, it can be fully annealed without cracking, producing a mechanically robust and durable material, although the fiber template is sacrificed. Alternatively, non-annealed casting preserves the template for potential reuse but results in cracked composites.

The imprinted surfaces provide multifunctional performance enhancements: increased surface area improves thermal regulation through higher emissivity; textured morphology reduces dust adhesion; light scattering enhances interior illumination and exterior reflectivity; and surface patterns can delay crack propagation, contributing to structural reinforcement. By embedding these functions directly into the material's surface, fiber-imprinted composites reduce the need for additional coatings or systems, lowering mass and complexity in lunar construction.

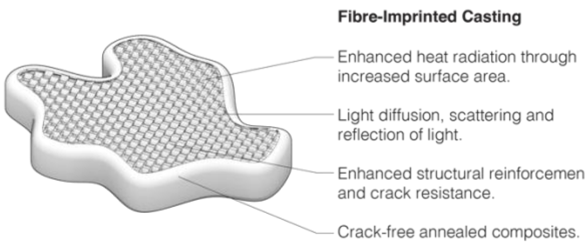

Fig. 12. Fiber-imprinted casting strategy.

Fig. 13. Fiber-imprinted casting. Sample produced during the printing campaign, with a close-up on the surface pattern.

Applications of fiber-imprinted composites may include habitat panels, pavement segments, or façade elements, where functional surface properties are important. Patterned façade panels can regulate heat radiation and scatter excess thermal energy, while imprinted road or platform segments improve traction and mitigate dust.. Interior panels may diffuse light, creating more uniform illumination while simultaneously reinforcing the structural shell.

3.4 Hybrid strategy

Finally, the hybrid approach combines aspects of woven reinforcement with surface imprinting. Here, molten regolith is cast onto woven fibre mats while simultaneously employing imprinting patterns. During annealing, the regolith cracks, but the woven mat preserves structural coherence, while the surface textures impart functional performance [see Fig. 14]. The resulting composites balance durability with multifunctionality: they resist failure, provide surface roughness for dust mitigation and friction, and enable enhanced thermal and optical regulation.

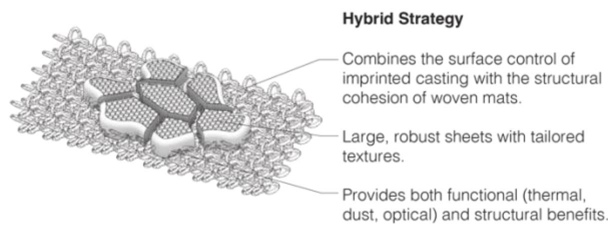

Fig.14. Hybrid strategy.

This hybrid strategy may be particularly well-suited to large-scale in-situ applications where precision shaping is not essential, but where robust, textured surfaces are advantageous. Examples include roadways, rover pathways, and habitat exteriors, where increased friction, light scattering, and dust control can be engineered directly into the surface. Roads and rover pathways constructed with hybrid mats would not only provide durable, crack-tolerant surfaces but also offer engineered roughness to improve traction and suppress dust mobilization. Similarly, habitat exteriors could benefit from panels that scatter incoming sunlight, regulate thermal flux, and resist degradation while remaining structurally stable. Landing pads represent another key application, where crack distribution is tolerated but cohesion and dust suppression are vital. By merging woven reinforcement with surface imprinting, the hybrid strategy provides a practical pathway toward scalable civil engineering solutions essential for establishing sustainable lunar settlements.

4. Discussion: Contribution to Sustainable Lunar Exploration

Although continuous fiber reinforcement during molten regolith extrusion proved unfeasible, the experimental findings highlight several alternative pathways where regolith–fiber systems could support lunar base operations. These applications remain fully aligned with ISRU principles, emphasizing on-site production of structural elements and everyday hardware from lunar resources.

The experiments demonstrate that fiber topology strongly influences regolith behavior. Single fibers act as localized anchors, whereas woven mats create porous scaffolds that maintain structural coherence in fractured regolith. This suggests that careful manipulation of fiber architecture can produce functionally graded composites, optimizing structural reinforcement in critical zones while tuning surface properties, such as roughness, light scattering, or thermal emissivity, in others. This approach aligns with ISRU principles by using material only where necessary, increasing efficiency, and integrating multifunctionality directly into structural elements.

Alternative fiber-based strategies, including fiber-imprinted casting, woven-mat stabilization, and hybrid methods, illustrate pathways to leverage fibers without exposing them to destructive temperatures. Fiber-imprinted surfaces enable functional tuning, improving thermal management, dust mitigation, and light diffusion, while woven mats stabilize fractured regolith, preventing catastrophic failure. Hybrid approaches combine these advantages, producing composites suitable for large-area infrastructure, habitat exteriors, roadways, or landing pads where precision geometry is secondary to durability and multifunctionality.

A key insight emerges from the trade-offs between thermal and non-thermal processes. Thermal annealing produces mechanically robust, crack-free components but is energy-intensive and incompatible with fiber retention. Non-thermal methods, including binder jetting and imprinting, preserve fibers and allow design flexibility, though sometimes with reduced mechanical strength. Recognizing these trade-offs informs energy-efficient, resource-conscious strategies for large-scale lunar construction.

The experiments also clarify scalability and automation potential. Fiber-stabilized mosaics and imprinted mats can be deployed robotically across large areas, supporting autonomous infrastructure construction. Smaller-scale methods, such as binder jetting or re-sintered terrazzo-like composites, allow precision fabrication for repairs or specialized components. By understanding how fiber structure, regolith behavior, and processing constraints interact, these approaches establish a framework for sustainable, multifunctional lunar infrastructure. Next steps toward sustainable lunar bases include:

1. Process refinement: Optimizing casting, imprinting, and hybrid methods to maximize structural integrity and multifunctional performance while minimizing energy consumption.
2. Material exploration: Testing additional regolith-derived fibers or natural fillers to enhance mechanical properties and functional surfaces.
3. Integration with autonomous systems: Developing robotic deployment strategies for large-area mats, paving, and habitat components.
4. Hybrid ISRU approaches: Combining thermal and non-thermal processing to produce both robust structural components and multifunctional elements efficiently.
5. Functional performance validation: Evaluating durability under lunar-relevant thermal cycling, dust exposure, and mechanical loading.

Collectively, these directions support a roadmap for resilient, resource-efficient lunar habitats, where fibers contribute both structural reinforcement and surface functionality, enabling multifunctional infrastructure with minimal reliance on Earth-supplied materials. By integrating these strategies, future lunar bases can achieve sustainability, autonomy, and operational resilience while maintaining flexibility for emergent habitat needs.

7. Conclusions

This study explored the feasibility of FFLD for lunar regolith-based AM and, through iterative experimentation, clarified both the limitations and opportunities of fiber–regolith composites. Continuous fiber reinforcement during molten regolith extrusion proved incompatible with the high temperatures required for annealing, highlighting a fundamental constraint in high-temperature lunar additive manufacturing.

Despite these limitations, the research identified alternative fiber-based strategies that align with ISRU principles and support sustainable lunar exploration:

- Fiber-stabilized casting: Woven mats provide mechanical scaffolding for fractured regolith, enabling coherent, sheet-like composites suitable for large-area infrastructure such as roads, landing pads, or habitat floors.
- Fiber-imprinted casting: Fibers used as temporary templates create multifunctional surfaces that enhance thermal management, dust mitigation, and light scattering, while allowing full annealing to produce mechanically robust components.
- Hybrid approaches: Combining woven reinforcement and surface imprinting produces durable, multifunctional composites that balance structural stability with functional performance, particularly for large-scale applications where precision shaping is secondary.
- Secondary processing pathways: Fragmented composites could be re-sintered or crushed and processed through binder jetting, offering a route to high-precision, geometrically complex components with enhanced mechanical and surface properties.

These findings contribute to a roadmap for sustainable lunar infrastructure, emphasizing the efficient use of locally available resources, the multifunctionality of structural components, and integration with robotic or automated deployment systems. By leveraging fibers indirectly – through scaffolding, imprinting, or hybrid strategies – lunar bases can minimize reliance on Earth-supplied materials while enhancing durability, safety, and operational versatility.

Future directions include optimizing casting and imprinting parameters, exploring new regolith-derived fiber materials, validating structural and functional performance under lunar conditions, and integrating these methods into autonomous ISRU manufacturing systems. Collectively, this work demonstrates that while direct fiber embedding in molten regolith is currently unfeasible, indirect fiber strategies offer a practical and sustainable pathway toward resilient, multifunctional lunar habitats and infrastructure.

Ackonwledgements

The authors would like to acknowledge the contributions of Dr Alexander Niecke and Mathias Wirth from the Institute of Textile Technology (ITA) at RWTH Aachen for their support in mono-fibre fabrication. The authors are particularly grateful to the FibreCoat GmbH team, especially Alexander Lüking and Severin Luhr, for their significant support in providing lunar fibre woven wool for the FFLD project.

This study was carried out within ESA-funded projects investigating FLD under ESA Contract No. 4000133528 and the FFLD Project, ESA contract no. 4000141391/23/NL/GLC/OV as part of the ESA OSIP programme.

References

[1] Fateri M, Gebhardt A. Process parameters development of selective Laser Melting of lunar regolith for on-site manufacturing applications. International Journal of Applied Ceramic Technology. 2015 Jan 1;12(1):46–52.

[2] Granier J, Cutard T, Pinet P, le Maoult Y, Chevrel S, Sentenac T, et al. Selective laser melting of partially amorphous regolith analog for ISRU lunar applications. Acta Astronautica. 2025 Jan 1;226:66–77.

[3] Lim S, Bowen J, Degli-Alessandrini G, Anand M, Cowley A, Levin Prabhu V. Investigating the microwave heating behaviour of lunar soil simulant JSC-1A at different input powers. Scientific Reports. 2021 Dec 1;11(1).

[4] Gatto A, Defanti S, Bassoli E, Mattioni A, Martini U, Incerti G. Preliminary study on localized microwave sintering of lunar regolith. Acta Astronautica. 2024 May 1;218:126–36.

[5] Prüß H, Vietor T. Design for Fiber-Reinforced Additive Manufacturing. Journal of Mechanical Design. 2015 Nov 1;137(11).

[6] Ivey M, Melenka GW, Carey JP, Ayranci C. Characterizing short-fiber-reinforced composites produced using additive manufacturing. Advanced Manufacturing: Polymer and Composites Science. 2017 Jul 3;3(3):81–91.

[7] Mazzanti V, Malagutti L, Mollica F. FDM 3D printing of polymers containing natural fillers: A review of their mechanical properties. Vol. 11, Polymers. MDPI AG; 2019.

[8] Makaya A, Pambaguian L, Ghidini T, Rohr T, Lafont U, Meurisse A. Towards out of earth manufacturing: overview of the ESA materials and processes activities on manufacturing in space. CEAS Space Journal. 2023 Jan 1;15(1):69–75.

[9] Ginés-Palomares JC, Fateri M, Kalhöfer E, Schubert T, Meyer L, Kolsch N, et al. Laser melting manufacturing of large elements of lunar regolith simulant for paving on the Moon. Scientific Reports. 2023 Dec 1;13(1).