Moon Basalt fiber – preliminary feasibility study.

D. Pico, A. Lüking, Á. Blay Sempere, T. Gries

Institut für Textiltechnik der RWTH Aachen University.
Email: davide.pico@ita.rwth-aachen.de

Bringing a spacecraft into orbit constitutes a tremendous share of the total costs of every space mission. For this task to be done, humanity has relied on Rocket Science ever since the first satellite was placed into orbit, while other alternative disciplines have not been able to become real or fulfill the requirements, such as the concept of space elevator. Rockets are the only used means of transportation into space, and even though they are subjected to technological improvement and optimization of costs, they are not expected to be replaced by other technology anytime soon. The next decades of space exploration will be strongly bounded to the restrictions of rockets and humans must learn how to adapt to these limitations: the high costs of launching and the impossibility to launch very heavy loads.

Current costs of launch to Low Earth Orbit (LEO) range from the 2719 USD/kg for SpaceX's Falcon 9 to the 8730 USD/kg for Ariane 5ME, bringing a maximum payload of 22800 kg and 25200 kg respectively. The maximum allowed payload per vehicle for a further away body, like Mars, is notoriously smaller, 4500 kg. The last generation of rockets is very efficient compared to their predecessors, but the mass limitation is still challenging, and this is an obstacle in the direction the space industry is taking. [www12a] [www16a]

In the last years, some relevant countries and enterprises have joined the traditional space agencies in the access to space and have changed the scenario: manned missions beyond LEO are now a part of the discussion. On one side, China sent probes to the Moon recently and has expressed its interest in manned missions to the Moon and Mars. On the other hand, the American company SpaceX has revolutionized the industry as a successful private rocket and capsule manufacturer. ESA is, among other projects, working on a future "Moon village" (Figure 1.1), which could become the first continuous human settlement on our satellite. [www13a] [www16b]

The previous weight restrictions are a problem for these interests: manned spacecraft needs considerably larger space and equipment for life support on board than the unmanned ones, and this is translated in more weight to launch. Humans in an exploration mission on another planet or moon would need to bring everything they need with them, especially if they intended to settle down. Lightweight design has been a key discipline in the solution for these issues, but it is not always enough. That is why in situ resource utilization (ISRU), the study of how materials in those places can be used, has got relevant and it has been specially promoted by space agencies, especially NASA. [www15a]

Aim of this project is to study a certain way of ISRU: the usage of Lunar soil for the production of fibers. Fibers are an excellent material that can be useful in these conditions, as they are very versatile and they can be shaped easily at will. Taking advantage of the inorganic resources of the Moon this way could help reduce the overall costs of transport, since once the required machines were brought there, a large amount of fibers would be able to be produced.

It is not possible to use actual Lunar sand for the experimentation of ISRU here on Earth, and therefore simulants have been made. Firstly, a composition-wise synthetic lunar soil was produced from commercial terrestrial basalt and selected additives. A composition-wise simulant would emulate the moon regolith in terms of the chemical composition and it could suitable for certain tests, even though other properties of this material are not the same as those of the Moon, like the grain size or crystal structure.

Lunar simulants are less rare than real samples, but their offer is also low. The NASA-designated company ORBITEC has produced the lunar simulant JSC-1 for years, but they finished their stock and never replaced it. However, they still sold Martian soil simulant until at least 2014. [www14a] Other private companies, universities and space agencies have taken over and decided to produce their own simulant for their own purposes. [MCB94] [SCS05] [ZWL05]

Lunar simulants

The first part of the project was focused on the obtainment of a lunar simulant, which is required for the fiberization experiments. Simulants are usually extracted from coarse volcanic rock and then they are mechanically milled in order to get the desired grain size. [SCS05] In this project the artificial soil will be produced by melting commercial basalt together with some additives, which will modify the chemical composition of the initial basalt into the Moon composition.

The Apollo missions gathered and brought to Earth 2200 different samples between 1969 and 1972. [www15b] These samples, in contrast with the samples of other planets, were brought to Earth, where they were able to be studied in depth by many different methods. The vicinity of the Moon permitted the return of 382 kg of material in total. In Table 1 the composition of different samples taken by the Apollo is shown and compared to the composition of terrestrial basalt

	Sample number and type of material				
	14163 (basaltic soil)	78221 (basaltic soil)	10084 (basaltic soil)	67215 (polymict breccia)	Basfiber® (terrestrial basalt)
SiO_2	47,30%	43,67%	42,16%	0,00%	55,69%
Fe_2O_3	0,00%	0,00%	0,00%	0,00%	10,80%
Al2O3	17,80%	17,13%	13,60%	24,30%	15,44%
MgO	9,60%	10,55%	7,76%	6,80%	4,06%
CaO	11,40%	11,79%	11,94%	14,90%	7,43%
Na_2O	0,70%	0,37%	0,47%	0,30%	2,40%
Cr_2O_3	0,20%	0,00%	0,00%	0,00%	0,00%
TiO_2	1,60%	3,84%	7,75%	0,43%	1,23%
K_2O	0,60%	0,09%	0,16%	0,00%	1,51%
FeO	10,50%	11,68%	15,34%	7,95%	0,00%
MnO	0,10%	0,16%	0,20%	0,00%	0,00%
P_2O_5	n.d.	0,08%	0,05%	0,00%	0,00%

Table 1: Composition of different moon samples by the Apollo missions and a basalt sample from Earth

Due to the fact that one of the major changes in the composition will be an increase of iron oxides to roughly 15 % of the overall composition, a project related to the effect of iron oxide content on the crystallization of diopside glass-ceramic glaze was of greatly useful. [RRA02] The main concept of this

literature work consisted on mixing iron-less diopside frit with granite, which has a higher ferric oxide content (17,79%wt), in different proportions (from 10%-90% to 100%-0%), and see how this affected the final structure. The positive results of this work backs up the method of mixing and melting and sets a starting point for the project.

Lunar simulants consist of materials found on Earth which have been combined in order to approximate the real Lunar soil in terms of composition, mechanical properties or other properties. [MCB94]

The use of a commercially available basalt product was important for the synthesis of an inexpensive and easily producible simulant, so a process has been developed to modify the Basfiber® into a product with a closer chemical composition to the moon sample 10084.

The first step, however, is to determine which additives should be added *a priori*. In Table 5.4 the composition differences between 10084 and Basfiber® are shown, and also the oxides whose concentration on Basfiber® should be increased (Incr.) or decreased (Decr.) in order to resemble 10084 are indicated:

%wt	**SiO_2**	**Fe_2O_3**	**FeO**	**Al_2O_3**	**MgO**	**CaO**	**Na_2O**	**TiO_2**	**K_2O**
Basfiber®	55,69	10,80	0,00	15,44	4,06	7,43	2,40	1,23	1,51
Moon sample 10084	42,16	0,00	15,34	13,60	7,76	11,94	0,47	7,75	0,16
	Decr.	Decr.	Incr.	Decr.	Incr.	Incr.	Decr.	Incr.	Decr

Two different lunar simulants have been produced. The samples have been referred as ITALUS (ITA Lunar Simulant). The base material was Basalt from Kammeny Vek's Basfiber®. ITALUS-1 was obtained by using Fe_3O_2, $CaCO_3$ and TiO_2; ITALUS-2 was obtained by using Fe_4O_3, $CaCO_3$ and TiO_2.

Fiberization process

The fiber forming, as mentioned before, consists on various phases: melting, sizing, winding and post-processing. [PSG10] The expected temperature window for fiberization has been determined.

In the bushing phase, the compensation of gravity, capillarity and thermo-fluid mechanic terms allows the melted basalt to flow through a small nozzle. A difference of around 50°C between the upper and lower part of the crucible allows to near the pilot plant to the industrial one. The diameter of the resulting fibers is determined by the temperature, the nozzle diameter and the take-up velocity.

The facilities used for this project are depicted in Figure 1:

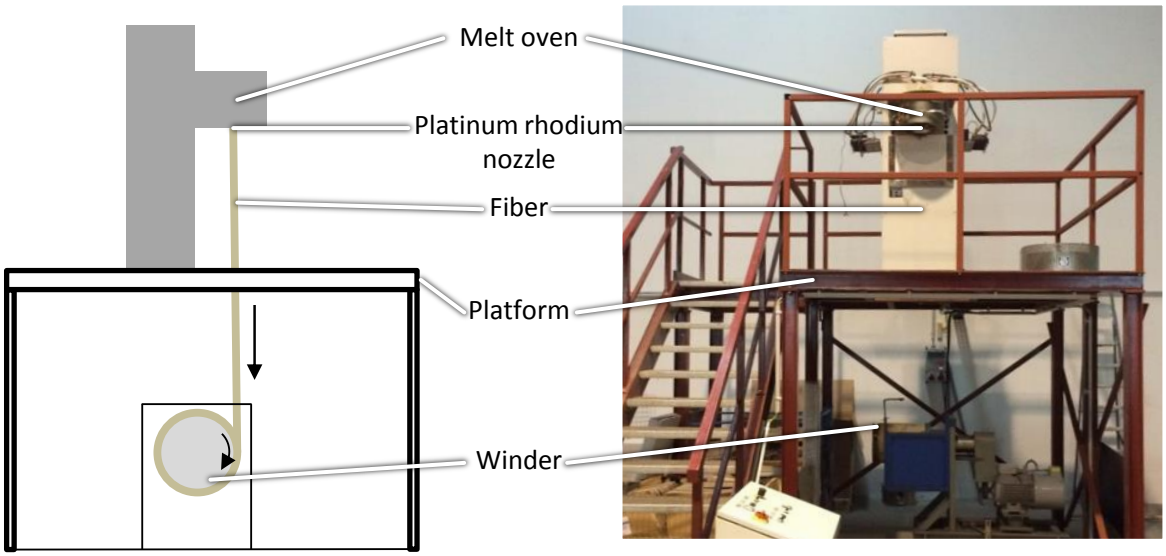

Figure 1: Schematic (left) and picture (right) of the spinning plant

The spinning process was successful for both ITALUS-1 and ITALUS-2. It was possible to spin different samples of fibers from ITALUS-1 and from ITALUS-2. Figure 2 shows the macroscopic (left) and microscopic (right) views of the ITALUS-1 resulting fibers. Figure 3 shows the macroscopic (left) and microscopic (right) views of the ITALUS-2 resulting fibers.

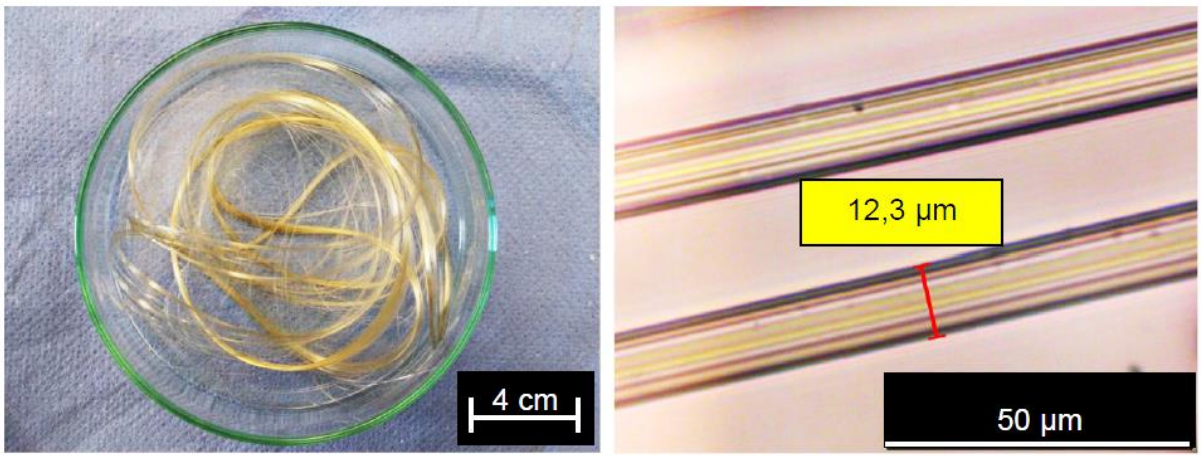

Figure 2: Macroscopic (left) and microscopic (right) view of the ITALUS-1 probe 1 resulting fibers. The measurement of diameter is appreciable.

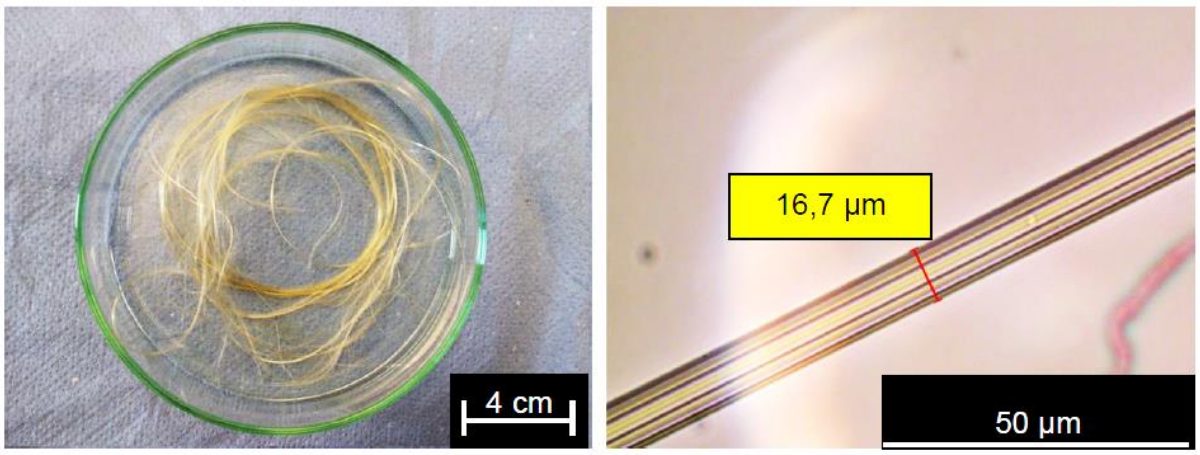

Figure 3: Macroscopic (left) and microscopic (right) view of the ITALUS-1 probe 2 resulting fibers. The measurement of diameter is appreciable.

Conclusion

Two different lunar simulants ITALUS-1 and ITALUS-2, were successfully produced. The synthesis of the materials needed a previous study of the Moon composition data to wholly understand the characteristics of the lunar surface material. This documentation helped in the correct selection of a target lunar sample whose composition was set as a target for the produced artificial soil. Commercially available materials were studied and chosen for the forming of this sample. However, a deeper insight in the data from lunar samples led to the diversification of the simulants to be produced, each one approaching the problematic differently. The simulants were produced by melting and quenching a mixture of terrestrial basalt and other additives. Due to quenching, the mixtures kept an amorphous structure and glass frites were formed.

Once the simulants were fabricated, the ISRU study of fiber production followed. The simulants were melted in a monofilament spinning machine, and fiber was drawn off the crucible. The process seemed to be more stable on the ITALUS-2 case than on the ITALUS-1, whose fibers fractured after some minutes of spinning. However, both simulants could be fiberized, and that positively fulfills the initial question. Aim of this research was to evaluate the possibility of fiber formation from the lunar regolith and has provided a valid method and data about the procedures for its reproduction in future experimentation.

If the results for these simulants are extrapolated for the real case, multiple applications and uses for the fibers arise. It is expected that they show similar properties to basalt fibers, as they consist mostly of that material. The commercial basalt fibers tensile strength would lie between 2700 and 3200 MPa, with a tensile modulus from 85 to 95 GPa.

Possible applications on the lunar surface include their use in the construction of underground habitats. Basalt fibers can be used as reinforcement of structures due to their high Young's modulus and their heat resistance. Bars made of basalt fibers can be produced for this application. Possible structural damaging of concrete columns can also be repaired by wrapping basalt fiber sheets. That would serve as an excellent reparation material for lunar based stations or mines.

Another application involving the use of basalt as reinforcement material is their use in “Lunar pykrete”. Pykrete is a composite material made primarily of water ice and wood pulp or sawdust. During the Second World War, Geoffrey Pyke proposed its use for the fabrication of ships, and it has been studied and perfectioned over time. Institutions like the Vienna University of Technology and Eindhoven University of Technology engineered a method to construct a pykrete-reinforced ice domes. Short lunar basalt fibers would substitute sawdust in the Moon, and habitats would be built by spraying over ice domes. Permanently shadowed areas could keep the ice in solid state. The Moon contains water in solid state, which can be extracted and serves as the matrix for this composite material. Pykrete could also be produced in smaller blocks for building structures for radiation shielding. In the field of construction, lunar fibers could also be used as insulation material in the form of rock wool. These pykrete and construction applications can be extrapolated to the Martian case as well. Mars has water ice stored in its poles, a soil composition which could be suitable for fiber production and temperatures below the freezing point of water to keep this material solid. The study of fiber formation from Martian soil and its applications should be continued in future works.

Lunar fibers could also be used in reinforcement for the manufacturing of mechanical pieces, tools, pieces of furniture, interior of habitats coating and can also be braided into fabric for clothing inside the habitat and for astronaut suits.

However, in order to study the actual applications of the lunar basalt fibers, the characterization of the fibers should be more extensive. Real lunar soil samples are needed for this task to yield completely reliable data~~,~~ as simulants are only an approximation. The gravity of the Moon, which is only 16% of Earth’s gravity, would also affect the formation of fibers: A lower gravitational pull would decrease the hydrostatic pressure of the melted material in the crucible, and destabilize the equilibrium of forces needed for the flow. Therefore, new spinning machines and crucibles adapted to this reduced gravity should be studied and manufactured.

The lunar simulants produced in this work can be upgraded and refined or directly used for future projects. The first version of ITALUS-1 and ITALUS-2 kept the chemical composition of the moon sample 10084, but further mechanical processing could improve it and make it more attractive to the usual users of lunar simulants, which mostly look for simulated physical characteristics, size, shape, particle size and grain size distribution. These properties should be determined in future works, as well as the characterization of the fibers from ITALUS-1 and ITALUS-2. By producing a simulant matrix from the Moon, the characterization of composites with the fibers can be done as well, and the properties of these composite materials can be determined.

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