1. Summary

Motivation:

The objective of the study is to investigate lunar regolith based geopolymer performance and shielding abilities when reinforced with basalt fibres and cured under environmental conditions of the lunar surface. The geopolymer building materials should be suitable for 3D-printing on the moon. Since there is a very limited supply of water on the moon, the study also focuses on lunar geopolymers with a reduced amount of water in the recipes, without the need for raw materials that cannot be resourced locally on the moon.

Methodology:

Geopolymers are interesting as potential construction materials on the moon, since they can be made from local lunar materials. The optimal lunar geopolymer recipe should:

- Be manufactured primarily with in-situ resources
- Be compatible with additive manufacturing/3D-printing techniques.
- Be able to withstand the harsh environmental lunar conditions, which includes vacuum, high radiation levels, micrometeorites, and extreme temperature variations.
- Have sufficient shielding capability to protect human occupants from radiation.
- Have sufficient strength for lunar construction purposes.

Lunar regolith simulants have been utilised in combination with water and NaOH to make lunar geopolymers. Urea has been incorporated as an additive/plasticiser to reduce the water requirement in the recipe, while retaining the viscosity and flowability required for 3D-printing. The effect of vacuum and lunar temperature variations on geopolymer curing has been studied, and the cured samples have been investigated for their shielding capability in a neutron beam radiation environment. Basalt fibres were added to increase the strength of the geopolymers, and mechanical strength, microstructure, setting times, and flow properties/buildability of reinforced geopolymer were characterized

Results obtained so far:

- Urea obtained from human urine can be used to reduce the amount of water required in the lunar geopolymer recipe by more than 30%.
- Preliminary results suggest that basalt fibres significantly improve the strength of lunar geopolymers.
- Some basalt fibres were found to dissolve during curing in the strongly basic geopolymer mixtures, thus it is important to ensure

that the utilized basalt fibres can withstand this harsh alkaline environment.
- The vacuum environment of the moon causes void formation within geopolymers at the curing stage. This has been shown to decrease overall compressive strength.
- Geopolymers can withstand the extreme temperature variations on the lunar surface
- The presence of basalt fibre reinforcement in the geopolymer recipe, as well as the curing environment of the geopolymer (ambient/vacuum) has little to no effect on the neutron shielding capability.

Publications published so far (see annex, pp. 4-50):

- Pilehvar, S., Arnhof, M., Erichsen, A., Valentini, L., Kjøniksen, A.-L., *"Investigation of severe lunar environmental conditions on the physical and mechanical properties of lunar regolith geopolymers"*, Submitted to Journal of Materials Research and Technology

- Arnhof, M., Pilehvar S., Kjøniksen A.-L., Cheibas I., 2019. Basalt *"Fibre Reinforced Geopolymer Made from Lunar Regolith Simulant."* Proceedings of the 8th European Conference for Aeronautics and Space Sciences, EUCASS, 1-4 July 2019, Madrid, Spain

- Pilehvar, S., Arnhof, M., Pamies, R., Valentini, L., Kjøniksen, A.-L., *"Utilization of urea as an accessible superplasticizer on the moon for lunar geopolymer mixtures",* Journal of Cleaner Production, Volume 247, 2020, 119177, ISSN 0959-6526, https://doi.org/10.1016/j.jclepro.2019.119177

Work to be completed until April 2021 and justification for delay:

Experimentations around the effect of basalt fibre reinforcement on the geopolymers has been delayed by a number of obstructions related to material procurement and other unexpected events
Firstly, basalt fibre delivery was significantly delayed. This was followed by delays in procuring the lunar regolith simulant; the initial batch received showed poor conformity with the expected mineralogy and powder characteristics, and thus a second replacement batch needed to be negotiated.
After obtaining the raw materials, samples were subjected to a one-month lunar temperature cycle. However, during the cycle the basalt fibres disintegrated in the strongly basic environment of the geopolymers, undermining the strengthening benefits that this study aims to investigate. This was an unexpected result, as the supplier had made

claims that the fibres would tolerate the alkaline environment. Efforts have been made to procure and investigate fibres from other suppliers which will be resistant to the curing process of the geopolymer.

Lastly, the study has experienced significant stoppages in laboratory work due to safety measures imposed for the COVID-19 pandemic, slowing the progress of several months of work.

In order to bring this study to a full conclusion, we therefore require at least three more months to study the effect of basalt fibres on the lunar geopolymers. Much of the work necessary to complete the study includes curing samples in vacuum, a month-long process in itself, followed by subjecting the samples to a one-month lunar day-and-night temperature cycle, and finally examining how the basalt fibres affect the microstructure, porosity, mechanical strength, and radiation shielding properties of the samples.

Additional work to be conducted under an extended Ariadna contract:

During the work on the project, it was found that vacuum significantly affects the properties of the lunar geopolymers. In order to develop a recipe that can be 3D-printed on the moon, it is therefore essential to test the 3D-printing of geopolymers in a vacuum. In particular, the flow properties of the pre-cured geopolymers are essential for 3D-printing the material: if it flows too easily, the structure will collapse before it has properly cured; if it is too viscous, it will be impossible to extrude it through the printer nozzle.

It is indicated that viscosity and flow properties will be affected by a vacuum. However, suitable equipment to test these properties in a simulated in-situ environment is not currently available. Since no other current known work or organisation is 3D-printing building materials under vacuum conditions, this study would require the construction of a vacuum 3D-printer to fully investigate the vacuum construction process.