WARSAW UNIVERSITY OF TECHNOLOGY Index 351733
FACULTY OF CIVIL ENGINEERING
COMMITTEE FOR CIVIL AND WATER ENGINEERING
POLISH ACADEMY OF SCIENCES ISSN 1230-2945

DOI: 10.24425/ace.2024.151888
ARCHIVES OF CIVIL ENGINEERING
Vol. LXX ISSUE 4 2024

pp. 199 –214

Research paper

Regolith as raw material for the production of aggregates and concrete-like composites on the Moon

Jacek Katzer[1], Janusz Kobaka[2]

Abstract: The presented research program is focused on harnessing lunar regolith as raw material for the production of aggregates and concrete-like composites on the Moon. The proposed complex technological solution covers technology of lunar aggregate production, lunar concrete-like composites, shape of a lunar habitat, a type of its structure and erection technique. Each element of the proposed solution is supported by tests or calculations. In authors' opinion magnetic separation seems to be the most promising technology of lunar aggregate production, habitats should be in egg-shaped form and the structure should be 3D printed as a Voronoi mesh. The research program was conducted using scientifically proven lunar soil simulants which were thoroughly tested by the authors. Production of lunar aggregate and subsequently concrete-like composite based on it is inevitable. The authors' proposed approach to the erection of lunar habitats is fully based on in-situ resource utilization philosophy increasing its feasibility. Necessary future research areas were pointed out.

Keywords: aggregate, concrete, composite, moon, regolith

---

[1] Associate Professor, PhD., Eng., University of Warmia and Mazury in Olsztyn, Faculty of Geoengineering, ul. Michała Oczapowskiego 2, 10-719 Olsztyn, Poland, e-mail: jacek.katzer@uwm.edu.pl, ORCID: 0000-0002-4049-5330

[2] PhD., Eng., University of Warmia and Mazury in Olsztyn, Faculty of Geoengineering, ul. Michała Oczapowskiego 2, 10-719 Olsztyn, Poland, e-mail: janusz.kobaka@umw.edu.pl, ORCID: 0000-0002-3596-3187

1. Introduction

Permanent or semi-permanent human presence on the Moon is very likely to occur within the next decade. This statement is supported by the Artemis program established by NASA, which aims to restore human presence on this natural satellite of the Earth. Ensuring proper living and working conditions for the crew of a future lunar base will require a large engineering effort related to construction of landing pads, habitats, storage facilities, mines, installations of rocket fuel production, etc. Such projects will be carried out in very unfavorable conditions and with little availability of materials and components brought from the Earth. The only possible solution is to use raw materials available locally on the Moon [1] for the production of building materials and construction process. This approach called *in situ resources utilization* (ISRU) is focused on extensive harnessing regolith (eroded lunar rock) as the main raw material for most lunar activities. From the civil engineering perspective the production of lunar aggregates and concrete-like composites is essential to create habitats and other necessary structures. Only in this way, basic living conditions for humans taking part in future missions, aimed at long-term stays, will be possible to achieve. Keeping the above facts in mind, the authors present a proposal of a full technological solution starting from the production of aggregates and concrete-like composites (characterized by strength properties similar to ordinary concrete) to construction technology and the structural shape of a future lunar habitat. The conceptualization part of the research project is supported by the results of the conducted research. Producing a concrete-like composite on the lunar surface, characterized by sufficient mechanical properties, requires appropriate preparation (and/or beneficiation) of the regolith. Separating the heavier regolith fractions, characterized by ferromagnetic properties (containing iron, cobalt and nickel), from the lighter fractions is necessary to obtain these valuable metals. Another application of this technique is the creation of lunar equivalents of aggregate dedicated for the production of concrete-like composite characterized by relatively high compressive strength and radiation absorption capacity.

Complex construction projects require appropriate planning that allows maximization of the use of available resources [2, 3]. The best source of iron and titanium on the Moon is ilmenite ($FeTiO_3$) [4]. Together with sulfur, applied as a binder in sulfur concrete, they could be used to build lunar habitats [4, 5]. Knowing the exact location of these elements, as well as water, is crucial to planning a long-term stay on the Moon.

A part of the research program was dedicated to select the most optimal external shape of the future lunar habitat. Authors decided to look at nature which, in favorable for the development of life Earth conditions, created a huge number of complex and optimized biological forms. One of such natural structural solutions proven over millions of years of evolution is the form of an egg [6]. It has key advantages such as: structural durability, very high load/weight ratio and increased height (in relation to the sphere form). The authors' proposal of a complex technological solution of a lunar habitat is based on an egg-shaped habitat, lunar aggregate created through magnetic separation, lunar cement-like composite and a protective layer mitigating the risk of meteorite impacts and radiation. The proposed technological solution harnesses natural resources found on our natural satellite to create permanent bases that are safe for astronauts.

2. Concept of a complex technological solution for a lunar base

2.1. Concept of the creation of lunar aggregate from regolith

Over the years multiple research teams have directed their efforts toward developing various construction technologies suitable for implementation on the Moon [7]. Most of the proposed solutions revolve around utilizing lunar soil in its natural state. Consequently, lunar soil has been suggested as the primary material for tasks such as covering erected structures, filling 3D-printed hollow components, and manufacturing concrete, among other applications [8]. In the view of the authors, the widespread production of lunar concrete-like composite is inevitable for several compelling reasons. Construction is an industry that relies heavily on large quantities of materials. Recently global concrete production has reached 26 Gt/year [9], which constitutes over 3 cubic meters per person annually. Ordinary concrete, along with its numerous variations, stands as the most versatile and commonly employed construction material throughout human history. There are currently no other materials that could realistically constitute a substitute for concrete in the realms of civil and structural engineering. From road surfaces, bridges, and dams to foundations, skyscrapers, and residential houses, concrete's ubiquity is undeniable. Given that human experience with construction materials is grounded in Earthly contexts, there is no evidence that lunar structural and civil engineering will significantly differ. This perspective is shared by research teams worldwide, dedicating their scientific endeavors to developing various types of lunar concrete-like composites [9–12]. Numerous concepts of lunar concrete-like composite have been put forward, including sulfur concrete [5], polymeric concrete [14], and 3D-printed concrete [6]. These composite materials are indeed intriguing, but they share a common drawback: their reliance on raw lunar soil. It is worth noting that on Earth, we do not use raw soil for concrete production, and for good reason. The same principle should apply to lunar concrete-like composite production. Lunar regolith differs significantly from Earthly soil, but it remains soil rather than an aggregate. The primary challenges associated with using raw lunar soil, as opposed to conventional Earthly aggregates, are linked to its regional and local variations. Lunar regolith exhibits variability in mineral composition, grading, and mechanical characteristics across its different regions [14, 15]. Consequently, its impact on the mechanical properties and durability of concrete remains uncertain. In concrete production, aggregate plays a pivotal role that cannot be substituted by raw soil. Considering all these factors, the authors have chosen to propose a lunar aggregate that mimics the characteristics of Earthly aggregate. Just as in case of Earthly aggregate, this aggregate will be manufactured locally (on the Moon) in close proximity to the construction site. The production of lunar aggregate would enable the application of established best practices from the concrete industry. Testing methods and quality control techniques could be readily adapted for lunar conditions [17]. Concrete-like composites produced using lunar aggregate as a base material would outperform those created using raw lunar soil. Some may raise objections regarding the technical feasibility and complexity of lunar aggregate production. However, the authors believe there is a relatively straightforward method for producing lunar aggregate by focusing on heavier ferromagnetic regolith fractions. The separation of ferromagnetic particles from lunar regolith could be achieved using a magnetic field [18]. This separation method has proven highly effective for isolating ilmenite and other particles characterized by ferromagnetic properties from ordinary quartz sand [19] using only a small neodymium magnet. It can be assumed that by employing an electro-induced magnetic field, with full control over its strength, it is possible to influence the size of separated ferromagnetic particles. Conducting magnetic separation on the Moon would be significantly easier than on Earth due to its weaker gravity and lack of atmosphere. During the conducted research program multiple lunar soil simulants were magnetically separated. In Fig. 1, one can observe microscopic pictures of the tested lunar soil simulant LHS-1 after magnetic separation. A thorough description of behavior of different scientifically proven lunar soil simulants during magnetic separation and properties of achieved lunar aggregates are presented in the previous publication.

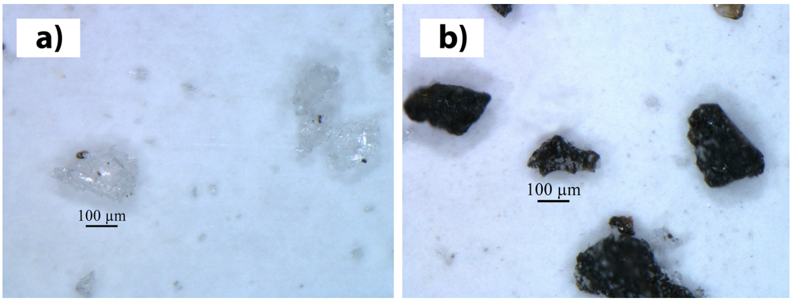

Fig. 1. Microscopic pictures of the tested lunar simulant LHS-1 after magnetic separation process: a) non-ferromagnetic particles, b) ferromagnetic particles

Carrying out magnetic separation will be most effective in the regions of the lunar seas where the content of the magnetic particles is high. This property is also reflected in lunar soil simulants used in the research program. For example, the percentage of the magnetic fraction in the LHS-1 (*Lunar Highlands Simulant*) is only 11.4%, while for the LMS-1 (*Lunar Mare Simulant*) it is equal to 47.5%. The magnetic fraction is understood here as grains containing ferromagnetic material. These grains may also contain non-ferromagnetic components. The separation of magnetic fraction was made manually by applying a neodymium magnet.

2.2. Concept of using lunar concrete-like composites

To establish lunar habitats, it is essential to supply the components required to build structures with the necessary mechanical durability. On Earth, the prevailing construction material is concrete, typically composed of aggregate, water, and cement. On the Moon production of such concrete is impossible due to available raw materials, limited water resources and lack of atmosphere. However, there exist alternative materials with potential to become lunar concrete-like composites. Two particularly promising options are sulfur concrete [19–22] and geopolymers [23–25]. The authors tested both technological approaches. Firstly sulfur concretes was tested. Initial tests were carried out using CEN (*European Committee for Standardization*) sand in order to select the appropriate proportions of ingredients. Subsequent tests were carried out using LHS-1 lunar regolith simulant with mineral composition characteristic of the lunar highlands. The main ingredients of LHS-1 are anorthosite and glass rich basalt (see Table 1). We tested mixtures with 20, 30, and 40 wt.% of sulfur.

The preparation of sulfur concrete specimens (see Fig. 2) was as follows:

1. Mixing dry ingredients: LHS-1 and sulfur in specific proportions (see Table 2).
2. Heating the mixed ingredients to the temperature above 115°C (the melting point of sulfur).
3. Simultaneous heating of the molds to the same temperature as the sulfur concrete.
4. Placing the mixture in molds 40 × 40 × 160 mm.
5. Vibrating the molds with the mixture for 60 seconds.

Fig. 2. Specimens made of sulfur concrete: a) SC_S20 (sand and 20% of sulfur), b) SC_LHS40 (lunar simulant LHS-1 and 30% of sulfur), c) SC_LHS40 (lunar simulant LHS-1 and 40% of sulfur)

Table 1. Mineral composition of LHS-1 (data sourced from [27])

Component	Wt.%
Anorthosite	74.4
Glass-rich basalt	24.7
Ilmenite	0.4
Pyroxene	0.3
Olivine	0.2

Table 2. Composition of the tested sulfur concrete

Material	SC_S20	SC_LHS30	SC_LHS40
Quartz sand Wt.%	80	–	–
Lunar simulant LHS-1 Wt. %	–	70	60
Sulfur Wt.%	20	30	40

The highest strength was achieved by sulfur concrete based on LHS-1 lunar soil simulant with 30% of sulfur (see Table 3). The highest compressive and flexural strengths also corresponded to the highest apparent density.

Table 3. Basic properties of the tested sulfur concretes

Property	**SC_S20**	**SC_LHS30**	**SC_LHS40**
Apparent density [g/cm^3]	2.04	2.43	2.36
Flexural strength [MPa]	0.5	9.6	8.3
Compressive strength [MPa]	15.2	44.1	43.2

In Fig. 3 cross-sections of sulfur concrete specimens with different sulfur content and visible most common material defects are presented: a) too low sulfur content resulted in increased porosity of the sulfur concrete sample, which also resulted in lower strength (see Table 4), b) excessive porosity was observed, c) too high sulfur content resulted in the formation of internal caverns, sulfur efflorescence is also visible on the sample surface.

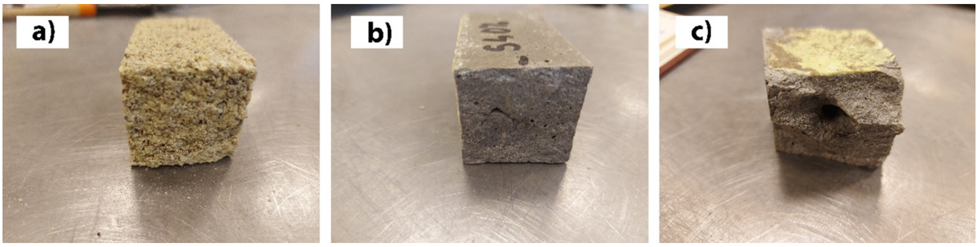

Fig. 3. Cross-sections of specimens made of sulfur concrete (with visible defects) after flexural strength test: a) SC_S20 (sand and 20% of sulfur), b) SC_LHS40 (lunar soil simulant LHS-1 and 30% of sulfur), c) SC_LHS40 (lunar soil simulant LHS-1 and 40% of sulfur)

Secondly geopolymers were tested. Two types of geopolymer were prepared (see Table 4):

1. Geopolymer based on sand mixed with fly ash (G_SF).
2. Geopolymer based on lunar soil simulant LHS-1 (G_LHS).

The preparation of geopolymer specimens (see Fig. 4) was as follows:

1. Mixing dry ingredients: sand and fly ash in specific proportions (in the case of G_SF), (see Table 4).
2. Mixing the chemical bond activator ingredients: sodium hydroxide (NaOH) and 40% water solution of sodium silicate in specific proportions (Table 4). An exothermic reaction occurs and the temperature of the mixture increases.
3. Time to cool the activator (about 2 hours) to room temperature.
4. Mixing dry ingredients with the activator.
5. Placing the mixture in molds 40 × 40 × 160 mm.
6. Vibrating the molds with the mixture for 60 seconds.
7. Placing the molds in an oven in temperature 65°C for 24 h.
8. Unmolding specimens and placing them in an oven in temperature 65°C for 48 hours.

The tested geopolymers are characterized by the compressive strength of 65.3 MPa and 25.9 MPa for the G_SF and G_LHS samples respectively (see Table 5). The lower value of the compressive strength of the G_LHS, in comparison to the G_SF geopolymer, was caused by the addition of higher amounts of sodium silicate water solution needed to maintain workability of the mixture. This also caused the reduction of apparent density of the G_LHS geopolymer in comparison to G_SF geopolymer. The flexural strength was equal to 10.3 MPa and 9.1 MPa for the G_SF and G_LHS respectively.

Table 4. Composition of the tested geopolymers

Material	**G_SF**	**G_LHS**
Sand [g]	250	–
Fly ash [g]	250	–
Lunar simulant LHS-1 [g]	–	500
NaOH [g]	5	28
40% water solution of sodium silicate [g]	100	185

Table 5. Basic properties of the tested geopolymer based on sand, fly ash and LHS-1

Property	**G_SF**	**G_LHS**
Apparent density [g/cm^3]	1.91	1.83
Flexural strength [MPa]	10.3	9.1
Compressive strength [MPa]	65.3	25.9

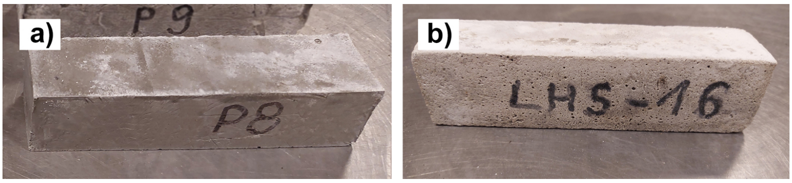

Fig. 4. Specimens made of geopolymer: a) G_SF (sand and fly ash), b) G_LHS (lunar soil simulant LHS-1)

The cross-sections of the tested geopolymer samples revealed considerable porosity (see Fig. 5), which in the case of the G_LHS geopolymer is higher than of G_SF.

2.3. Concept of a lunar egg-shaped habitat

The egg shape serves as an exemplary structure crafted by nature itself, offering resistance to various mechanical factors and optimal material efficiency in its construction. Additionally, the egg’s cross-sectional walls are closer to the vertical axis compared to those of a sphere, enabling more efficient partitioning into functional living spaces. From the authors’ perspective, a lunar habitat designed to harness the natural shape of an egg should be produced on the Moon through in-situ 3D printing. A universal formula applicable for any egg was proposed

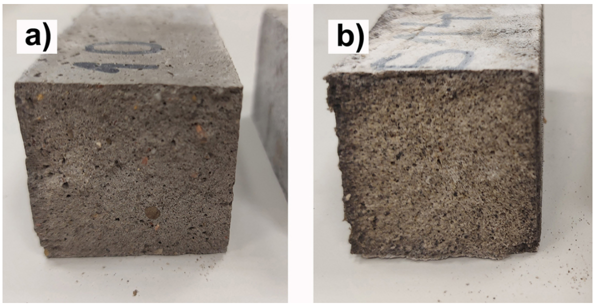

Fig. 5. Cross-sections of specimens made of geopolymer after flexural strength test: a) G_SF (sand and fly ash), b) G_LHS (lunar soil simulant LHS-1)

by Narushin [28] and used for the tests in this research:

$$y = \pm \frac{B}{2}\sqrt{\frac{L^2-4x^2}{L^2+8wx+4w^2}}\times \left(\left(1-\frac{\sqrt{5.5L^2+11\,Lw+4w^2}\left(\sqrt{3}BL-2D_{L/4}\sqrt{L^2+2wL+4w^2}\right)}{\sqrt{3}BL\left(\sqrt{5.5L^2+11Lw+4w^2}-2\sqrt{L^2+2wL+4w^2}\right)}\right)\times \left(1-\sqrt{\frac{L\left(L^2+8wx+4w^2\right)}{2\left(L-2w\right)x^2+\left(L^2+8Lw-4w^2\right)x+2Lw^2+L^2w+L^3}}\right)\right), \tag{2.1}$$

where y is the distance from the point x located on the longitudinal axis (for example, for $x=-w$, $y=B/2$, see Fig. 2), $DL/4$ is a diameter of egg at the point of $L/4$ from the pointed end, L is length, B is egg's breadth, and w is the distance between the points on the long axis of the egg and corresponding to the maximum breadth and half the length of the egg.

The shape presented in Fig. 6 corresponds to the parameters close to a hen's egg: $L = 5.7$ cm, $B = 4.2$ cm, $DL/4 = 3.2$ cm, $w = 0.6$ cm. The volume of a hen's egg was described in the following formula by Narushin [29]:

$$V = 0.5202LB^2 - 0.4065. \tag{2.2}$$

The formula can be useful for calculating the volume of future lunar habitats. Taking into account the height of a habitat based on the egg shape and keeping the other parameters in a proportional relationship, the volume (V) of lunar habitat can be calculated as presented in Table 6.

Due to its structural toughness an egg-shaped lunar habitat can be erected as semi-submerged, fully submerged or buried in a crater. Possible access to the habitat is directly associated with the type of habitat's placement. A thorough description of conceptualization of an egg-shaped lunar habitat was thoroughly discussed in the previous publication [6].

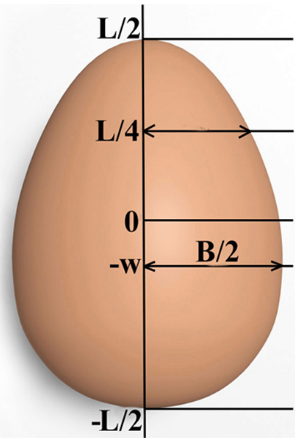

Fig. 6. Parameters needed to solve the egg formula, Eq. (2.1)

Table 6. Calculation of egg shaped habitats volume (referred to a hen's egg)

Description	***L***	***B***	***V***
Hen's egg	5.7 cm	4.2 cm	52 cm^3
One floor habitat	5.7 m	4.2 m	52 m^3
Two floor habitat	10.0 m	7.3 m	282 m^3
Three floor habitat	14.0 m	10.3 m	775 m^3
Four floor habitat	18.0 m	13.3 m	1647 m^3

2.4. Concept of a lunar openwork habitat structure

A lunar habitat structures will be erected fully automatically or semi-automatically. 3D printing is currently the most promising technology enabling the erection of a future habitat structure on the Moon. 3D printing offers a distinctive opportunity for crafting intricate designs, such as Voronoi structures. Georgy Voronoi, a mathematician of Ukrainian origin who lived during the late 19^{th} and early 20^{th} centuries, gained renown for expanding upon a diagram also known as Dirichlet tessellation. In its simplest form, a Voronoi diagram divides a plane into regions whose boundaries are edges, which are straight lines running perpendicular to the line between two points referred to as "seeds at its midpoint" (see Fig. 7). This diagram effectively breaks down an area or volume into smaller sections, with each resulting Voronoi cell comprising points nearest to the respective Voronoi site [30]. When these seeds are arranged in a three-dimensional space, the partition is confined to that specific spatial domain. One of the most notable advantages of employing Voronoi structures is their ability to conserve material while retaining mechanical properties [31]. In fact, Voronoi structures can reduce the mass of stiffeners by as much as 67% [32] and they are easy to 3D print [6].

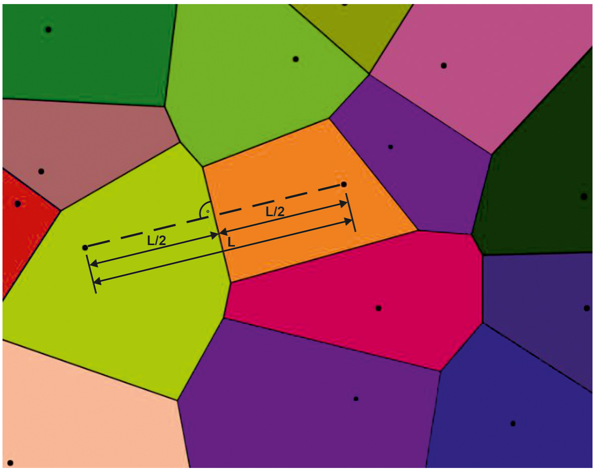

Fig. 7. An example of a Voronoi diagram in 2D dimensions, created using on-line Voronoi generator [33]

Therefore, the authors believe that an ideal lunar habitat should be constructed directly on the Moon in the form of a 3D-printed egg-shaped openwork Voronoi mesh. During the research program shapes of egg-shaped openwork and closed structures were were taking into account and 3D printed as scale models, using acrylonitrile butadiene styrene (ABS) filament to tests their printability. Two examples of such models (differentiated by the thickness of the structure) are presented in Fig. 8.

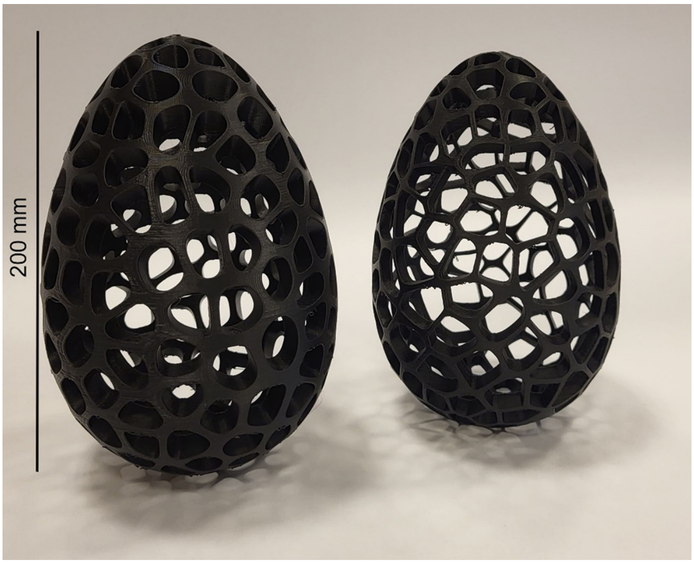

Fig. 8. 3D-printed scale models of an egg-shaped openwork Voronoi structures

2.5. Concept of a protective layer

A base erected on a lunar surface will be directly exposed to solar radiation and meteorites. There are two possible ways of mitigating these dangers: the creation of a very robust structure or covering the structure by a protective layer of regolith. Authors conceptualized that the later solution would be much more practical and feasible. The main challenge lies in shielding the habitat from cosmic radiation. To address this issue, a protective layer of regolith should envelop the entire habitat, thereby adding a sufficiently thick covering throughout its volume. Consequently, there is no need for excessively thick outer walls. However, constructing such a habitat becomes more complex and labor-intensive. There is also a risk of the prepared building materials sliding downward. To study these problems authors tested multiple properties of lunar soil simulants associated with its possible behavior while covering the egg-shaped habitat. The main focus was put on the angle of repose. In Fig. 9 the process of covering the 3-D printed model of the egg-shaped habitat with lunar soil simulant LHS-1 is presented.

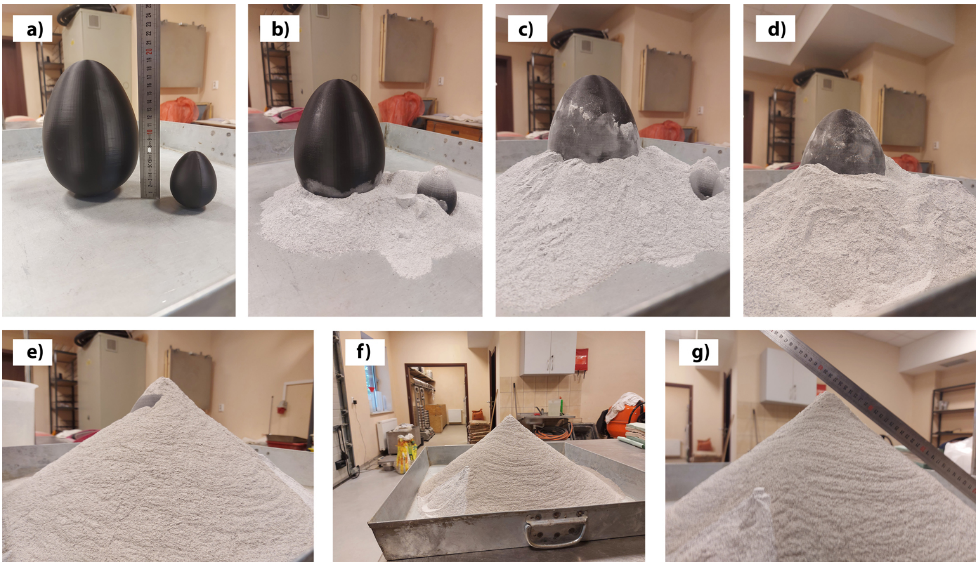

Fig. 9. The process of covering the 3-D printed habitat model with LHS-1

A thorough description of these tests and achieved results are presented in the recent publication by authors [1] where ten different lunar soil simulants were used.

3. Discussion

Currently, it is evident that a human return to the Moon is imminent [33, 34], with missions planned to establish a lasting presence on the lunar surface, setting the stage for future ventures to Mars. Various technological and design approaches have been explored for the lunar aggregate [36], concrete-like material and concept of the base using the egg-shaped design and 3D printing. In authors' opinion the key aspect of a successful construction effort on the Moon is production of lunar aggregate. The proposed technology based on magnetic separation have multiple advantages: it is easy to execute in comparison to other mining techniques (which are quite elaborate due to low lunar gravity and odd behavior of small regolith particles due to lack of atmosphere [37]. Characteristics of the acquired aggregate are promising (homogenized properties) enabling full scale production of a concrete-like lunar composite and further creation of full scale structures. Due to high content of iron-oxides in a created aggregate its properties regarding attenuation of cosmic radiation should be significantly higher in comparison to raw regolith. This phenomenon is currently under investigation of the research team. Moreover, the process of covering the habitat structure by magnetically separated aggregate should be relatively easy to execute in comparison to other techniques based on more traditional approach. In Fig. 10 a visualization of multi egg-shaped habitat construction site is presented. A simple frame is used to operate an electromagnetic device to source and move lunar aggregate.

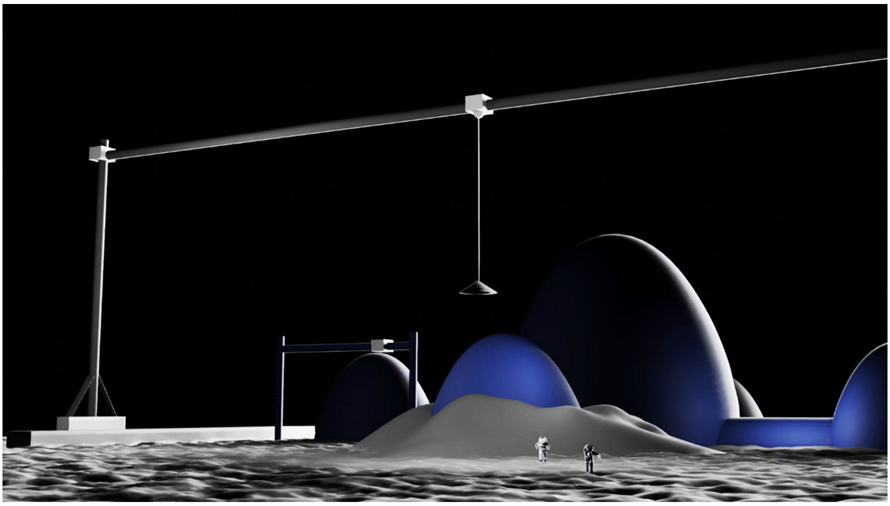

Fig. 10. Visualization of a multi egg-shaped habitat construction site

Only basic variants of the egg-shaped habitats were considered regarding designing a lunar base concept. It is possible to create a single egg-shaped habitat or an entire complex consisting of large and small eggs with varied purposes including storage, energy production, fuel production, lunar soil beneficiation processes etc. This allows for a versatile and functional lunar base. Although egg-shaped habitat seems an impractical structural solution at first, advancements in 3D printing technology make it a feasible option. Further development of the egg-shaped habitat variant should bring a solution for variable layouts, convenient access and ensuring enough light for each floor. These factors are crucial for creating habitable and functional spaces within the lunar base. The aim of the research program was to check egg-shaped habitat in the context of both structures and materials. The research program explores the use of openwork Voronoi structures, which are intricate and efficient lattice-like patterns, and lunar concrete-like composites. These materials offer potential solutions for constructing the egg-shaped habitats on the moon. It's important to note that this is a proposal and further research and testing are required to fully evaluate the viability of the egg-shaped habitat design for a lunar base. The mentioned steps are part of the ongoing research program to develop a complete construction technology for a lunar base.

The harsh conditions on the Moon will affect the effectiveness of the lunar habitats construction. It is hard to predict, how the lack of atmosphere, low gravity and extreme temperatures will disturb the process of lunar concrete formation and the building process. The conditions for constructing such structures on Earth, as well as the tests proposed in this article, differ significantly from those on the Moon. However, without performing this type of testing on Earth, we will not come close to achieving any effects beyond it.

The conducted tests supported initial concepts. In authors' opinion the proposed full technological solution for lunar base, harnessing regolith as raw material for the production of aggregates and concrete-like composites, is feasible. More tests are needed (especially in low gravity conditions and in vacuum) to fully develop the proposed solution.

4. Conclusions

The conducted conceptualization and its supporting research program was mainly focused on regolith as raw material for the production of aggregates and concrete-like composites on the Moon. The concept was further developed into a complex technological solution for a lunar base. The result of the research work conducted by the authors supports key elements of the proposed complex technological solution. Nevertheless, more tests are needed to prove its full feasibility. Firstly, scaled models of the egg-shaped habitat and lunar soil simulants (LSS) should be used to test the main technological concept. Subsequently, the development and thorough tests of a printable lunar geopolymer and sulfur concrete should be conducted. Tests executed in a low gravity conditions, in vacuum and utilizing radiation are also necessary.

Acknowledgements

This research was partially funded by the National Science Centre (Poland) through grant number DEC-2020/38/E/ST8/00527 Regolith harvesting on Moon surface: excavation and beneficiation in low gravity environments.

Conceptualization J.Kat., J.Kob.; Methodology J.Kat., J.Kob.; Software J.Kat., J.Kob.; Validation J.Kat., J.Kob.; Formal analysis J.Kat., J.Kob.; Investigation J.Kat., J.Kob.; Resources J.Kat., J.Kob.; Data Curation J.Kat., J.Kob.; Writing – Original Draft J.Kat., J.Kob.; Writing – Review & Editing J.Kat., J.Kob.; Visualization J.Kat., J.Kob.; Supervision J.Kat., J.Kob.; Project administration J.Kat., J.Kob.; Funding acquisition J.Kat., J.Kob.

References

[1] J. Kobaka, J. Katzer, K. Seweryn, P. Srokosz, M. Bujko, and P. Konečný, "A study of lunar soil simulants from construction and building materials perspective", *Case Studies in Construction Materials*, vol. 18, 2023, doi: 10.1016/j.cscm.2023.e02082.

[2] P. Kostrzewa-Demczuk and M. Rogalska, "Planning of construction projects taking into account the design risk", *Archives of Civil Engineering*, vol. 69, no. 1, pp. 613–626, 2023, doi: 10.24425/ace.2023.144191.

[3] B. Langier, J. Katzer, M. Major, J. Halbiniak, and I. Major, "Strength and durability characteristics of concretes with crushed side window glass as partial aggregate substitution", *Archives of Civil Engineering*, vol. 69, no. 2, pp. 5–21, 2023, doi: 10.24425/ace.2023.145249.

[4] J. Ciazela, et al., "Lunar ore geology and feasibility of ore mineral detection using a far-IR spectrometer", *Front Earth Science (Lausanne)*, vol. 11, 2023, doi: 10.3389/feart.2023.1190825.

[5] R.N. Grugel and H. Toutanji, "Sulfur 'concrete' for lunar applications - Sublimation concerns", *Advances in Space Research*, vol. 41, no. 1, pp. 103–112, 2008, doi: 10.1016/j.asr.2007.08.018.

[6] D. Juračka, J. Katzer, J. Kobaka, I. Świca, and K. Seweryn, "Concept of a 3D-Printed Voronoi Egg-Shaped Habitat for Permanent Lunar Outpost", *Applied Sciences (Switzerland)*, vol. 13, no. 2, 2023, doi: 10.3390/app13021153.

[7] C. Heinicke and M. Arnhof, "A review of existing analog habitats and lessons for future lunar and Martian habitats", *REACH*, vol. 21–22, 2021, doi: 10.1016/j.reach.2021.100038.

[8] G. Cesaretti, E. Dini, X. De Kestelier, V. Colla, and L. Pambaguian, "Building components for an outpost on the Lunar soil by means of a novel 3D printing technology", *Acta Astronautica*, vol. 93, pp. 430–450, 2014, doi: 10.1016/j.actaastro.2013.07.034.

[9] T. Watari, Z. Cao, A.C. Serrenho, and J. Cullen, "Growing role of concrete in sand and climate crises", *iScience*, vol. 26, no. 5, art. no. 106782, 2023, doi: 10.1016/J.ISCI.2023.106782.

[10] T. Sik Lee, J. Lee, and K. Yong Ann, "Manufacture of polymeric concrete on the Moon", *Acta Astronautica*, vol. 114, pp. 60–64, 2015, doi: 10.1016/j.actaastro.2015.04.004.

[11] H.A. Toutanji, S. Evans, and R.N. Grugel, "Performance of lunar sulfur concrete in lunar environments", *Construction and Building Materials*, vol. 29, pp. 444–448, 2012, doi: 10.1016/j.conbuildmat.2011.10.041.

[12] C.S. Ray, S.T. Reis, S. Sen, and J.S. O'Dell, "JSC-1A lunar soil simulant: Characterization, glass formation, and selected glass properties", *Journal of Non-Crystalline Solids*, vol. 356, no. 44-49, pp. 2369–2374, 2010, doi: 10.1016/j.jnoncrysol.2010.04.049.

[13] K.T. Wang, P.N. Lemougna, Q. Tang, W. Li, and X. min Cui, "Lunar regolith can allow the synthesis of cement materials with near-zero water consumption", *Gondwana Research*, vol. 44, 2017, doi: 10.1016/j.gr.2016.11.001.

[14] P.J. Collins, J. Edmunson, M. Fiske, and A. Radlińska, "Materials characterization of various lunar regolith simulants for use in geopolymer lunar concrete", *Advances in Space Research*, vol. 69, no. 11, pp. 3941–3951, 2022, doi: 10.1016/J.ASR.2022.03.012.

[15] D.S. McKay and D.W. Ming, "Mineralogical and chemical properties of the lunar regolith", in *Lunar Base Agriculture: Soils for Plant Growth.* American Society of Agronomy, 1989, doi: 10.2134/1989.lunarbaseagriculture.c4.

[16] L.A. Taylor, et al., "Mineralogical and chemical characterization of lunar highland soils: Insights into the space weathering of soils on airless bodies", *Journal of Geophysical Research Planets*, vol. 115, no. E2, 2010, doi: 10.1029/2009JE003427.

[17] J. Katzer and J. Kobaka, "Influence of fine aggregate grading on properties of cement composite", *Silicates Industriels*, vol. 74, no. 1–2, 2009.

[18] J. Chen, J. Wang, and W. Jin, "Study of magnetically driven concrete", *Construction and Building Materials*, vol. 121, pp. 53–59, 2016, doi: 10.1016/j.conbuildmat.2016.05.152.

[19] P.K. Zarzycki and J. Katzer, "A proposition for a lunar aggregate and its simulant", *Advances in Space Research*, vol. 65, no. 12, pp. 2894–2901, 2020, doi: 10.1016/j.asr.2020.03.032.

[20] H.A. Omar and M. Issa, "Production of lunar concrete using molten sulfur", in *Proceedings of the 4th International Conference on Engineering, Construction and Operations in Space*. 1994, pp. 952–959.

[21] M.H. Shahsavari, M.M. Karbala, S. Iranfar, and V. Vandeginste, "Martian and lunar sulfur concrete mechanical and chemical properties considering regolith ingredients and sublimation", *Construction and Building Materials*, vol. 350, art. no. 128914, 2022, doi: 10.1016/J.CONBUILDMAT.2022.128914.

[22] H.A. Toutanji, S. Evans, and R.N. Grugel, "Performance of lunar sulfur concrete in lunar environments", *Construction and Building Materials*, vol. 29, pp. 444–448, 2012, doi: 10.1016/J.CONBUILDMAT.2011.10.041.

[23] Z. Hu, et al., "Research progress on lunar and Martian concrete", *Construction and Building Materials*, vol. 343, 2022, doi: 10.1016/j.conbuildmat.2022.128117.

[24] C. Montes, et al., "Evaluation of lunar regolith geopolymer binder as a radioactive shielding material for space exploration applications", *Advances in Space Research*, vol. 56, no. 6, pp. 1212–1221, 2015, doi: 10.1016/j.asr.2015.05.044.

[25] G. Xiong, X. Guo, S. Yuan, M. Xia, and Z. Wang, "The mechanical and structural properties of lunar regolith simulant based geopolymer under extreme temperature environment on the moon through experimental and simulation methods", *Construction and Building Materials*, vol. 325, 2022, doi: 10.1016/j.conbuildmat.2022.126679.

[26] M. Arnhof, S. Pilehvar, A.L. Kjøniksen, and I. Cheibas, "Basalt fibre reinforced geopolymer made from lunar regolith simulant", presented at Proceedings of the 8TH European Conference for Aeronautics and Space Sciences (EUCASS), 2019.

[27] Exolith, "Lunar Highlands (LHS-1) High-Fidelity Moon Dirt Simulant". [Online] Available: https://exolithsimulants.com/collections/regolith-simulants/products/lhs-1-lunar-highlands-simulant.

[28] V.G. Narushin, M.N. Romanov, and D.K. Griffin, "Egg and math: introducing a universal formula for egg shape", *Annals of the New York Academy of Sciences*, vol. 1505, no. 1, pp. 169–177, 2021, doi: 10.1111/nyas.14680.

[29] V.G. Narushin, M.N. Romanov, and D.K. Griffin, "Non-destructive measurement of chicken egg characteristics: Improved formulae for calculating egg volume and surface area", *Biosystems Engineering*, vol. 201, pp. 42–49, 2021, doi: 10.1016/j.biosystemseng.2020.11.006.

[30] M. Özcan and U. Yaman, "A continuous path planning approach on Voronoi diagrams for robotics and manufacturing applications", *Procedia Manufacturing*, vol. 38, pp. 1–8, 2019, doi: 10.1016/J.PROMFG.2020.01.001.

[31] C.C. Tung, Y.Y. Lai, Y.Z. Chen, C.C. Lin, and P.Y. Chen, "Optimization of mechanical properties of bio-inspired Voronoi structures by genetic algorithm", *Journal of Materials Research and Technology*, vol. 26, pp. 3813–3829, 2023, doi: 10.1016/J.JMRT.2023.08.210.

[32] B. Bostan, M. Küsbeci, M. Çetin, and M. Kırca, "Buckling performance of fuselage panels reinforced with Voronoi-type stiffeners", *International Journal of Mechanical Sciences*, vol. 240, art. no. 107923, 2023, doi: 10.1016/J.IJMECSCI.2022.107923.

[33] https://cfbrasz.github.io/Voronoi.html.

[34] B. Sherwood, "Principles for a practical Moon base", *Acta Astronautica*, vol. 160, pp. 116–124, 2019, doi: 10.1016/J.ACTAASTRO.2019.04.018.

[35] J.M. Sarkissian, "Return to the Moon: A sustainable strategy", *Space Policy*, vol. 22, no. 2, pp. 118–127, 2006, doi: 10.1016/J.SPACEPOL.2005.12.007.

[36] N.I. Cool, et al., "Matrix transformation of lunar regolith and its use as a feedstock for additive manufacturing", *iScience*, vol. 26, no. 4, art. no. 106382, 2023, doi: 10.1016/J.ISCI.2023.106382.

[37] K. Seweryn, P. Paśko, and G. Visentin, "The Prototype of Regolith Sampling Tool Dedicated to Low Gravity Planetary Bodies", in *Mechanisms and Machine Science*, vol. 73. Springer, 2019, pp. 2711–2720, doi: 10.1007/978-3-030-20131-9_268.

Regolit jako surowiec do produkcji kruszyw i kompozytów betonopodobnych na Księżycu

Słowa kluczowe: księżyc, regolit, baza, budowa, stały pobyt

Streszczenie:

Stała obecność człowieka na Księżycu nastąpi prawdopodobnie w ciągu najbliższej dekady. Zapewnienie właściwych warunków życia i pracy załogi bazy księżycowej będzie wymagało dużego wysiłku budowlanego związanego z budową lądowisk, habitatów, magazynów, kopalń i obiektów

związanych z produkcją paliwa. Przedsięwzięcia takie będą prowadzone w bardzo niekorzystnych warunkach i przy znikomej dostępności materiałów i komponentów przywiezionych z Ziemi. Jedynym możliwym rozwiązaniem jest stosowanie wyłącznie surowców lokalnie dostępnych na Księżycu. Regolit, czyli rozdrobniona skał a księżycowa, w założeniu przyszłych misji nastawionych na długi pobyt ludzi, będzie stanowił główny surowiec do produkcji kruszyw budowlanych oraz kompozytów betonopodobnych niezbędnych do stworzenia podstawowych warunków bytowych dla człowieka. W referacie autorzy przedstawiają propozycje produkcji kruszyw budowlanych oraz kompozytów betonopodobnych (charakteryzujących się właściwościami wytrzymałościowymi podobnymi do betonu zwykłego) wytworzonych z regolitu księżycowego, wsparte wynikami badań własnych oraz oryginalnymi propozycjami pełnych rozwiązań technologicznych, które w założeniu będą mogły być zaimplementowane na Księżycu. Wykonanie materiału betonopodobnego na powierzchni Księżyca zapewniającego odpowiednie właściwości konstrukcyjne, wiąże się z odpowiednim przygotowaniem regolitu. Oddzielenie cięższych frakcji regolitu, cechujących się właściwościami ferromagnetycznymi, czyli zawierającymi żelazo, kobalt i nikiel od frakcji lżejszych jest niezbędne w celu uzyskania tych cennych metali. Innym zastosowaniem może być użycie ich do wykonania księżycowych odpowiedników betonów ciężkich o zwiększonej wytrzymałości oraz zdolności pochłaniania promieniowania. W ramach przeprowadzonego programu badawczego zrealizowano serię prób materiałów betonopodobnych, które mogłyby być wykonane na Księżycu z dostępnych tam materiałów. Testy początkowe wykonano z wykorzystaniem piasku normowego CEN w celu doboru właściwych proporcji składników, następne próby przeprowadzono z wykorzystaniem symulantu gruntu księżycowego. Wyniki badań wytrzymałościowych wykazały, że możliwe jest otrzymanie materiału spełniającego wymagania wytrzymałościowe powyżej 40 MPa. W przypadku symulantu gruntu księżycowego LHS-1 było to 44,1 MPa przy zawartości siarki na poziomie 30%. Wewnętrzna struktura tego materiału była najbardziej zwarta z badanych, co odzwierciedla również gęstość pozorna na poziomie 2,43 g/cm^3. Wciąż prowadzone są prace badawcze nad wyborem najbardziej optymalnej bryły zewnętrznej habitatu. Jednym z rozwiązań sprawdzonych w ciągu milionów lat ewolucji, które podsuwa natura jest forma jajka. Posiada ona zalety takie jak: trwałość konstrukcyjna oraz zwiększona wysokość w stosunku do formy sfery. Tego rodzaju habitaty z uwagi na niebezpieczeństwo uderzenia meteorytów oraz promieniowanie powinny być zabezpieczone dodatkową warstwą ochronną w postaci regolitu. Wykorzystanie surowców naturalnych znajdujących się na naszym naturalnym satelicie w racjonalny sposób jest kluczem do utworzenia trwałych miejsc pobytu bezpiecznych dla przebywających tam ludzi.

Received: 2023-09-28, Revised: 2023-12-12