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MAGNETIC SEPARATION OF LUNAR REGOLITH AS ITS BENEFICIATION FOR CONSTRUCTION EFFORT ON THE MOON

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ABSTRACT. A concept of magnetic separation of regolith for production of lunar aggregate is presented in the paper. Future construction effort on the Moon will require significant amounts of concrete-like composites. The authors formulate a hypothesis that magnetic separation of regolith would be a very efficient beneficiation procedure solving multiple civil engineering problems associated with properties of raw lunar soil. For the research program, 10 lunar soil simulants were used. The magnetic separation was feasible in majority of cases. Acquired lunar aggregate would be useful for both concrete-like composite production and covering the surface of a habitat. The aims of future research are pointed out in the paper.

Keywords: regolith, beneficiation, magnetic separation, building material, the Moon

1. INTRODUCTION

After the first successful landing of humans on the lunar surface in 1969, more than half a century later, a permanent base on the moon still remains in the design and planning phases. The complexity of technical problems associated with the erection of a habitat on the Moon proved to be very difficult to solve using only locally available materials. *In situ* resource utilization (ISRU), which should be fully addressed during the construction of a habitat on the Moon, creates a very unique situation both from materials and civil engineering points of view. Colonization and “commercialization” of the Moon will create a need for numerous construction activities (Benaroya & Bernold, 2008). Globally, multiple research teams have targeted this problem and worked on the development of technologies of creating lunar building materials and full construction technologies. Almost all of conceptualized technologies utilize lunar soil in its raw state. Basically, lunar regolith is foreseen as a bulk material for key construction activities such as production of concrete-like composites, covering erected habitats and storage structures, filling 3D-printed formworks, and so on. From civil engineering point of view, the full industrial scale production of a lunar concrete-like composite is inevitable (Cesaretti et al., 2014; Grugel, 2012; Pinheiro et al., 2013). Any construction activity is associated with significant volumes of needed materials. For example, on Earth, the yearly production of concrete has exceeded 1 m^3 per person. Ordinary concrete (based on Portland cement) is the most common and universal building material in human history. Human experience with building materials and construction technologies is limited only to Earth, and there are no proofs that lunar construction effort will be any different. This vision seems to be shared by numerous research teams worldwide. They focus their research effort mainly on the development of lunar concrete-like composites (Ray et al., 2010; Sik Lee et al., 2015; Toutanji et al., 2012). Proposed production technologies of lunar concrete-like composites are based on sulfur, polymers, and 3-D printing. All these technologies use raw lunar soil. In authors' opinion, using raw lunar soil is inappropriate from a technological point of view. It may also result in misleading conclusions. It should be firmly stated that on Earth, for production of ordinary concrete, raw soil is not used. Only solicitously sourced and tested aggregate is used for creation of an ordinary concrete. The aggregate is characterized by specific graining properties (described by national and international codes), shape of particles, uniformity of mineral composition, high mechanical properties, and lack of chemical and biological impurities. For similar reasons, raw lunar soil should not be considered for concrete-like composite production on the Moon. Lunar soil should go through some kind of beneficiation process before being used for the construction purposes. Shaping aggregate properties by mixing different types of aggregates and utilizing their advantages is a well-known practice in civil engineering (Katzer, Kobaka and Ponikiewski, 2020). Another problem associated with the raw lunar soil as a building material is its sourcing. Excavation of regolith on lunar surface faces many problems that do not exist on Earth (e.g., low gravity, which disables traditional digging). Special devices were conceptualized and developed to source regolith while coping with very specific conditions on the Moon surface. One such promising approach is a sampling device which, after scaling up, could play the role of an industrial regolith excavator. The device named PACKMOON (Seweryn, Paśko and Visentin, 2019) was created in the Space Research Centre of Polish Academy of Sciences (see Figure 1). PACKMOON is a rotary hammering device that generates rotary movement of the jaws. Sample acquisition is possible due to the gradual movement of the spherical jaws. The jaws' closure is enforced by hammering, where the hammer's energy and momentum are transferred to the jaws in consecutive strokes. After a number of strokes, the jaws close and the sample is collected (Seweryn, Paśko and Visentin, 2019).

Future industrial excavator systems of lunar regolith are nowadays classified as discrete excavators and continuous excavators. Discrete excavators are characterized by the need to break contact with the soil in between cuts to clear the cutting surface or to dump the excavated material (a single large bite). Systems where multiple cutting surfaces are continually in contact with the soil and multiple cuts are possible can be referred to as continuous excavators (Just et al., 2020). Discrete excavators (e.g., PACKMOON) could be applied for excavating smaller amounts of regolith in the initial phase of building lunar habitat. For the full systems continuous excavator (e.g. Rassor, developed by NASA) could be used (Schuler et al., 2019).

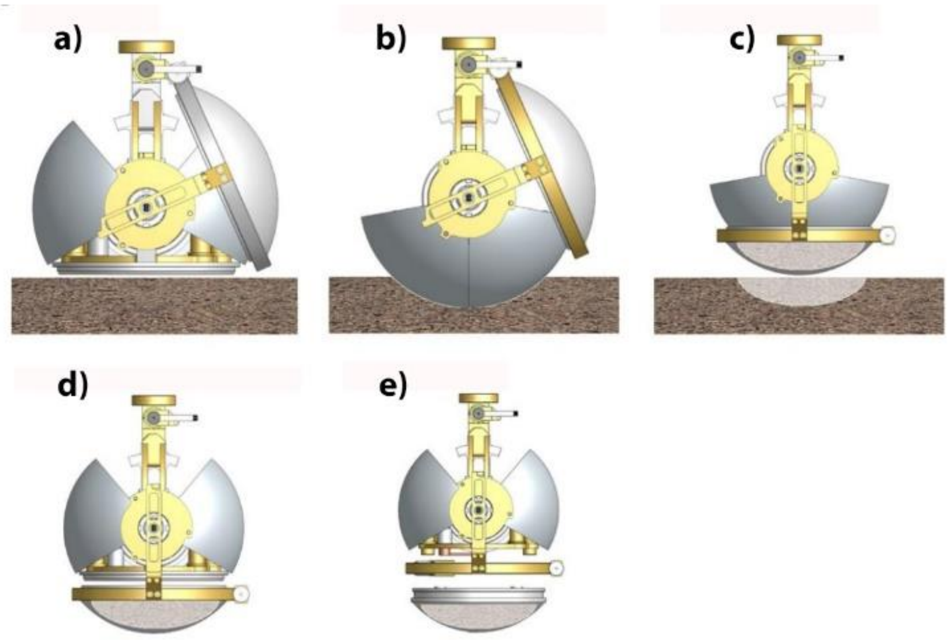

Figure 1. Regolith sampling tool PACKMOON (Seweryn, Paśko and Visentin, 2019). Phases of operation: a) initial position, b) hammering and jaws closure, c) container deployment, d) jaws opening and sample removal, e) container release.

Considering future construction of lunar habitat, obtaining building materials that meet a number of strength, durability, and safety requirements is crucial. The key issue is the usefulness of lunar regolith as a construction material (Ferrone et al., 2022). Lunar regolith was created during the process of largely mechanical weathering on the Moon, in which particles are ground to finer and finer size over time. The regolith is a granular, dry, and porous material with small particle size, irregular adsorption area, high gas solubility, and extremely large surface area-to-volume ratio (Zhang et al., 2021). An analysis of the lunar soil confirmed high content of fractions characterized by ferromagnetic properties (Rochette et al., 2010; Song et al., 2020), which are the cumulative effects of solar wind bombardment, micrometeorite impacts, and cosmic rays (Bentley et al., 2009).

Effective sourcing of ferromagnetic fractions from the lunar soil might be the first step toward obtaining a building material with uniform and predictable properties. Beneficiation of lunar soil through the technique of magnetic separation would result in dividing it into ferromagnetic and non-ferromagnetic parts. The ferromagnetic part could be used as a building material (an equivalent of Earthly aggregate). For the production of any kind of concrete or concrete-like composite, aggregate is an essential ingredient which cannot be replaced by raw soil. Taking into account all of the above facts, the authors proposed a method of lunar soil beneficiation through the means of magnetic separation. The separated material could be used as an aggregate or for creation of a lunar concrete-like composite (Momi et al., 2021; Zhou et al., 2021). It could be also utilized as a cover (insulating) material for erected habitats. The conducted research program proved the concept and enabled pointing out the axis of future research.

Table 1. Simulants used in the tests

Name	**Producer**	**Country**	**Description**	**Loose state bulk density (g/cm^3)**
LHS-1	Exolith Lab	The USA	Lunar highlands simulant	1.36
AGK2010	AGH	Poland	General lunar simulant (the only analog available in Poland in a large quantity)	1.35
OPRL2N	Off Planet Research	The USA	Lunar mare simulant	1.28
JSC 1A	NASA and the Johnson Space Center	The USA	Lunar regolith simulant	1.56
CHENOBI	Deltion Innovations Ltd.	Canada	General lunar simulant	1.39
LMS-1	Exolith Lab	The USA	Lunar mare simulant	1.62
ESA 06-A	European Space Agency	The EU	Iceland basaltic sand	1.35
ESA 01-E	European Space Agency	The EU	3 mm basalt aggregate	1.53
UoM-B	University of Manchester	GB	Volcanic black dust/slag or iron ore	1.36
UoM-W	University of Manchester	GB	Crushed, dried, and graded glass sand	0.95

2. MATERIALS AND METHODS

Since the original lunar soil is unavailable for researchers (especially in large volumes which are needed for tests of concrete-like composites), a number of research teams have developed their lunar composites using different types of lunar soil simulants (LSS) (Hill et al., 2007; Arslan, Sture and Batiste, 2008; Wallace et al., 2009; Zheng et al., 2009; Bednarz et al., 2013; Seweryn et al., 2014). Leaving aside the problem of the questionable quality of some LSS and their specific testing purposes for other discussions (Taylor et al., 2016; Zarzycki & Katzer, 2019), the authors decided to use 10 LSS, which are well-known and described in literature, for the current research program. The used LSS (which originated from North America and Europe) are listed in Table 1.

The aim of the conducted test was magnetic separation of the simulants. For the test, a manually operated device was used, which proved to be very effective in a previous research program focused on sourcing the Baltic sea magnetic fractions including ilmenite (Zarzycki & Katzer, 2019). The magnetic separator (see Figure 2a) was based on a neodymium magnet. After the ferromagnetic fraction sticks to the surface of the device, it can be easily transferred to the storage location (see Figure 2b). When the handle of the device is lifted, the neodymium magnet changes its position and the material falls down into the storage area. In the future, during full-scale works on the Moon, electromagnets will be used instead of neodymium magnets. The scale of works and demagnetization problem of permanent magnets due to excessive radiation levels (Samin, 2018) would be the main factors for choosing electromagnets.

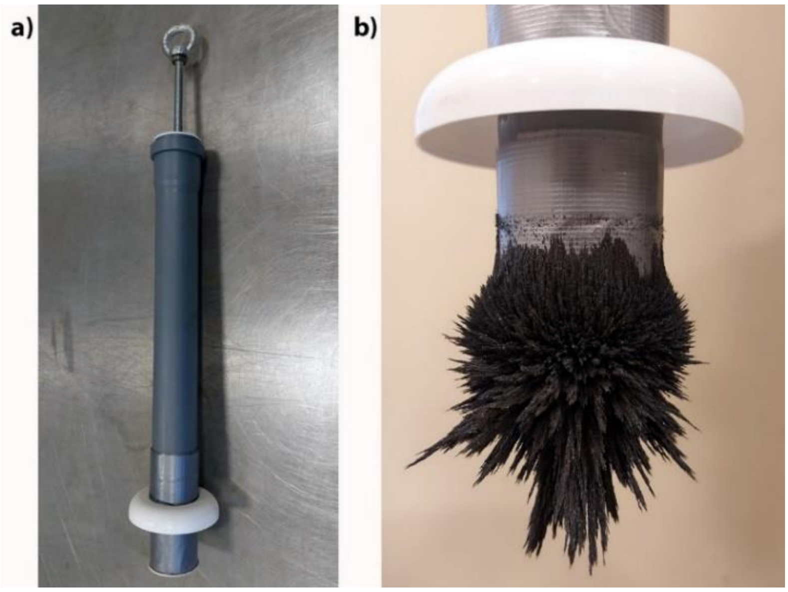

Figure 2. The magnetic separator used during the research program: a) overall view, b) ferromagnetic particles of lunar simulant attached to the device

3. TEST RESULTS

Magnetic separation revealed large discrepancy between LSS regarding the content of fractions characterized by ferromagnetic properties (see Table 2). The amount of the magnetic fraction ranged from 0% (in case of UoM-W simulant) to almost 100% (in case of OPRL2N and UoM-B simulants). The fraction was calculated by weight.

Table 2. Ferromagnetic fraction after magnetic separation.

No.	Name	Ferromagnetic fraction (%)
1	LHS-1	11.44
2	AGK2010	0.86
3	OPRL2N	97.06
4	JSC 1A	68.66
5	CHENOBI	4.48
6	LMS-1	47.48
7	ESA 06-A	15.42
8	ESA 01-E	63.78
9	UoM-B	99.70
10	UoM-W	0.00

Separated ferromagnetic and non-ferromagnetic fractions were analyzed using an optical microscope. Shapes of lunar simulants observed under the microscope have an irregular form and are characterized by sharp edges (see Figures 3–5). This characteristic corresponds to the real lunar soil particles which are characterized by sharp edges and an extended shape. The complex shape of lunar soil particles is caused by lack of an atmosphere on the Moon and the erosion processes associated with it (Kobaka, Katzer and Zarzycki, 2019). Microscopic photographs of ferromagnetic and non-ferromagnetic fractions of the simulants revealed their completely different appearance. The non-ferromagnetic fraction is brighter than the ferromagnetic one (see Figures 3–5). In case of LMS-1 and ESA01, the grains seem to be almost transparent (see Figures 4a and 5a). The dark color of a ferromagnetic fraction is justified by the iron content.

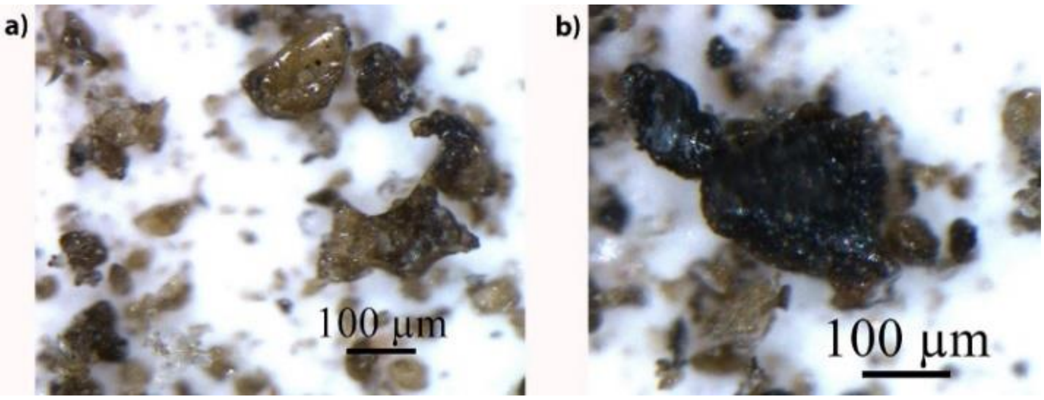

Figure 3. JSC 1A lunar soil simulant: a) non-ferromagnetic fraction, b) ferromagnetic fraction

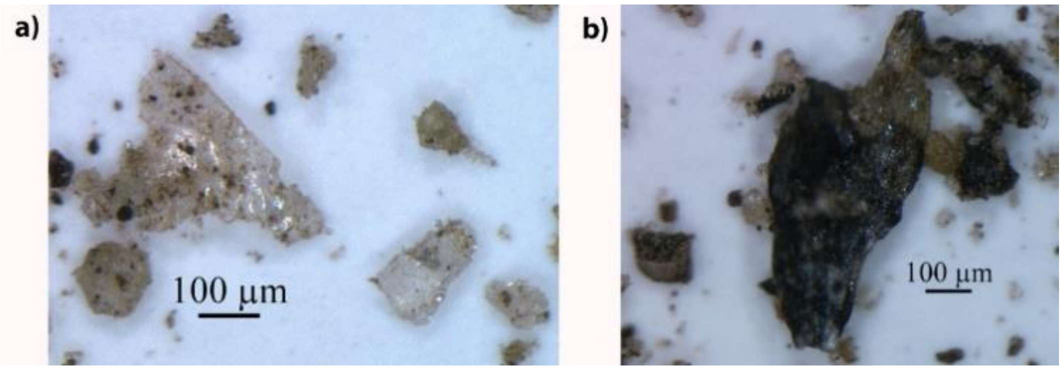

Figure 4. LMS-1 lunar soil simulant: a) non-ferromagnetic fraction, b) ferromagnetic fraction

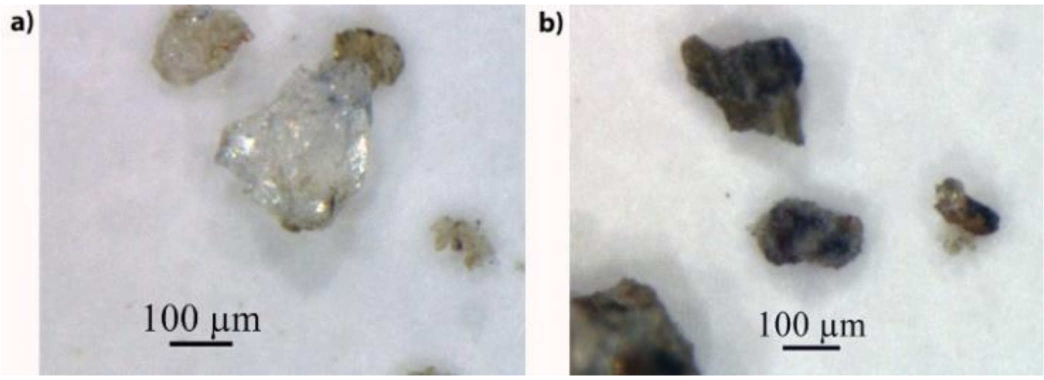

Figure 5. ESA01 lunar soil simulant: a) non-ferromagnetic fraction, b) ferromagnetic fraction

4. DISCUSSION

Key problems associated with utilization of lunar soil in its raw state in comparison to ordinary Earthly aggregate are its regional and local variances. All characteristics (regarding mineral composition, grading, shape of particles, and mechanical properties) are varied across the regolith. Influence of such varying characteristics on the mechanical properties and durability of concrete-like lunar composite would be significant. The production of lunar aggregate through the means of magnetic separation of raw regolith would enable harnessing of all good practices developed on Earth in the construction industry. Adapting Earthly testing methods and quality control procedures for lunar conditions would also be reasonably easy (Katzer and Kobaka, 2009a, 2009b). Lunar concrete-like composites created on the basis of segregated regolith would be superior than concrete-like composites created using raw regolith. It is likely that the ferromagnetic fraction of segregated regolith would be dominated by ilmenite (the titanium-iron oxide). Ilmenite is quite common in both lunar regolith and Earth rocks. The amount of ilmenite in lunar soil is up to 5% (Heiken and Vaniman, 1990; Kong, Jolliff and Wang, 2013). Moreover, using a regolith-rich aggregate instead of ordinary post-glacial aggregate does not significantly affect the properties of created ordinary concrete (see the results achieved in a previous research program: Zarzycki & Katzer, 2020).

In Figure 6, a visualization of a possible lunar magnetic separator is presented. The separator would be located in the area with regolith reach in the ferromagnetic fraction. Material sourced on one side of the separator would be placed on a created dome as a cover material of the habitat.

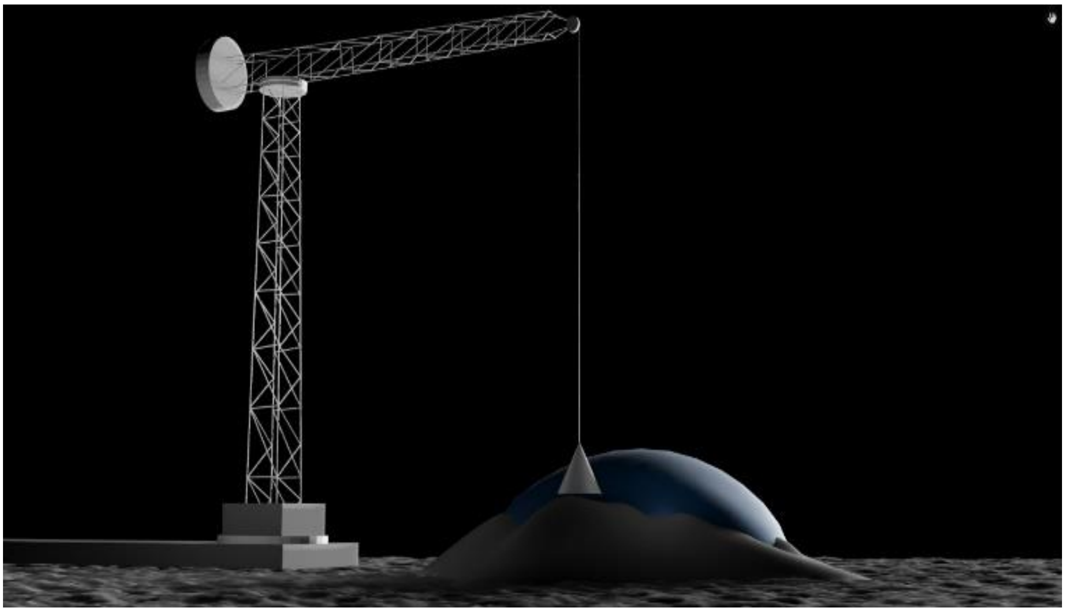

Figure 6. Hypothetical lunar crane using electromagnetic separator for covering the surface of the habitat with ferromagnetic fractions of regolith (authors: J. Katzer, J. Kobaka)

The process of proposed magnetic separation would be much easier to execute on the Moon than it is during the tests on Earth due to lack of atmosphere and significantly lower gravity. The sourced ferromagnetic fraction (playing the role of lunar aggregate) would be characterized by homogenized grading, uniform mechanical properties, and no unsound particles. The granulometric properties of aggregate are a key element which would influence the properties of concrete-like composites created on the Moon. By changing the strength of the magnetic field used for separation process, one could also influence the diameter of separated ferromagnetic particles. Such a process is very important from civil engineering point of view. Very fine particles (diameter $d \leq 0.125$ mm) are restrained to the amount of 5% (by mass) regarding the production of ordinary concrete on Earth. The increased amount of fine particles influences numerous properties of ordinary concrete both in the state of fresh mix and hardened composite. The main problems are associated with the need of using significantly increased volumes of cement paste to cover all aggregate particles. Higher volume of cement in a cubic meter of concrete results in large creep, shrinkage, and the large gradient of temperatures (during the curing period) inside the cast element. It is justified to predict that similar problems would arise in case of using fine particles for the creation of concrete-like lunar composite. The amount of particles with d ≤0.125 mm in regolith usually exceeds 50% (Zarzycki & Katzer, 2019). Concrete with high volume of fine aggregate particles is prone to cracking throughout the whole cast element, which subsequently causes its rapid deterioration. Very fine aggregate particles require significantly increased amounts of binder. Creating lunar aggregate by means of magnetic separation would allow to get less than 1% of very fine particles (Zarzycki and Katzer 2020). Such granular material would be perfectly suitable for the production of lunar concrete-like composite. Using lunar aggregate, instead of raw lunar regolith, for production of concrete-like composite guarantees the lowest possible consumption of binders (Wang et al., 2017), polymers, or sulfur (depending on the adopted technology). From ISRU's perspective, minimizing the needed binders, inorganic polymers (so-called geopolymers), or sulfur for the creation of a cubic meter of a good-quality lunar concrete-like composite is a key factor. One should also consider, apart from strength characteristics, the radiation resistance of the created lunar cement-like composite. It would be one of the most important properties of lunar concrete-like composites. Ferromagnetic particles, as heavy minerals, are characterized by significantly higher radiation resistance (Makarious et al., 1989) in comparison to untreated regolith. Using only ferromagnetic particles as an aggregate for production of lunar concrete-like composite and for soil works would result in much more effective radiation barriers than those created with raw lunar soil.

The extremely complicated shape (in comparison to sub-rounded shape of ordinary post-glacial aggregate) of the regolith particles will affect the properties of a lunar concrete. The magnitude of this influence will be associated with the type of produced concrete-like composite and technology of its production. Future research effort (and publications) should be focused on this problem.

Future research programs should be focused on the creation of concrete-like composites using lunar binders, polymers, or sulfur. The tests should be conducted with the help of both LSS and real lunar soil samples. Composites based on segregated ferromagnetic particles should be thoroughly tested, including micro-gravity.

5. CONCLUSIONS

- Magnetic separation of the regolith is a promising technique for lunar civil engineering for highlands in the middle latitude, where significant amount of ilmenite is envisaged.

- Ferromagnetic fractions of lunar regolith would provide better protection against radiation as a cover of habitats than raw regolith.

- Ferromagnetic fractions of lunar regolith would play a role of lunar aggregate with much more uniform properties (both in terms of mineral composition and granulometric properties) in comparison to raw regolith.

- Non-ferromagnetic fraction of lunar regolith could be used for other purposes, that is, farming.

- Future research should cover creation of concrete-like composites (based on binders, polymers, or sulfur) using both LSS and real lunar soil samples and their tests conducted in micro-gravity.

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