Microwave processing of lunar soil for supporting longer-term surface exploration on the Moon

Vibha Srivastava[a], Sungwoo Lim[a], Mahesh Anand[b]

[a]Department of Engineering & Innovation, The Open University, Walton Hall, Milton Keynes, MK7 6AA, UK,

[b]Department of Physical Sciences, The Open University, Walton Hall, Milton Keynes, MK7 6AA, UK

Email address: vibha.vibha@open.ac.uk

Abstract

The future of human space exploration will inevitably involve longer-term stays and possibly permanent settlement on the surfaces of other planetary bodies. It will, therefore, be advantageous or perhaps even necessary to utilise local resources for building an infrastructure for human habitation on the destination planetary body. In this context human lunar exploration is the next obvious step. Lunar soil is regarded as an ideal feedstock for lunar construction materials. However, significant gaps remain in our knowledge and understanding of certain chemical and physical properties of lunar soil, which need to be better understood in order to develop appropriate construction techniques and materials for lunar applications.

This article reviews our current understanding of the dielectric behaviour of lunar soil in the microwave spectrum, which is increasingly recognised as an important topic of research in the Space Architecture field. Although the coupling between the lunar soil and microwave energy is already recognised, considerable challenges must be overcome before microwave processing could be used as a main fabrication method for producing robust structures on the Moon. We also review the existing literature on the microwave processing of lunar soil and identify three key research areas where future efforts are needed to make significant advances in understanding the potential of microwave processing of lunar soil for construction purposes.

Keywords: Space Architecture, lunar soil, microwave, dielectric properties

1. Introduction

It is anticipated that future human exploration will involve longer-term stays and possibly permanent settlement on the Moon and planetary bodies such as Mars. To sustain such longer-term missions, it will be necessary to build robust infrastructure and habitats. Mass - a critical component of spaceflight - must be minimised in order to maximise cargo [1]. Because of the impracticality of transporting construction materials from the Earth, which would require huge mass for the anticipated scale of construction, using *in-situ* resources for construction on the target planetary bodies would be an ideal option. This research therefore addresses the field of construction processes which use lunar regolith and Additive Manufacturing techniques (a.k.a. 3D printing) on the Moon to build infrastructure and components such as human habitats, launching pads or scientific instruments.

In recent years considerable attention has been given to using Additive Manufacturing techniques for extra-terrestrial constructions, because of the minimal waste of raw material, reduced human intervention and new architectural forms and functions [1]. It involves the process of constructing a 3D object by sequentially adding and bonding raw materials under automated computer control [2], using a specific binder which could be a chemical or a heat source. The potential raw material for construction on the Moon is lunar regolith. Regolith is the unconsolidated heterogeneous material overlying solid rocks[3, 4]. For 3D printing using *in-situ* resources, the most effective way to bind the layers to fabricate a structure would be to either extrude a slurry of regolith or melted regolith, or sinter the raw material [1]. Sintering is a method where the material is heated to a temperature below its melting point to enable it to bond together to form a solid. The heat sources for fabrication on the Moon for either sintering or melting could be solar energy, nuclear energy or electromagnetic radiation, i.e. microwave radiation energy. Some 3D printing techniques including Fused Deposition Modelling and Selective Laser (or Solar or Microwave) Sintering could be used with these binding methods [1]. Among these, microwave processing (sintering or melting) is one of the most attractive fabrication methods for construction on the Moon because lunar regolith acts as a dielectric, readily absorbing microwave energy on the same principle as a kitchen microwave.

2. Microwave interaction with lunar soil

Microwave radiation is the region in the electromagnetic spectrum with a frequency range between 300 MHz and 300 GHz, and wavelength between 1 mm to 1 m.

Lunar soil is the finer fraction of lunar regolith, less than 1 cm in grain size [5]. The particle-size distribution of lunar soil is very broad and regarded as 'well-graded' in geotechnical terms. During the 4.5 billion year geological history of the Solar System, the lunar surface has been bombarded by micrometeorite impacts, solar flares and galactic cosmic radiation. Collectively, modification of the lunar surface material through these processes is termed 'space weathering'. The presence of single domain (40 – 330 Å in size) Fe particles in lunar soil (also commonly called nanophase Fe^0 or np-Fe^0) is thought to have been produced by space weathering processes. Previously, researchers [5-8] have hypothesised that the presence of this np-Fe^0 in the lunar soil promotes coupling with microwave energy. Metals readily reflect microwaves, and the same metal in powdered form acts effectively as a conductor separated by dielectric (insulators such as particles and air) and absorbs microwave energy very effectively [5]. Microwave energy penetrates metals at a very shallow skin-depth, so metallic objects reflect microwaves. However, the minute size of np-Fe^0 has an even smaller skin-depth allowing penetration of microwave energy. Lunar soil is a mixture of np-Fe^0 grains separated by the dielectric glass and other rock-forming minerals (e.g., silicate, oxides, sulfides, etc.). The microwave absorbing abilities of the np-Fe^0 particles thus create 'energy sinks' with the effective generation of large quantities of heat under microwave radiation [5].

Previous researchers have undertaken experiments involving heating of both actual lunar soil and lunar simulants at 2.45 GHz microwave frequency, the standard kitchen microwave frequency [5]. Because it is easily available and affordable, 2.45GHz has been chosen for most lunar soil research experiments. Lunar soil and the lunar simulant JSC-1A appear to be completely melted at between 1,100 °C and 1,400 °C. JSC-1A, a reproduction of the original JSC-1 simulant, is crushed volcanic tuff with abundant glass with large amounts of nano-meter sized magnetite ($Fe^{2+}Fe^{3+}{}_2O_4$) grains [9]. Although JSC-1A mimics the geotechnical properties of lunar soil, it does not contain np-Fe^0. As actual lunar soil availability is fairly restricted, the majority of studies have performed experiments on the lunar simulant JSC-1A, which is widely available from commercial sources [9, 10]. However, using JSC-1A as a proxy for lunar soil with respect to microwave processing presents certain challenges. One such challenge includes the observation that JSC-1A when heated at 2.45 GHz did not absorb microwave radiation effectively up to 200 °C - 400 °C, although it heated up rapidly at higher temperatures [11]. Thermal runaway condition is another challenge associated with microwave heating. Microwave energy is preferentially absorbed by the inner portions, leaving the surfaces less thoroughly heated. Microwave heating at 2.45 GHz is therefore usually discussed in combination with some other form of radiant heating [12]. Although microwave heating can be combined with other radiant heating, it is important to understand the factors contributing to the behaviour of JSC-1A when heated using microwave energy. Some of these factors are related to the fundamental physical properties of natural materials which affect and govern the nature of microwave coupling.

The absorption of microwave energy by a material depends on its dielectric properties. These properties help define three parameters: power density, heating rate and the half-power depth of any material [5]. Thus, it is necessary to understand the dielectric properties of lunar soil and the factors which affect them. The following section briefly discusses some aspects of the dielectric properties and the work carried out by previous researchers to investigate the relation between these properties and some of the factors, e.g. density, frequency, temperature, etc.

3. Dielectrics

Dielectrics are essentially insulators. When exposed to an electromagnetic field, they become polarized [13]. The two important dielectric properties are dielectric constant and dielectric loss. Dielectric constant relates to the permittivity of a material. Permittivity is the ability of a material to store energy in an applied electromagnetic field and is the degree to which a material polarises in response to this applied field. The dielectric constant is sometimes also referred to as relative permittivity: the ratio of permittivity of the dielectric to the permittivity of a vacuum. Thus, the greater the polarisation developed by the dielectric in an applied electromagnetic field of given strength, the greater will be the dielectric constant [14]. An efficient dielectric supports a varying charge with minimal dissipation of heat. Dielectric loss is the form of loss in a dielectric which dissipates energy through the movement of charges in an alternating electromagnetic field as polarisation switches direction. This dielectric loss is utilised to heat the food in a kitchen microwave oven [14].

The two properties are crucial to determining the heating of a material in the presence of an electromagnetic wave such as the microwave. The properties depend on the frequency and are also influenced by density, mineral composition, grain size, moisture and temperature, etc. [15]. Study of the variation of dielectric properties with these factors will help determine the absorption spectrum for lunar soil in the microwave range. We have thus reviewed the data from previous studies to understand the relationship between dielectric properties and some of the factors mentioned above.

3.1 Dielectric properties of Apollo lunar soils

Olhoeft and Strangway [16] investigated the dielectric properties of the first 100 meters below the Moon’s surface by analysing nearly ninety-two Apollo lunar soil samples at frequencies ranging from 0.0001 GHz to 9 GHz. They used several core tube specimens of lunar regolith sampled from 1 -3 m depth, to examine the dielectric properties of lunar soil as a function of density under controlled laboratory conditions [16, 17]. A formula derived from studying these samples indicated that the density increases rapidly with increasing depth below about 1 m, but the density increase becomes unrealistic. Another set of data [18] for density versus depth profile is generated from the laboratory determined self-compression data of lunar soil samples. These data were used to derive estimates for the range of soil density using depth profiles in the lunar sub-surface at depths of up to 100 m. The data also show an increase in density with depth at the shallowest depths. However, these data are derived from the measurement of surface fines only and do not represent coarser rock mixtures or solid rock. The experiments conducted at the Apollo 17 site evidenced the presence of rock at close to 7 m depth. The authors claimed, therefore, that results from the estimates made for soils to the depth of 100 m are probably realistic only up to 7-10 m below the surface of the Moon[16].

According to their study, the dielectric constant in dry materials does not vary with frequency above a few KHz below temperatures of 200 °C [16]. However, it was found to increase with density, as shown in Figure 1. It is worth noting that the samples, whether in solid or soil form, have the same density dependence.

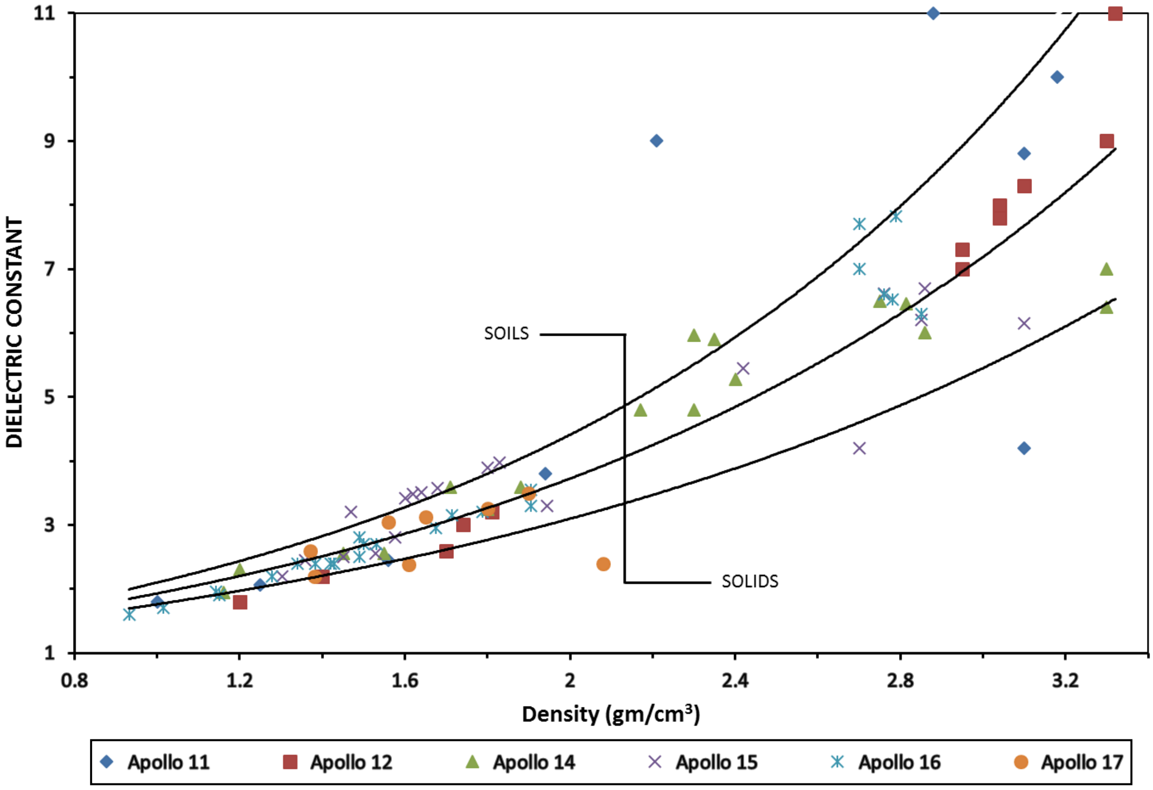

Figure 1: Dielectric constant versus density (after[16]). Figures 1-3 have been redrawn using the data reported in Table 2 of Olhoeft and Strangway [16]. In each case, the data have been fitted by standard regression analysis. The upper and lower bounds to the regressed data are also plotted at one standard deviation uncertainty.

Olhoeft [19] also observed that the dielectric constant is mainly dependent on density at higher frequencies.

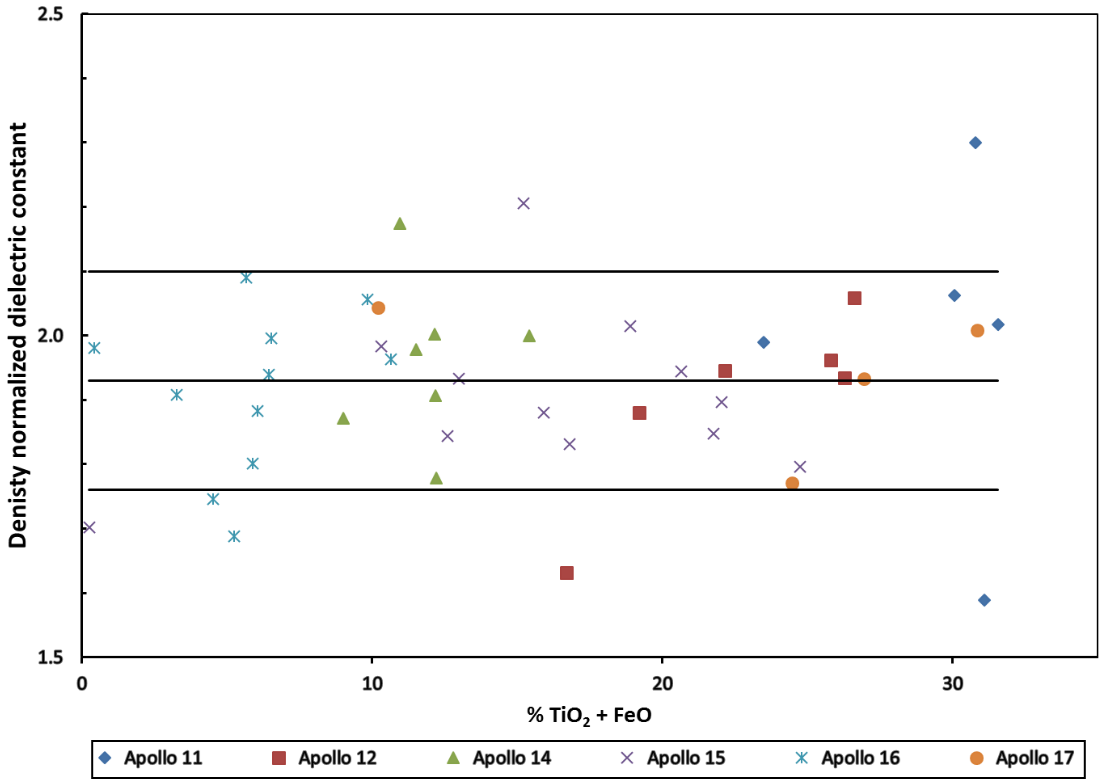

Figure 2: Density normalised dielectric constant versus rock-forming oxides (titanium and total iron oxides) (after [16])

As the lunar regolith varies considerably in composition, the literature offers relatively limited information about the variation of dielectric constant with the chemistry of lunar samples. However, Olhoeft and Strangway [16] studied the relationship between the ilmenite content (an iron and titanium oxide) and the dielectric constant. Figure 2 shows that there is no correlation between the dielectric constant and the chemical index (total Fe and Ti oxides in this case) for either soils or solids. However, this lack of correlation does not mean there is no relationship between the dielectric constant and the ilmenite content: increasing the ilmenite content increases the density. The result therefore implies indirectly that the ilmenite content has a correlation with the dielectric constant.

The factor indicating the material's ability to be polarised and heated is the loss tangent: a ratio of loss factor (dielectric loss) to the permittivity of the dielectric [20]. The loss factor measures the material's ability to transfer microwave energy into heat, and the permittivity measures its capacity to become polarised. The loss tangent is not easily measured as even very slight atmospheric moisture content in the Apollo samples would have a profound effect. Some of the early Apollo mission samples were deemed to have been contaminated and yielded very high values for loss tangent because of the moisture effects. Thus, data from the samples collected by early Apollo missions were omitted while studying the dependence of loss tangent on density and ilmenite content. Data from the uncontaminated samples of later missions (Apollo 14, 15, 16 and 17) when studied showed a clear increase in the loss tangent with both the density and ilmenite content [16, 21], as shown in Figure 3.

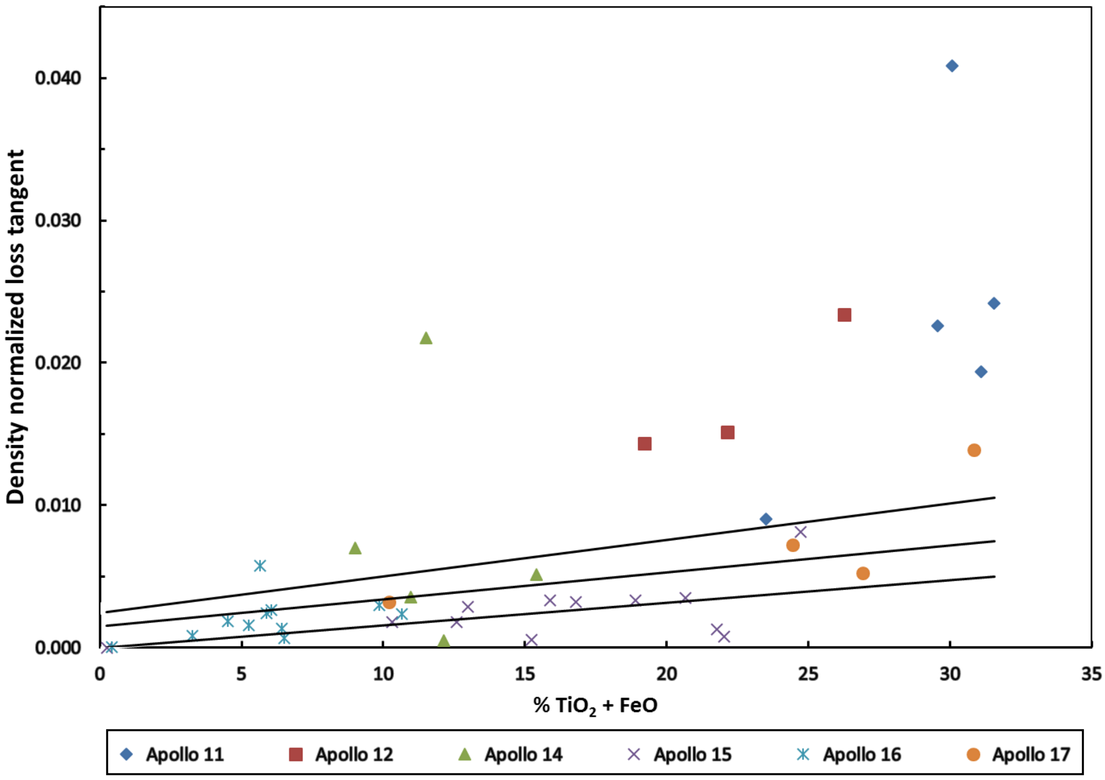

Figure 3: Density normalised loss tangent versus titanium and total iron oxides content (after [16])

Apart from density and ilmenite content, the loss tangent is thought to vary with frequencies above 0.0001 GHz. In summary, previous work has shown that there is a relationship between dielectric properties and three factors - density, frequency and ilmenite content in the frequency range of 0.0001 GHz and above [16].

3.2 Dielectric properties of lunar simulant JSC-1A

Calla and Rathore [15] reviewed the dielectric properties of the lunar stimulant JSC-1A. The measurements for dielectric constant and loss tangent were taken at four different frequencies: 1.7 GHz, 2.5 GHz, 6.6 GHz and 31.6 GHz. The rationale for choosing these frequencies was not given. However, the research was carried out for remote sensing applications, which may have dictated the choice of certain microwave frequencies. The dielectric properties were measured at temperatures ranging from -190 °C to 200 °C, mainly because this is the range of temperature experiences on the lunar surface between the lunar day and night cycles. Their work showed that the dielectric properties of JSC-1A increase with the increase in temperature at all four frequencies.

The same study found that at ambient room temperature (30 °C) both the dielectric constant and the loss factor slightly decreased from 1.7 GHz to 2.5 GHz. From 2.5 to 6.6 GHz, the dielectric constant slightly decreased but the loss factor remained approximately the same, and further from 6.6 GHz to 31.6 GHz both properties again decreased. Though the decrease is small, it is an important indicator of the nature of dielectric properties with increasing microwave frequency. The range of results obtained for the dielectric constant and loss factor at all four frequencies for JSC-1A at room temperature showed a good match with the value of some Apollo samples [15].

4. Summary and recommendations

Interest is growing in the planetary scientific community in exploring the possibility of using 3D printing techniques utilising microwave sintering of lunar regolith to construct human outposts on the Moon. Ondrej et al [22] proposed an idea for a lunar base for a crew of ten with an accompanying astronomical telescope dedicated to observations in the infrared region of the spectrum at the Moon's North Pole. They also suggested that roads for transportation connecting major units of the settlement and the landing pads could be constructed using the sintering of the lunar regolith by emitted directed microwave radiation. It is also envisaged that the inflatable habitat structure could be covered with a minimum of 2 m of sintered regolith for protection against solar flares and micrometeorites. Various researchers' interest in this field is encouraging, exploring the utilisation of microwave energy in order to develop an extra-terrestrial construction process using 3D printing techniques on the Moon.

On the basis of the review presented above, three key research areas have been identified, which should be pursued in order to improve our understanding of the potential of microwave processing of lunar soil. These are:

- To address the challenges of heating lunar soil at 2.45 GHz and test heating at other frequencies of the microwave spectrum.

  Some other form of radiant heating such as the use of a microwave absorbing material (a susceptor) [12] can potentially be combined with the microwave heating to enhance the efficiency of the heating process. Such hybrid heating techniques could also reduce thermal imbalance in the material which can cause weak mechanical properties of the finished product. While addressing the challenges at 2.45 GHz, it is equally important to examine the behaviour of lunar soil at other frequencies in the microwave range. Because the depth of penetration in a material will decrease with increasing frequency, a set of frequencies might be required for processing different depths of material, making investigating multiple frequencies an important research area.

- To understand the behaviour of dielectric properties of lunar soil with certain factors such as density and particle grain size.

  Understanding the dielectric properties of lunar soil is important to evaluate the coupling behaviour of microwave with it. Their variation with these factors will contribute in determining the absorption spectrum for lunar soil in the microwave range. The dielectric properties would help engineers in calculating the response of the lunar soil to microwave heating for construction purposes. Meantime scientists' knowledge of these properties can help design active and passive sensors for remote sensing studies of the Moon[15].

- To test the strength and endurance of the product fabricated by microwave processing of lunar soil for micrometeoroids and radiation damage.

  It is mandatory to ensure that structures built on the Moon can withstand the micrometeorite impact and radiation damage protection for long-term functional operations in the lunar environment. Understanding the mechanical properties of the fabricated structures by microwave processing of the lunar soil is therefore crucial.

The value addition to this research will be the opportunity to experiment with Apollo lunar samples and analyse the effect of microwave heating on them, bearing in mind that the Apollo landings were restricted to near the equatorial regions on the Moon, the samples collected representing only limited geographical extent. The lunar geology, however, varies at different locations, so sample return missions are required from a range of lunar locations. It would also be advisable in the future to conduct *in-situ* measurements on lunar robotic missions, to test the samples for *in-situ* resource utilization experiments involving microwave processing.

Detailed research in the key research areas mentioned above, involving microwave processing of lunar soil, will benefit both the scientific and engineering communities to better understand and explore our nearest neighbour –the Moon.

Acknowledgements:

The authors thank Ian Crawford for inviting us to make this contribution. V. Srivastava would also like to thank The Open University for providing a PhD studentship.

References

[1] R.P. Mueller, S. Howe, D. Kochmann, H. Ali, C. Andersen, H. Burgoyne, et al., Automated Additive Construction (AAC) for Earth and Space Using In-situ Resources, Proceedings of the Fifteenth Biennial ASCE Aerospace Division International Conference on Engineering, Science, Construction, and Operations in Challenging Environments (Earth & Space 2016): American Society of Civil Engineers, (2016).
[2] S. Lim, R.A. Buswell, P.J. Valentine, D. Piker, S.A. Austin, X. De Kestelier, Modelling curved-layered printing paths for fabricating large-scale construction components, Additive Manufacturing (2016).
[3] M. Anand, I.A. Crawford, M. Balat-Pichelin, S. Abanades, W. van Westrenen, G. Péraudeau, et al, A brief review of chemical and mineralogical resources on the Moon and likely initial In Situ Resource Utilization (ISRU) applications, Planetary and Space Science. 74 (2012)42-48.
[4] D.S. McKay, G.H. Heiken, A. Basu, G. Blanford, S. Simon, R. Reedy, et al., The Lunar Regolith, in: Heiken G, Vaniman D, French BM (Eds.), The Lunar Sourcebook: A User’s Guide to the Moon,CUP Archive, 1991, pp. 285-356.
[5] L.A. Taylor, T.T. Meek, Microwave sintering of lunar soil: properties, theory, and practice, Journal of Aerospace Engineering. 18 (2005) 188-196.
[6] E.C. Ethridge, W. Kaukler, Extraction of Water from Polar Lunar Permafrost with Microwaves-Dielectric Property Measurements, 47th AIAA Aerospace Sciences Meeting, Orlando, FL (2009).
[7] L.A. Taylor, H.H. Schmitt, W.D. Carrier, M. Nakagawa, The lunar dust problem: from liability to asset, 1st Space Exploration Conference: Continuing the Voyage of Discovery AIAA (2005), pp. 184.
[8] Y. Liu, L.A. Taylor, J.R. Thompson, D.W. Schnare, Jae-Sung Park, Unique properties of lunar impact glass: Nanophase metallic Fe synthesis, American Mineralogist. 92 (2007)1420-1427.
[9] L. Taylor, Status of Lunar Regolith Simulants and Demand for Apollo Lunar Samples, Simulant Working Group of the Lunar Exploration Analysis Group and Curation and Analysis Planning Team for Extraterrestrial Materials, (2010), http://www.lpi.usra.edu/leag/reports/SIM_SATReport2010.pdf
[10] L.A. Taylor, C.M. Pieters, D. Britt, Evaluations of lunar regolith simulants, Planetary and Space Science. 126 (2016) 1-7.
[11] S.M. Allan, B.J. Merritt, B.F. Griffin, P.E. Hintze, H.S. Shulman, High Temperature Microwave Dielectric Properties of JSC-1AC Lunar Simulant, (2011).
[12] S. Allan, J. Braunstein, I. Baranova, N. Vandervoort, M. Fall, H. Shulman, Computational Modeling and Experimental Microwave Processing of JSC-1A Lunar Simulant, Journal of Aerospace Engineering. 26 (2012) 143-151.
[13] C. Romulo, D. Eric, H. Jim, H. Mehdi, M. Laurent, R. Tarek, et al., Zapping Rocks, Oilfield Review, Schlumberger, (2011).

[14] Dielectric Materials, Dissemination of IT for the Promotion of Materials Science (DoITPoMS), University of Cambridge. http://www.doitpoms.ac.uk/tlplib/dielectrics/dielectric_constant.php, 2004 - 2015 (accessed 30.05.2016)

[15] O.P.N. Calla, I.S. Rathore, Study of complex dielectric properties of lunar simulants and comparison with Apollo samples at microwave frequencies, Advances in Space Research. 50 (2012)1607-1614.

[16] G. Olhoeft, D. Strangway, Dielectric properties of the first 100 meters of the Moon, Earth and Planetary Science Letters. 24 (1975) 394-404.

[17] G. Heiken, D. Vaniman, B.M. French, Lunar sourcebook: A user's guide to the Moon, CUP Archive, 1991.

[18] W.D. Carrier III , l L.G. Bromwel, R. Torrence Martin, Strength and compressibility of returned lunar soil, Lunar and Planetary Science Conference Proceedings (1972), pp. 3223.

[19] G.R. Olhoeft, Electrical properties of rocks, Physical properties of rocks and minerals. 2 (1981) 257-297.

[20] M. Oghbaei, O. Mirzaee, Microwave versus conventional sintering: a review of fundamentals, advantages and applications. Journal of Alloys and Compounds. 494 (2010) 175-189.

[21] D. Strangway, G. Olhoeft, Electrical properties of planetary surfaces, Philosophical Transactions of the Royal Society of London, Series A: Mathematical, Physical and Engineering Sciences. 285 (1977) 441-450.

[22] O. Doule, E. Detsis, A. Ebrahimi, A lunar base with astronomical observatory, Proceedings of the International Conference on Environmental Systems (2011), http://www.spacearchitect.org/pubs/AIAA-2011-5063.pdf