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

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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.

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

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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 and 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, 2.45 GHz has been chosen for most lunar soil research experiments. Lunar soil and the lunar simulant JSC-1A appear to be completely melted at between 1100 °C and 1400 °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 ($Fe^{2+}Fe_2^{3+}O_4$) 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 polarised [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 m 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 to 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 Fig. 1. It is worth noting that the samples, whether in solid