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How to cite:

Prabhu, V. L.; Lim, S.; Bowen, J.; Cowley, A.; Katrib, J.; Dodds, C. and Anand, M. (2018). Microwave Heating of Lunar Simulants JSC-1A and NU-LHT-3M: Experimental And Theoretical Analysis. In: European Lunar Symposium (ELS), 13-16 May 2018, Toulouse, France.

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# MICROWAVE HEATING OF LUNAR SIMULANTS JSC-1A AND NU-LHT-3M: EXPERIMENTAL AND THEORETICAL ANALYSIS

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**Introduction:** The future of sustained human space exploration is likely to rely on the use of local resources on the respective planetary bodies. The continuing exploration of the Moon via orbiter, lander and sample return makes it the next logical destination for setting up human outposts, laboratories, and observatories. Its proximity to Earth also makes it an ideal first destination before we explore further out in the Solar System. Lunar soil is a potential construction resource which can be melted or sintered for building structures [1].

To process the lunar soil, some form of compact, lightweight, electrically powered heat source is required and for this work microwave energy has been selected as it fulfils these criteria well. This research focusses on understanding the interaction of microwave energy with lunar soil. The heat-treated soil can then be fed into a 3D printing apparatus, enabling robotic missions to build structures on the Moon [2]. Lunar soil simulants JSC-1A (lunar mare soil simulant) and NU-LHT-3M (lunar highlands soil simulant) have been used for the experiments in this research. Lunar soil [3] is abundant in silicate minerals and glasses with traces of some other minerals. JSC-1A [4] and NU-LHT-3M [5] also has silicates, glass and other minerals. Previous research has shown that lunar soils and lunar soil simulants (LSS) melt during sustained exposure to microwave radiation at a frequency of 2.45 GHz [1, 6]. The melting of lunar soil under microwave heating is commonly attributed to the presence of nano phase Fe<sup>0</sup> (np-Fe<sup>0</sup>) [1, 7-9]. However, JSC-1A being a terrestrially manufactured lunar soil simulant, does not contain np-Fe<sup>0</sup>; however, it melts under microwave heating [6].

**Experimental microwave heating:** A preliminary set of experiments were undertaken to assess the feasibility of heating LSS via microwaves. JSC-1A and NU-LHT-3M were exposed to 2.45 GHz incident radiation at 1kW power in a domestic microwave. Experiments began at ambient atmospheric pressure and temperature. An infra-red camera was used to monitor the temperature changes inside the cavity. The camera was adjusted to point to the sample under heating through the microwave door. It is estimated that 95% of radiation will transmit through the glass of the microwave door; the metallic mesh limits the transmission to approximately 30% on an area basis. Studies revealed that melting of different masses, different densities, and different particle

sizes of JSC-1A consistently occurred within approximately 10-17 minutes. Time-temperature profiles are generated for each of the tests and melted/sintered specimens thus obtained are characterized for their physical and chemical properties.

The experimental results provide information regarding the behaviour of LSS under microwave heating in ambient conditions, which includes the effect of heat losses by conduction and convection.

## Theoretical analysis of microwave heating:

The complex permittivity of a material dictates its absorption behaviour in the presence of an incident microwave radiation at a given frequency. The permittivity of the multicomponent particulate mixture varies with mineral content, temperature, packing density, particle size, and moisture content [10]. The complex permittivity is defined as  $\epsilon^* = \epsilon' - j\epsilon''$ , where,  $\epsilon^*$  is the complex permittivity,  $\epsilon'$  is the dielectric constant, and  $\epsilon''$  is the dielectric loss [11, 12].

The complex permittivities of JSC-1A and NU-LHT-3M were assessed at microwave frequencies of 910, 1429, 1949, 2470 and 2989 MHz. Samples were heated at 20 °C and from 50 °C to 950 °C at a step temperature of 50 °C using a cavity perturbation apparatus housed adjacent to a furnace. The cavity perturbation technique allows measurement of powder samples and requires only small quantities of material [11]. The frequencies at which complex permittivity values are measured are close to the ISM (Industrial, Scientific and Medical) frequencies of 896 MHz and 2.45 GHz and are dictated by the dimensions of the cavity.

The tendency of a material to absorb microwave radiation can be estimated via three parameters: power density, power penetration depth, and temperature, all of which depend on the dielectric constant and dielectric loss. [1, 12]. Power density is the power deposited per unit volume into a material by the microwave energy [1]. Power penetration depth is defined as the depth into material at which the power has fallen to 1/e (= 0.368) of its value at the surface [12]. A theoretical model describing the time/temperature relationship under vacuum conditions has been established.

**Discussion:** The specimens from the experiments in ambient atmospheric condition have resulted in a molten core with sintered/partially melted layer surrounding it. This observation indicates the specimens have undergone uneven heating.

The experimental heating and the theoretical model are critically compared. We discuss the differences between performing these tests in the presence and absence of a gas phase, specifically the importance of heat loss from the sample via conduction and convection.

The preliminary finding of complex permittivity values of JSC-1A and NU-LHT-3M are shown in Figure 1 and Figure 2. The permittivity values increase with the increase in temperature for both the simulants. These are higher for lunar mare simulant than for lunar highland simulant at the given microwave frequencies. For JSC-1A (Figure 1), with the increase in frequency, dielectric constant increases up to a temperature of 600 °C. Beyond this temperature, there is significant deviation in the trend and the values corresponding to lower frequencies are higher than those corresponding to higher frequencies. The dielectric loss values of JSC-1A (Figure 1) are closer at all frequencies in the lower temperature range. Beyond 400 °C, the values continue to increase with temperature at all frequencies; however, the values are lower for higher frequencies. A sudden increase in the values of dielectric loss can be observed at all the frequencies beyond 800 °C. Ray et al. [13] have reported an endothermic peak corresponding to glass transition temperature at about 670 °C and an exothermic peak corresponding to crystallization temperature at about 880 °C for JSC-1A. These changes in the permittivity values may be attributed to the changes due to glass transition and crystallization temperatures in JSC-1A. Figure 2 shows that in NU-LHT-3M, with the increase in frequencies, the dielectric constant increases with temperature. The plot at 910 MHz does show abruptly higher values beyond 700 °C. The dielectric loss of NU-LHT-3M (Figure 2) shows the increasing value with temperature, while it shows the decreasing value with increase in frequencies. For now, there is no thermal profile obtained for NU-LHT-3M to compare the phase transformations associated with changing temperature regime. However, these values give valuable information regarding the simulant's behaviour to the microwave frequencies. Further tests will be carried out to confirm the results from this preliminary finding.

Such comparison of the microwave heating behaviour of different lunar simulants clearly suggests the challenges posed by microwave absorption characteristics of lunar soil from different locations on the surface of Moon.

As the mineral content plays a key role in determining the microwave absorption properties of a heterogenous material, future work will assess the

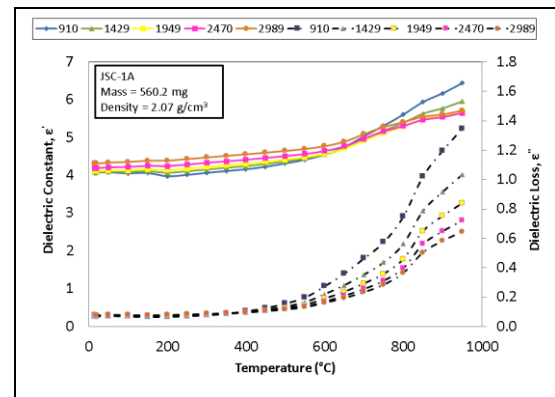


Figure 1: Dielectric constant and dielectric loss of JSC-1A.

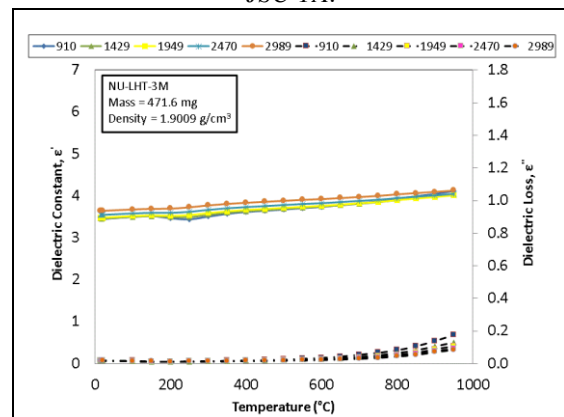


Figure 2: Dielectric constant and dielectric loss of NU-LHT-3M.

permittivity of the major mineral constituents of JSC-1A. It will highlight the major microwave absorbing phases in JSC-1A, providing information regarding why JSC-1A melts in the absence of  $\text{np-Fe}^0$ .

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