Compaction Dependent Thermal Properties of Icy Lunar Regolith in Vacuum Travis Wavrunek[1], Ben Flowers[2], Anurag Rajan[3], and Paul van Susante[4] [1,2,3]Dept. of Mechanical Engineering-Engineering Mechanics, Michigan Technological University 1400 Townsend Drive, Houghton, MI 49931 (contact: pjvansus@mtu.edu).

Introduction: Ice bearing lunar regolith is of primary relevance to future lunar infrastructure. Available water on the lunar surface would be a supply of fuel and life support for long-term human missions. Evidence of water on the lunar surface has been detected by multiple remote sensing instruments, but in-situ measurements have yet to be collected in Lunar permanently shaded regions [1][2]. Due to the sensitivity limitations and nature of the remote sensing tools, the form and volatile content of the icy regolith is unknown. Models and testing must provide missing data to inform future missions and better prepare us to understand results when data does exist.

The formation of ice on the lunar surface is still uncertain, with various possibilities being proposed.[3] Of the proposed homogeneous formations, cemented icy regolith and discrete icy regolith present the two extremes of inter-particle contact area and thermal conductivity. They are also the two forms of icy regolith most tested in the literature, though not necessarily realistic of what we expect to find on the lunar surface in permanently shaded regions. While the compaction range for cemented icy regolith is small, discrete icy regolith can vary similarly to dry regolith. Dry regolith has been shown to have compaction dependent thermal properties due to contact resistance changing with contact pressure[4], though research is limited on compaction dependent thermal properties of icy regolith.

Background: The LuSTR grant, awarded to the Planetary Surface Technology Development Lab (PSTDL) in 2020, facilitated the development of the Percussive Hot Cone Penetrometer, (PHCP). The PHCP is coupled with a ground penetrating radar to be a combined geotechnical measurement tool, able to measure the spatial distribution of lunar volatiles Figure 1.

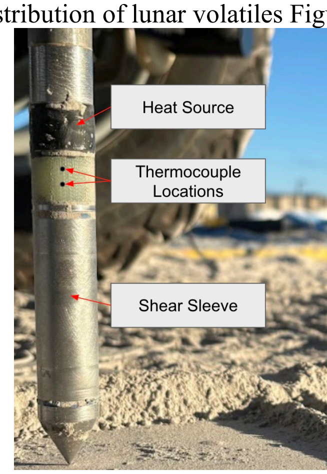

Figure 1. Percussive Hot Cone Penetrometer and Key Instruments During Field Testing

The volatile detection process performed by the PHCP is similar to calorimetry. Like the Chandrayaan-3 Chandra's Surface Thermophysical Experiment (ChaSTE) Lander tool[5], the PHCP is penetrated into the ground. Unlike ChaSTE which was used at a depth of 10 cm, the PHCP is designed to reach at a greater depth of one meter.

During thermal profile collection, the PHCP is heated at a constant power rate and temperature measurements are taken at locations on the cone at 5mm and 10mm distances from the heat source. As the regolith is heated, volatiles in the regolith undergo sublimation. The latent heat of phase change and change in thermal conductivity impact the thermal curves collected by the PHCP and can be used to interpret volatile content.

Methods: A line heat source test setup was developed with considerations for testing icy regolith in a vacuum environment (Figure 2). A nichrome wire was suspended in a polycarbonate box with ten 30-gauge T-type thermocouples. Thermocouples were held in place by G10 standoffs at 3mm and 6mm distances from the nichrome wire. A linear actuator was used to evenly deposit dry or granular icy regolith in the test volume, reducing particle separation and trapped air for vacuum testing. A liquid nitrogen feedthrough on the back of the tray was used in vacuum testing to keep the regolith icy mixture below sublimation temperatures as the chamber was brought to vacuum.

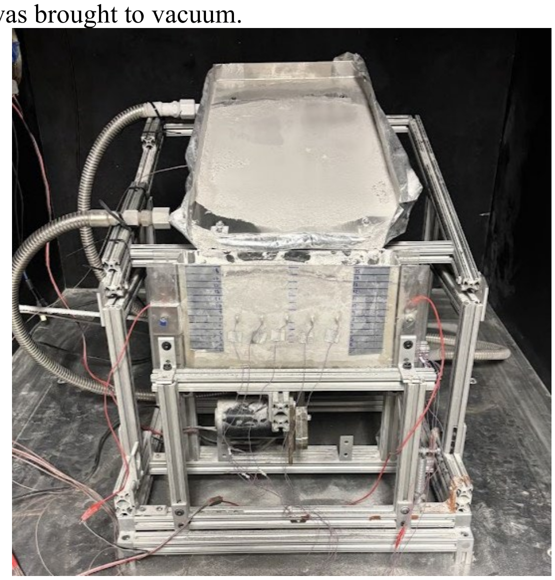

Figure 2: Line Source Test Setup in PSTDL's DTVAC

Atmospheric pressure testing was performed on three compaction levels of dry, cemented, and discrete icy regolith. Curve fitting of a radial heat flow equation was used to back out conductivity from the transient curves. Figure 3 presents an example of thermal profiles taken from testing and resulting calculations.

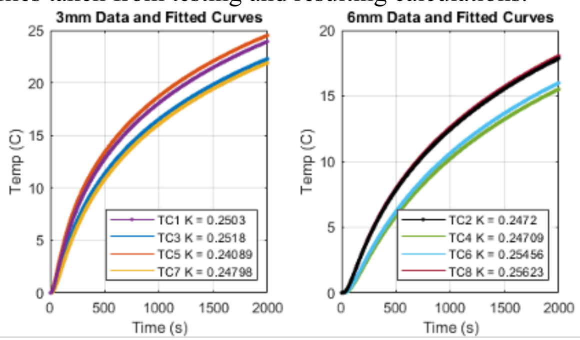

Figure 3. Thermal Curves Taken from Line Source Testing with Curve Fitting to Determine Thermal Conductivity

A series of vacuum tests following the same test campaign as atmospheric pressure testing is ongoing. In this thermal vacuum testing, icy regolith is precooled to <-80 °C before being transferred to the vacuum chamber where it was loaded onto the tray precooled to <-50°C. Once loaded, the chamber was pumped down to pressures (<1mtorr). Vacuum test results of dry regolith have followed compaction trends seen in dry testing. While testing is still ongoing, initial analysis has confirmed that granular icy regolith has conductivity values similar to that of dry regolith, likely due to the increased particle contact resistance.

Results: Though testing is ongoing, results of dry regolith conductivity trends are consistent with published trends. Figure 4 shows a distribution of calculated thermal conductivities from dry atmospheric tests. Conductivity is seen to vary by as much as 50%. Vacuum tests of JSC-1A, have shown conductivity similarly dramatic changes in thermal property values with compression[4].

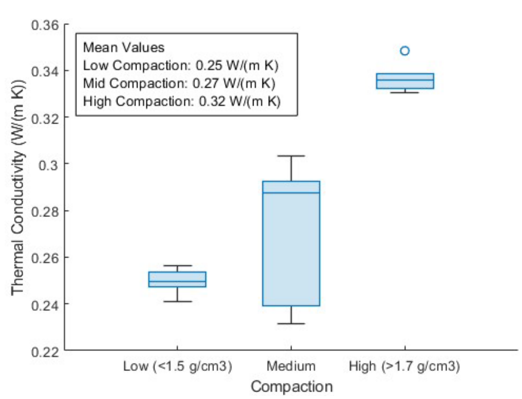

Figure 4. Box Plots of Calculated Thermal Conductivity from Six Tests at Atmospheric Pressure

Due to ice temperatures and sublimation, results from initial icy tests in vacuum have been delayed. This has mostly been due to ice sublimation at low vacuum pressures. Sublimation within the regolith causes a pressure build up within the regolith and jetting during dumping due to trapped air/water vapor. Sublimation has also limited chamber pressures and caused pressure spikes.

In addition, icy regolith has been seen to clump together and stick to the chilled aluminum surface during dumping. This could be caused by icy regolith sintering, creating a hybrid between discrete and cemented. Both these challenges can likely be circumvented by further precooling the regolith before exposure to vacuum pressures.

Conclusions and Future work: Thermal property data extracted from these tests has further illustrated the importance of ice phase and geotechnical properties of icy regolith. In a vacuum environment, particle contact is a crucial variable in determining bulk thermal properties. The variations due to ice bridging and compaction pressure demonstrate its sensitivity. Finalizing this dataset will generate bounds on thermal property values that can be expected through testing.

In addition to collecting this experimental dataset, a thermal network model is in development to predict conductivity values. This model takes mineral properties, ice formation, and compaction data as inputs to provide bulk thermal conductivity values, analogous of regolith or ice content.

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References:

[1] A. Colaprete *et al.* (2010) *Science*, vol. 330, no. 6003, pp. 463–468 [2] S. Li *et al.* (2018) *Proc. Natl. Acad. Sci.*, vol. 115, no. 36, pp. 8907–8912 [3] D. K. M. Johnson, C. B. Dreyer, K. M. Cannon, and G. Sowers (2024) *Icarus*, vol. 410, p. 115885 [4] N. Sakatani, K. Ogawa, M. Arakawa, and S. Tanaka (2018) [5] D. P. K *et al. (2025) Earth Environ.*, vol. 6, no. 1, pp. 1–11