Cryogenic Vacuum Testing of a Heated Cone Pentrometer for Thermal Detection and Quantification of Water in Icy Lunar Regolith Simulant.

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Introduction: Recent observations of the lunar surface have established the widespread presence of water ice within the top 1 mm of lunar regolith [1]. Surface water concentration estimations range from less than 30 ppm to 560 ppm in the lunar midlatitudes and poles, respectively [2] [3], but water concentrations below the first 1 mm of the lunar surface are largely unknown. However, analysis of the LCROSS impact site has suggested that permanently shaded regions of the moon may contain a water concentration up to 7.9% by mass within the first 1 m of regolith [4]. In order to detect and quantify water within the first 1 m of regolith, the Planetary Surface Technology Development Lab (PSTDL) at Michigan Technological University developed the volatile thermal profiling project. This project examines the thermal curves from a percussive hot cone penetrometer (PHCP) that has been submerged and heated within icy regolith in cryogenic vacuum conditions. The project aims to estimate the ice content of icy regolith within ±1 wt%.

Methods: The "hot" component of the PHCP is the nichrome heater that is epoxied in place around the cone (Fig. 1). The temperature of the cone is measured by six thermocouples, two of which are T-type and four that are K-type. The two T-type thermocouples are placed 5 mm and 10 mm below the heater and are separated from the heater with G-10 (Fig. 1). Three of the four K-type thermocouples are fixed to the exterior of the cone using copper tape and measure the heater, cone tip exterior, and cone top temperatures, respectively. The last K-type thermocouple is placed inside the cone and measures the temperature of cone tip interior (Fig. 1).

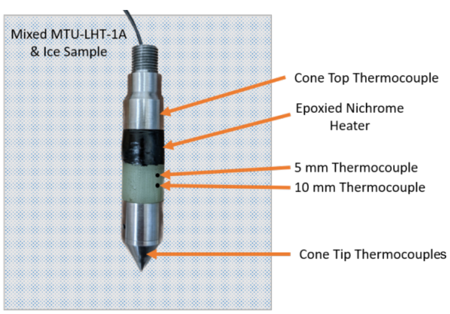

Fig. 1. MTU PHCP with annotated thermocouple and heater locations

All thermal volatile profiling tests were conducted in compacted icy MTU-LHT-1A lunar regolith simulant. The following concentrations of ice (weight percent) were tested throughout the project: 1.5, 2, 2.5, 5, 7, and 10 percent. Each weight percentage was tested three times for a total of 18 tests. All test samples were prepared in a freezer container held at -4.4ºC and then further cooled during the pre-test procedure to -110°C. The cone was tested in two types of icy simulant samples: discrete ice samples and cemented ice samples, though discrete ice samples were the focus of testing.

Discrete Ice Sample Preparation: Discrete ice samples consisted of regolith simulant mixed with discrete, shaved ice particles with particle diameters ranging from less than 425 µm to 600 µm. Each sample was prepared in the freezer container in 2 kg layers. For each layer, 2 kg of pre-cooled simulant was measured out using a 2g-accuracy scale while the ice content was measured using a 0.1g-accuracy scale. The simulant and ice shavings were mixed together using a KitchenAid mixer. Once each layer was homogenously mixed, it was transferred from the mixer to a 8.75in x 7.625in x 8.25in aluminum box and compacted by hand with a square wooden dowel. This mixing and compacting process was repeated until the compacted sample reached an approximate height of 8in within the box, resulting in bulk densities ranging from 0.94g/cc to 1.85g/cc depending on the weight percent ice content of the sample. The final volume and mass of the each sample was recorded for bulk density calculations. The finished sample was transferred to a -80ºC freezer where it would remain for a minimum of 12 hours prior to testing. The cone was percussed into each discrete ice sample while it was in the -80 ºC freezer.

Cemented Ice Sample Preparation: Each cemented ice sample was prepared in the freezer container by placing 2 kg of pre-cooled simulant in the KitchenAid stand mixer, turning the mixer on, and spraying water into the mixer via portable pressure sprayer. The mass of the water sprayed into the sample was measured by placing the pressure sprayer on a 2g-accuracy scale, zeroing the scale with the full weight of the portable sprayer, and observing the change in mass as the water was sprayed into the sample. Once each layer was homogenously mixed, it was transferred from the mixer to a 8.75in x 7.625in x 8.25in aluminum box and compacted by hand with a square wooden dowel. After 2 layers of compaction, the cone was placed vertically in the center of the box and held in place while the subsequent layers of wet regolith were compacted around it. This mixing and compacting process was repeated until the compacted sample reached an approximate height of 8in within the box. The final volume and mass of the each sample was recorded for bulk density calculations. The finished sample was transferred to a -80ºC freezer where it would remain for a minimum of 12 hours prior to testing.

Thermal Profiling Vacuum Test Procedure: Before testing, all samples were removed from the freezer and placed in a liquid Nitrogen (LN_2) bath until the sample reached a temperature of -110ºC. The temperature of the sample was monitored using the two T-type thermocouples. The sample was then placed into an LN_2-cooled shroud within an 18in x 18in x 18in acrylic vacuum chamber. Once the chamber reached a pressure below 50 mTorr, a constant power supply of 5 Watts was supplied to the nichrome heater. Power was supplied to the heater for 1.5 hours or until the heater surface reached 100ºC. The following data was logged and recorded with an NI DAQ chassis until 30 minutes after the heater was turned off: temperature data from all six thermocouples, vacuum chamber pressure data from a convection vacuum gauge, and the power being supplied to the heater by the power supply.

Results: Examples of the thermal profiles of discrete and cemented ice samples can be found in Fig.2 and Fig. 3, respectively. Discrete ice samples were more insulative and tended to reach higher temperatures than cemented ice samples.

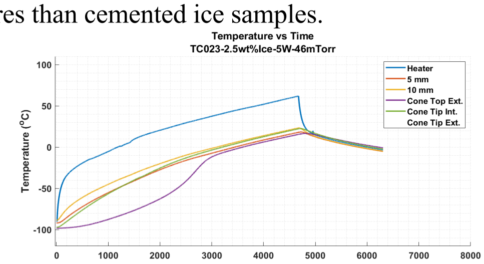

Fig. 2. Thermal curves of a 2.5 weight percent discrete ice test

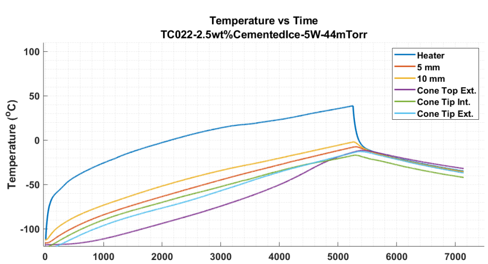

Fig. 3. Thermal curves of a 2.5 weight percent cemented ice test

Discussion: There were noticeable differences between discrete and cemented ice samples during testing. When tested with constant power supplies greater than 5 Watts, cemented ice samples exhibited more obvious thermal phase change behavior than discrete ice samples did; cemented ice samples demonstrated thermal inflections at the expected melt temperatures while discrete ice tests did not. Although the phase change behavior in discrete ice testing was not obvious, initial analysis indicates that other indicator values such as maximum test temperature and rate of temperature change can be used to predict the ice content of discrete samples. Further analysis is being conducted to empirically correlate various thermal indicator values with ice content for discrete ice testing.

Conclusions: A percussive hot cone pentrometer has been successfully developed for lunar in-situ detection and quantification of water ice. Initial results show that discrete icy regolith does not demonstrate obvious thermal phase change when heated. However, there are many other indicator values, such a maximum test temperature and maximum rate of temperature change, that can be used to predict the ice content of discrete ice regolith samples. Additional analysis of the thermal data is being conducted in an effort to create an empirical correlation between thermal properties and ice content of regolith.

Acknowledgements
This research was supported by NASA's LuSTR 2020 research grant funding 80NSSC21K0769

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