Sintered Icy Regolith Simulants and their Implications for Lunar Subsurface Modification on Geologic Time-scales D. K.M. Johnson[1] and C. B. Dreyer[2], Ross M. Lieblappen[3], Emily Asenath-Smith[4], and Kevin M. Cannon[5]; [1]1500 Illinois St. Golden, CO 80401; dkjohnson@mines.edu, [2]1500 Illinois St. Golden, CO 80401; cbdreyer@mines.edu, [3]575 Stone Cutters Way, Montpelier, VT 05602; Ross.Lieblappen@vermontstate.edu, [4]72 Lyme Rd, Hanover, NH 03755; Emily.Asenath-Smith@usace.army.mil, [5]1500 Illinois St. Golden, CO 80401, cannon@mines.edu.

Introduction: Sintering occurs in materials near their melting or vaporization points, which is typically considered in the context of high temperature ceramics [1]. Because water ice is commonly found in nature near its vaporization, melting, and sublimation curves, it can be treated similarly to metals or ceramics in terms of the sintering process [1, 2]. Accordingly, extensive terrestrial work has been performed on the sintering of ice, particularly of snow particles over time [2, 3, 4, 5, 6]. Ice sintering work has already been extrapolated into the field of planetary science to predict sintering time-scales for several locations in the solar system, such as Europa, Enceladus, and comets for the purpose of understanding surface and subsurface ice modification on these bodies [7], and was proposed as a modification process in lunar PSRs [8].

Due to the granular nature of regolith and the propensity of water ice to sinter, it is useful to consider the complex interactions and modifications between regolith and ice in the context of sintering. This has been demonstrated with the novel icy simulant production method PSS, which sinters ice granules and regolith together with two primary accelerators: elevated temperature (-10˚C to -25˚C), and applied pressure [8]. With this process, contiguous icy simulants are sintered in timescales on the order of 10 minutes. Only one component of the mixture, ice, is capable of contributing mass transport to the sintering process at these temperatures. Whether ice granules form bonds to regolith over millions or billions of years, or PSS samples are produced in a laboratory in 10 minutes, the process is fundamentally solid state sintering in both cases, but the latter case has drastically accelerated mass transport through the application of pressure.

Furthermore, sintering processes driven primarily by sublimation/deposition have a tendency to coarsen without densification [1]. In this case, total surface area decreases, but pore spaces grow in size, with total porosity for the material remaining unchanged. The reduced surface energy is consumed in coarsening so that densification cannot occur. Mass transport from one surface to another (surface diffusion, sublimation-deposition, volume diffusion) provides the neck material from elsewhere on a particle's surface, so the centers of the grains that are sintering together do not move (i.e. the bulk material does not change in density). Bulk diffusion mass transport includes grain boundary diffusion, plastic flow, creep, viscous flow, which all result in densification, as the centers of particles get closer together.

Experimental Methodology: Icy lunar regolith samples were produced according to the method outlined in [8], known as the pressure sintered method, in which a piston is used to apply pressure to a dry mixture of ice grains and regolith simulant, inducing plastic flow in the ice grains, sintering the mixture together. One of these samples of PSS can be seen in Figure 1

Figure 1: PSS sample shown on the lid of its sample jar, diameter 2 inches.

An additional, novel method was used to sinter ice and regolith together, in which samples were pressed at a relatively low pressure (.11 MPa) and duration (30 seconds) compared to those required to induce sintering through pressure alone (3600 seconds, .47 MPa). In doing so, the mixtures were consolidated from their very low bulk density upon being poured into the sample cup. These samples were then placed inside a cooler, which in turn was place in a Free Piston Stirling Cryocooler set to -2.5˚C. The temperature probe provides confidence that the ice never melted, so any modification observed must have been due to sintering. These samples were then allowed to thermally sinter for several days before being placed in a -40˚C freezer to prevent further sintering. Samples produced in this manner are called Thermally Sintered icy lunar regolith Simulant, or TSS.

A temperature probe was placed with each of these samples, which recorded the minimum and maximum temperatures the samples experienced. These thermally sintered samples showed a minimum temperature of -2.51˚C and maximum temperature of -1.96˚C for the entire time they were sintered.

Samples were scanned using a Bruker Skyscan 1173 Micro-CT scanner. We used X-ray voltage of 130 kV, and a current of 61 µA. A .25 mm brass filter was used, and an exposure time of 345 ms, and rotational step of .3 degrees, with 180 degrees total rotation on each sample. The voxel size was 29.823 µm. The micro CT scanner was kept in a freezer set to -3˚C to prevent melting in the samples.

Results: Figure 2 shows micro-CT scans of three different samples. In these images, dark gray or black indicates low density material (void space), white indicates high density material (regolith simulant), and light gray indicates intermediate density (ice). Each of the samples shown in Figure 2 are 5% ice by weight, but have each been prepared with a different method.

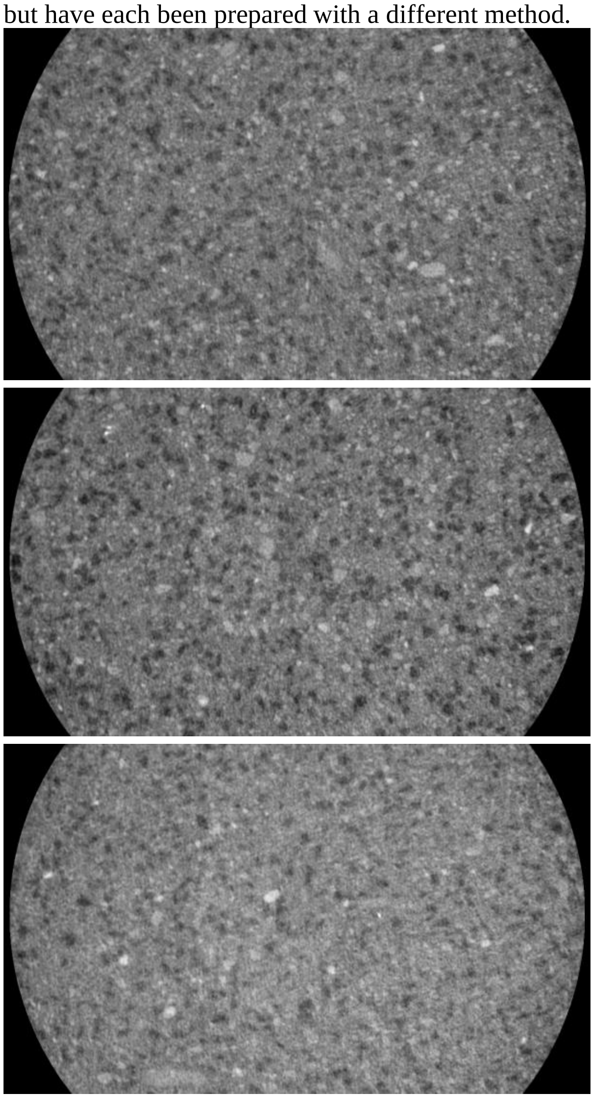

Figure 2: From top to bottom: thermally sintered, non-sintered, pressure-sintered, all 5% ice by weight.

From top to bottom, Figure 2 shows scans of thermally sintered, non-sintered, and pressure sintered samples. These preliminary images have only been lightly processed, and additional work is underway to segment the images to more easily discern the difference between the three phases present (ice, regolith, and air). One challenge is the problem of quartering, in which a voxel partially filled with a high density material may look very similar to a lower density material, making segmentation of the phases challenging.

Although more advanced image processing techniques are underway, clear differences can be observed between the central non-sintered sample, which contains much more porosity (dark). The top and bottom images in Figure 2 show less porosity, indicating movement of regolith grains and ice, tending toward increased homogeneity as would be expected through a sintering process. More sophisticated methods for segmentation and 3-dimensional rendering are underway with the goal of improving the discernability of the three phases of interest, and providing quantifiable metrics for each sample type.

Conclusions: We have shown clear differencs in ice microstructure between sintered and insintered icy lunar regolith simulant, which corroborates the differences in bulk density and penetration resistance that hav already been observed [8].

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