Measurement of Icy Regolith Permeability and Tortuosity Estimations

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Motivations

Various collection and desiccations processes have been proposed as possible technologies to utilize lunar ice as a water source. However, many physical aspects of the water ice are unknown. Proposed technologies must make assumptions related to ice morphology and content causing uncertainties in transport of sublimated vapor.

Mass transport in porous media is dictated by multiple flow regimes, determined by the Knudsen number – a ratio between mean free path of a gas particle and the characteristic void space diameter. Scans of lunar simulants have shown pore spaces in icy regolith may vary in orders of magnitude, particularly for simulants with ice [1], [2]. During desiccation and in vacuum testing, pressures cause the mass transfer to move outside of a purely Knudsen diffusion and into a transition regime.

Permeability measurements of different icy regolith samples may present a low cost and low complexity method to finding parameters relevant to transition regime flow, as well as providing material properties for continuum region flow in various icy regolith morphologies.

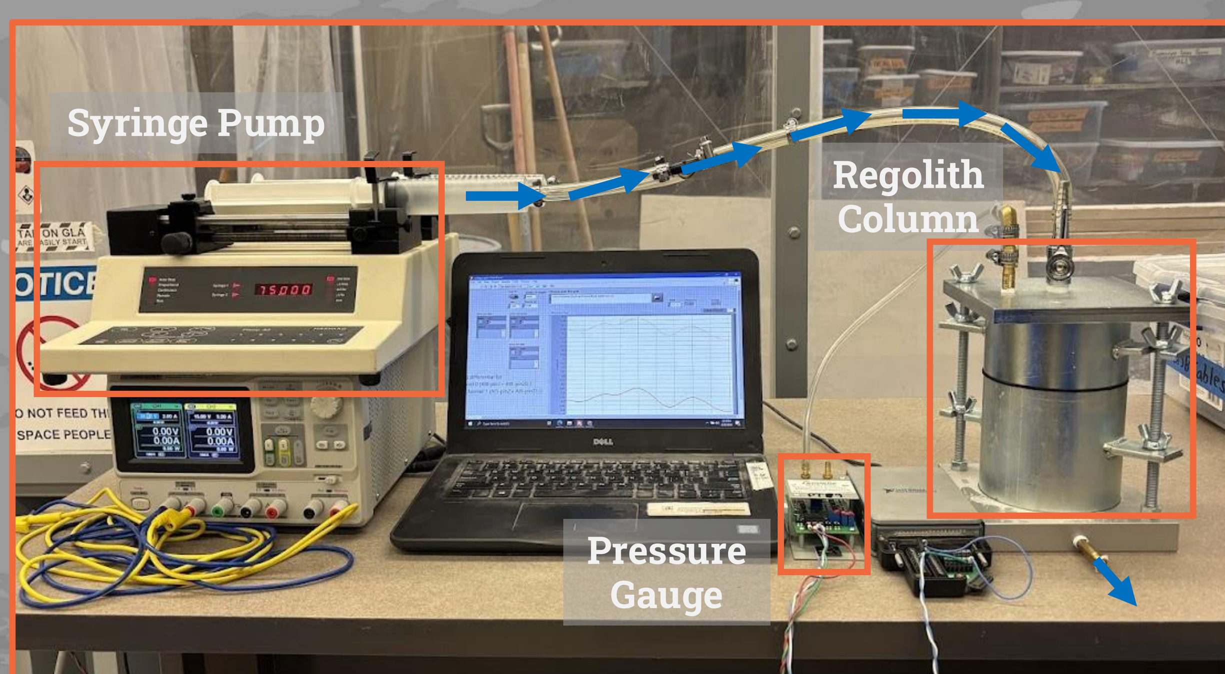

Figure 1: Ambient Temperature Gas Permeability Test Setup

Methods

MTU-LHT-1A, a highland simulant developed at Michigan Tech, was used as the test material. The simulant was compacted to three levels in a permeameter through manual vibratory compaction and hand tamping. Permeability measurements were taken following a version of ASTM D5856-95(2002)e1 modified to use ambient air as a working fluid [3]. A constant flow rate was controlled through a use of a programed syringe pump at different flow velocities and differential pressure over the regolith column were measured, shown in Fig 3.

Icy regolith production and tests were preformed in an environment chilled below -12°C. Ice was produced using an ice shaver and sieved to <600 μm before being mixed with chilled regolith.

Figure 2: Icy Regolith Production

Equations

$$Q = \frac{K}{\mu}\frac{A}{L}\Delta P$$

Darcys Law (Eq 1)

$$K = \frac{1}{\tau^2 k_0}\frac{\theta^3}{S_0^2(1-\theta)^2}$$

Carman–Kozeny (Eq 2)

- K = Permeability (m²)
- Q = Flow Rate (m³/s)
- μ = Dynamic Viscosity (Pa s)
- A = Surface Area (m²)
- L = Column Height (m)
- θ = Porosity
- τ = Tortuosity
- k_0 = Shape Factor
- S_0 = Particle Specific Surface Area (m^{-1})

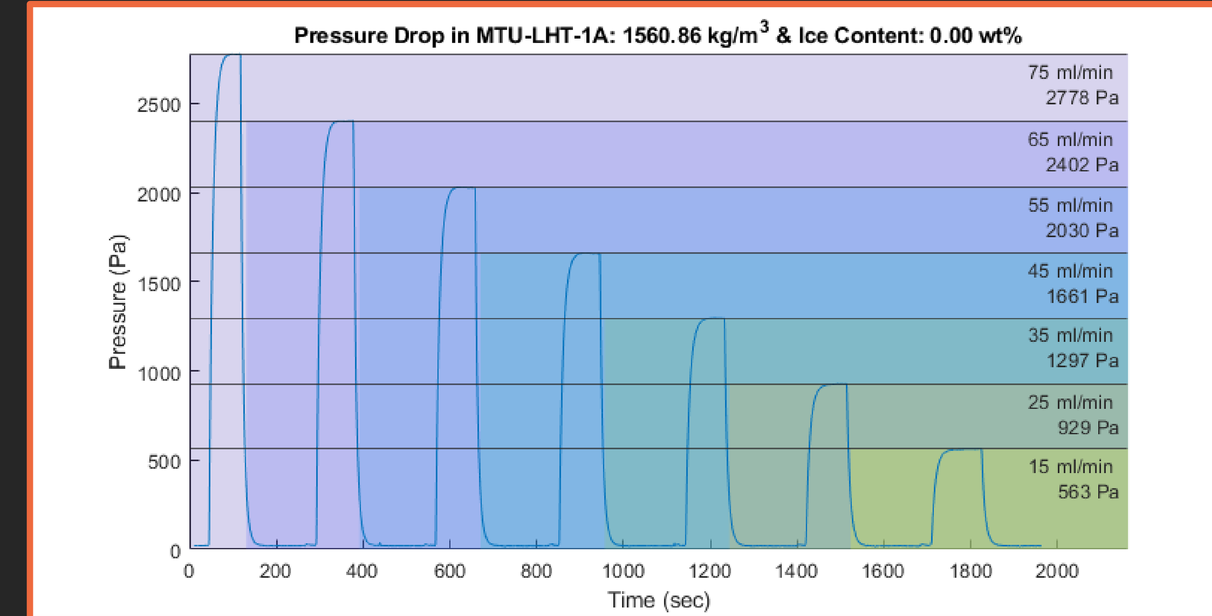

Figure 3: Example Test Data

Results & Analysis

Pressure drops through the regolith column were measured at seven flow rates for 12 samples at ice contents of 1.5 wt%, 3wt%, and 6wt%. The steady state pressures rates were recorded and, using Darcy's Law (Eq. 1,) permeability was determined.

The Carmen-Kozeny equation with a known specific surface area (k_0) of MTU-LHT-1A was used to curve fit the dry data. When fitted to the dry data, the Carmen-Kozeny equation diverged from the icy data at lower porosities. This divergence is likely due to the change in particle size distribution impacting either the tortuosity or effective specific surface area.

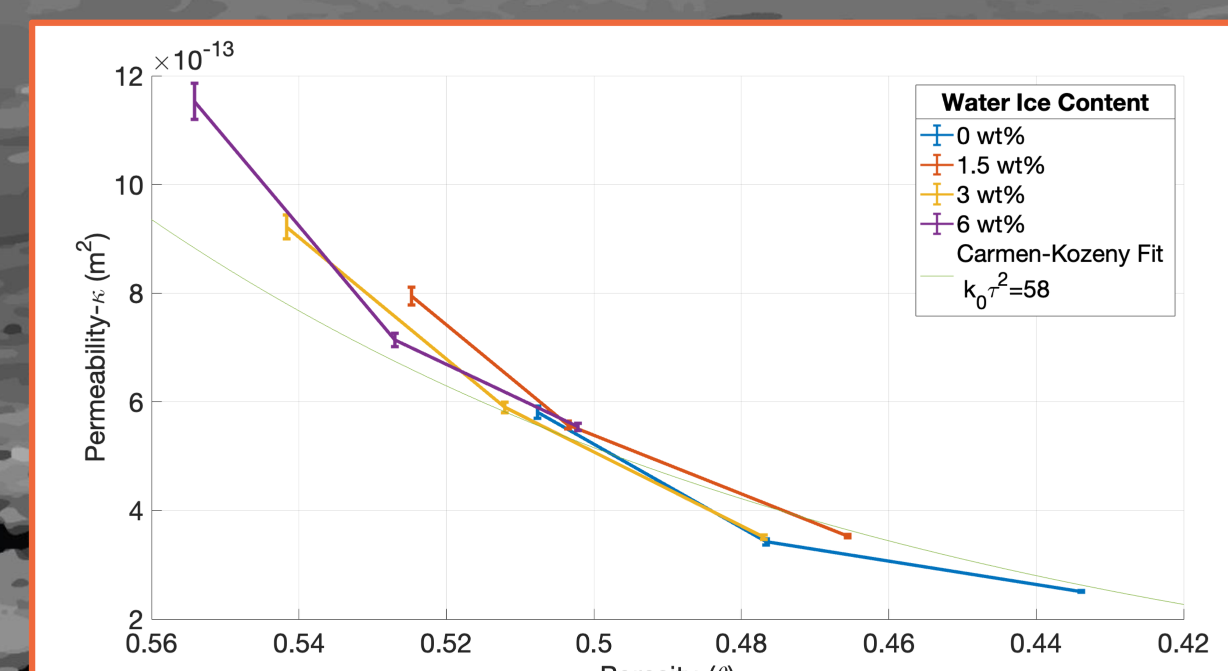

Figure 4: Permeability Variation at Various Ice Contents and Compaction

Conclusions & Future Work

Discrete sieved icy regolith has a similar permeability to that of dry regolith. However, variations are notable and may be due a shift in particle size distribution when ice is added.

Further testing should also be preformed on other simulants morphologies, such as cemented and sintered simulants where pores are be blocked by ice bridging.

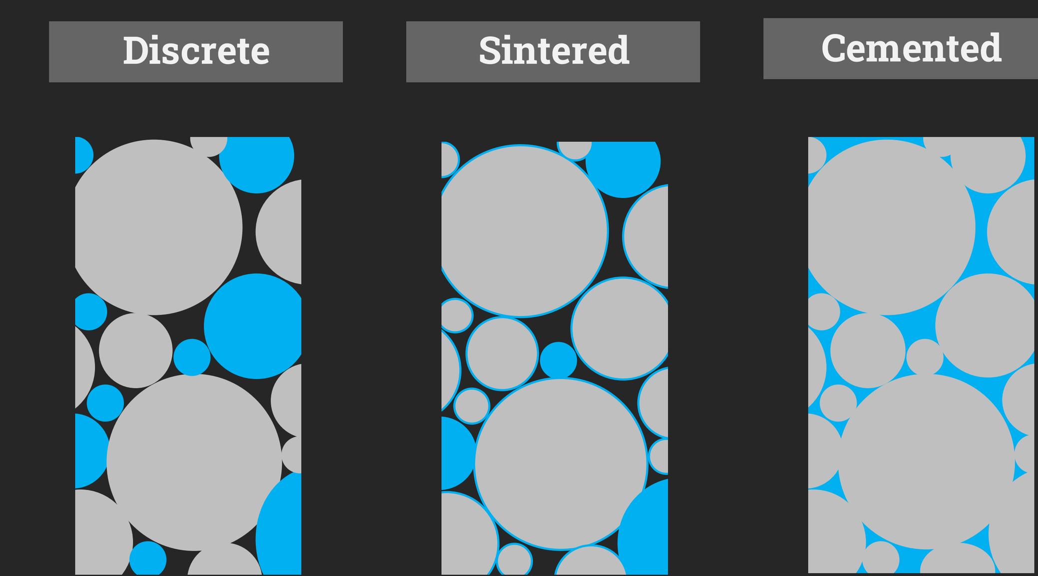

Table 1: Regolith Permeabilities

JSC-1A [3]	0.981 - 6.210 E-12 (m²)
MTU-LHT-1A (Dry)	0.251 - 0.580 E-12 (m²)
MTU-LHT-1A (1.5 wt%)	0.352 – 0.795 E-12 (m²)
MTU-LHT-1A (3 wt%)	0.351-0.922 E-12 (m²)
MTU-LHT-1A (6 wt%))	0.554-1.153 E-12 (m²)
BP-1 [4]	0.04-0.19 E-12 (m²)

References

[1]D. K. M. Johnson *et al.*, "Microstructure of Icy Lunar Regolith Simulants," *J. Phys. Chem. C*, vol. 129, no. 4, pp. 2152–2164, Jan. 2025 [2] D. Ricardo, S. Wong, J. Hodgkinson, M. A. Rhamdhani, and G. Brooks, "Characterizing the microstructure of icy lunar regolith simulants using microcomputed tomography," *Acta Astronaut.*, vol. 238, pp. 432–453, Jan. 2026 [3] C. Q. LaMarche, J. S. Curtis, and P. T. Metzger, "Permeability of JSC-1A: A lunar soil simulant," *Icarus*, vol. 212, no. 1, pp. 383–389, Mar. 2011 [4] D.P. Batcheldor *et al., "Gas permeability of BP-1 lunar regolith simulant at sub-atmospheric pressures," Icarus,* vol. 441 Jun. 2025