UNVEILING THE MECHANICS OF FROZEN FRONTIERS WITH A ROBOTIC RHEOMETER. J. G. Ruck¹, J. Bush², J. D. Caporale³, E. Fulcher³, N. A. Jones⁴, S. Thompson⁴, B. McKeelby⁵, K. R. Fisher⁶, M. Nachon⁶, D. E. Koditschek¹, R. C. Ewing⁵, F. Rivera-Hernandez⁵, T. Shipley⁷, C. G. Wilson⁸, F. Qian¹, and D. J. Jerolmack¹.

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Introduction: As NASA prepares for Artemis, there is a burgeoning need for characterizing the mechanical properties of lunar regolith. Goals for efficient human and robot interactions with the surface are complicated by uncertainty surrounding the distribution of ice, and in particular ice’s influence on the strength of regolith-ice mixtures. What is necessary is a technique for rapid and reliable in-situ measurements of the mechanical properties of these mixtures.

We propose such a method in the form of a novel, robotic leg rheometer, capable of examining the strength of these mixtures through a force-based sensing technique [1]. Laboratory validation of field measurements demonstrate that our robotic leg is sensitive to variations in ice texture and content. This is useful for predicting physically distinct mechanical behaviors in regolith in unknown and hazardous environments. Our robotic leg can also be attached to a proprioceptive legged robot for automated mapping of the strength of regolith-ice mixtures across landscapes. Using this technique in tandem with thermal data and other measurements made possible by our team, we position ourselves to better understand how surficial ice influences regolith strength and offer advantages of using legged robots to sense and improve mobility in complex environments.

Fieldwork at Mt. Hood, OR: We deployed our robotic leg to study the varied mechanical behaviors of regolith-ice mixtures in Mt. Hood, OR. The materials on this site are situated on steep slopes along a gradient defined by the transition from clean ice to sediment-rich ice to ice-free slopes of unconsolidated volcanic sediments and glacial till [2]. In this way, Mt. Hood provides a robust analogue to icy lunar landscapes ideal for our mission of exploring the relationship between primary environmental gradients in ice and regolith strength.

Our team, LASSIE (Legged Autonomous Surface Science In Analogue Environments), recorded coordinated measurements along multiple transects of different ice content and texture to characterize the strength of surface regolith. We use Laser Induced Breakdown Spectroscopy (LIBS) and X-ray Fluorescence (XRF) for determining compositional characterizations, microscopic imaging as well as LiDAR for characterizing grain size and morphology, and a radiometric thermal camera for determining spatial ice content distributions. For measuring geotechnical properties, we use our robotic rheometer (Fig. 1).

Robotic Leg as a Regolith Rheometer: Our team utilizes a modified form of a single-leg direct-drive hopper [3, 4] in our study of the mechanics of regolith-ice mixtures.

![Figure 1: Robotic rheometer actuated with two direct-drive motors obtains mechanically-sensitive and time-efficient strength measurements of granular materials.](image)

This robotic rheometer is comprised of two high-torque brushless DC motors, with position control enabled by a v3.6 ODrive motor controller. Through penetration tests that provide insight into regolith-ice mixture deformation behaviors, we obtain an accurate and continuous measurement of the external forces in the vertical plane using the motor’s current draw and leg kinematics [5]. The intrusion direction is constrained along the vertical axis, yet a range of intrusion parameters is permissible; we can change intrusion velocity, intrusion depth, and the geometry of the intruder. These sensitive force measurements and adaptable intrusion protocols allow us to employ the robotic leg as an in-situ field rheometer effective for answering how ice content changes regolith force responses to penetration.

Mechanical Properties of Ice-Regolith Mixtures From Field & Laboratory Results: Our fieldwork along changing gradients in ice content and texture in Mt. Hood reveal varied and distinct mechanical responses to penetration tests. We organized these responses in categories based on the composition of the substrate (i.e. loose particle regolith, unyielding frozen regolith, ductile frozen regolith, and yield-
ing/unyielding ice) and their resulting force response profiles (Fig. 2a). We then recreated these categories in the lab (Fig. 2b) with the minimum ingredients required to illicit similar mechanical responses.

![Graph](image)

Figure 2: (A) Force-depth characterizations from Mt. Hood LASSIE field campaign using the robotic rheometer. (B) Laboratory force-depth profiles for sand-ice mixtures.

Our preliminary results suggest that the mechanical strength of regolith is dependent on the interaction between the physical characteristics of the regolith and the ice. Fig. 2a illustrates an array of mechanical responses of regolith as a function of ice content. For all five substrates, the vertical force $F_z$ increases with penetration depth $z$. Monotonic force-depth curves for loose particle (dry) regolith (Fig. 2a, blue) exhibit all of the qualitative features reported in previous studies for cohesionless granular materials [1, 3]. In regolith-ice mixtures with lower ice content, regolith exhibits mechanical properties akin to dry soils [6].

However, increasing regolith ice content yields different mechanical responses. Generally, mechanical strength tends to increase due to the cohesive nature of ice, serving as a binding agent which increases internal friction [7]. In the ductile frozen regolith profile (Fig. 2a, green), a thin icy cap, warmer than unyielding ice, yields in a brittle manner following initial penetration ($z < 0.005$ m), and an underlying colder-regolith-ice mixture exhibits a ductile response to forcing ($0.02 < z < 0.04$ m), marked by an elongated failure envelope from $0.025 < z < 0.035$ m. Further increasing ice content results in a markedly stronger regolith material and an unyielding force response (Fig. 2a, orange), where the intruder is incapable of penetrating the substrate. This particular force response is remarkably similar to what is observed in clean, unyielding ice (Fig. 2a, red).

We perform penetration experiments in the lab to reproduce these behaviors using a thermoelectric Peltier chamber. This system provides an upward freezing front and is capable of maintaining an internal temperature of $-10^\circ$ C. We use quartz sand as our initial regolith substitute, which is evenly mixed with known volumes of water and frozen to specifically probe the suggested control of ice on regolith strength. These results (Fig. 2b) are comparable to behaviors observed in Mt. Hood. Freezing sand with 3% water by volume (Fig. 2b, orange), we see a linear increase in $F_z$ similar to that of loose particle regolith (Fig 2a, blue), suggesting a negligible influence of ice in the mixture’s strength. Drastically increasing the ice content to 25% water by volume (Fig. 2b, blue), we observe a much stronger mixture. There is slight evidence of ductile behavior at shallow depths, followed by a divergence in resisting force as the material behaves similarly to unyielding frozen regolith (Fig. 2a, orange) at $z > 0.0125$ m.

Future and ongoing work concerns integrating the compositional and grain size data with our mechanical measurements. We expect that our observed mechanical responses of ice-regolith mixtures to penetration as well as thermal and morphological data and imagery, will deeply inform our ongoing geotechnical work in predicting regolith behavior in unknown and planetary environments.

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