Introduction: Given the imminent landing of astronauts and robotic spacecraft on the surface of the Moon, understanding the geotechnical properties of lunar regolith is critical, particularly for building infrastructure, landing pads, and mitigating rocket exhaust effects [1]. Accurate characterization of regolith geotechnical properties also helps to ensure that spacecraft touchdown locations can withstand the immense forces of rocket plumes and the weight of lunar habitats. Miscalculations in this domain could jeopardize mission objectives, as well as spacecraft and astronaut safety.

Important geotechnical properties associated with regolith and granular materials include cohesion, shear strength, internal angle of friction, and bearing capacity. Cohesion is a measure of the inherent force holding constituent particles together in a granular material [2]. It reflects the strength of the interparticle bonds, without a normal load applied, and is influenced by factors including particle size, shape, mineralogy, electrostatics, and Van der Waal’s forces [1]. Similarly, shear strength is a material property representing the pre-failure resistance force (per unit area) to shearing forces and is related to cohesion and the internal angle of friction through the Mohr-Coulomb failure criterion [2]. Cohesion, shear strength, and internal angle of friction directly influence the maximum load a material can support without causing failure or instability, known as bearing capacity [e.g. 3]. Together, these geotechnical properties are crucial for planning surface operations, rover wheel design, development of requisite lunar infrastructure, and in-situ resource utilization (ISRU) systems [3].

While previous studies by Dotson et al. (2023) found that shear strength and cohesion are influenced by bulk density, particle size distribution, and absorbed water content, these initial measurements were limited to atmospheric conditions [1, 4]. To be more consistent with the lunar environment, this study examines the cohesion and internal angle of friction of regolith simulants under vacuum conditions using regolith simulants. Characterization of geotechnical properties under vacuum conditions reduces Earth’s atmospheric bias, ensuring reliable translation of terrestrial experiments and studies to actual behavior on the Moon.

Methods: Using lunar highlands simulant (LHS-1) from Space Resource Technologies (formerly known as Exolith Lab), direct shear tests were conducted using a 9 cm x 9 cm x 9 cm aluminum shear box in accordance with ASTM D3080, under vacuum conditions [5, 6]. Direct shear measurements were conducted with sample densities between 1.52-1.79 g/cm³, ambient pressures between 160-170 mTorr, and with normal loads between 0.1-6.7 N applied. Sample density was adjusted using a vibration motor between 20-40 Hz with <1.0 N normal loads applied for compaction, before ambient pressures were reduced to vacuum conditions over the span of roughly 1 hour. Direct shear strength measurements were then obtained using a linear actuator connected to the shear box with a force gauge inside a vacuum chamber, noting the maximum force prior to material failure.

LHS-1 samples were not baked or purged prior to shear testing, and sample temperatures were not controlled or monitored while inside the vacuum chamber. However, samples were exposed to ambient pressures <20 Torr for approximately 1 hour prior to shear testing to remove water vapor and air. Two vacuum pumps were kept on during the shear tests, with vacuum chamber pressures being continuously monitored using a Lesker KJL275804 transducer.

Results: Initial cohesion results for LHS-1 under vacuum conditions are shown in Figure 1, for various sample densities. Similar cohesion measurements for LHS-1 in atmosphere, as reported by Dotson et al. (2023), are also shown in Figure 1 for comparison [1]. Cohesion for LHS-1 was calculated between 280-471 Pa under vacuum conditions for the range of sample densities examined.

![Figure 1. Cohesion of LHS-1 as a function of density in atmosphere and vacuum.](image-url)
Similar to previous studies, an increase in sample density also corresponds to an increase in cohesion while under vacuum conditions. However, the overall change in cohesion with an increase in sample density appears to be reduced under vacuum conditions when compared to atmosphere. For example, with LHS-1 at sample densities near 1.52 g/cm³, cohesion was roughly 15-20% less when measured in vacuum when compared to atmosphere. Yet, for LHS-1 with a bulk density of 1.79 g/cm³ under vacuum, cohesion was measured to be roughly 60-70% less than when measured in atmosphere.

As it relates to PSI events during rocket landings or launches on the Moon, a decrease in cohesion may result in higher viscous erosion rates under vacuum conditions when compared to similar tests in atmosphere [7]. Since rocket exhaust plumes are expected to expand radially with reduced ambient pressures, the decrease in cohesion of granular materials may further amplify shearing erosion effects from PSI under vacuum conditions; potentially damaging nearby structures or spacecraft with high velocity ejected particles. Additionally, the increase in internal angle of friction could allow for steeper crater features from PSI or impact events. The overall impact of internal angle of friction and cohesion with respect to PSI events should be examined in more detail by future studies.

While not directly measured during this experiment, a reduction in cohesion while exposed to vacuum conditions implies a potential decrease in regolith bearing capacity at reduced ambient pressures [3]. However, given the complex interaction between geotechnical properties, an increase in internal angle of friction may help to improve regolith bearing capacity under vacuum [3]. The interplay between these opposing effects highlights the need for careful consideration of regolith mechanics when planning future lunar missions. As such, bearing capacity should be measured more directly under vacuum conditions in future studies before attempting to use Earth-based measurements as a reference for actual space exploration missions.

Since the behavior of granular materials is known to also change in reduced gravity environments, including non-linear Mohr-Coulomb effects, future measurements should be considered using simulants with reduced gravity and ambient pressures as well [1, 8].

**Conclusions:** The mechanical and geotechnical properties of regolith can vary greatly when exposed to vacuum conditions; these parameters should be considered during any PSI or IRSU applications, particularly while simulating these applications in atmosphere for upcoming lunar missions. Future studies should examine the effects on geotechnical properties for other simulants under vacuum conditions, as well as for lower ambient pressures consistent with the lunar environment.