Behavior of BP-1 and LHS-1 Lunar Regolith Simulants Under Vacuum Conditions

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Introduction

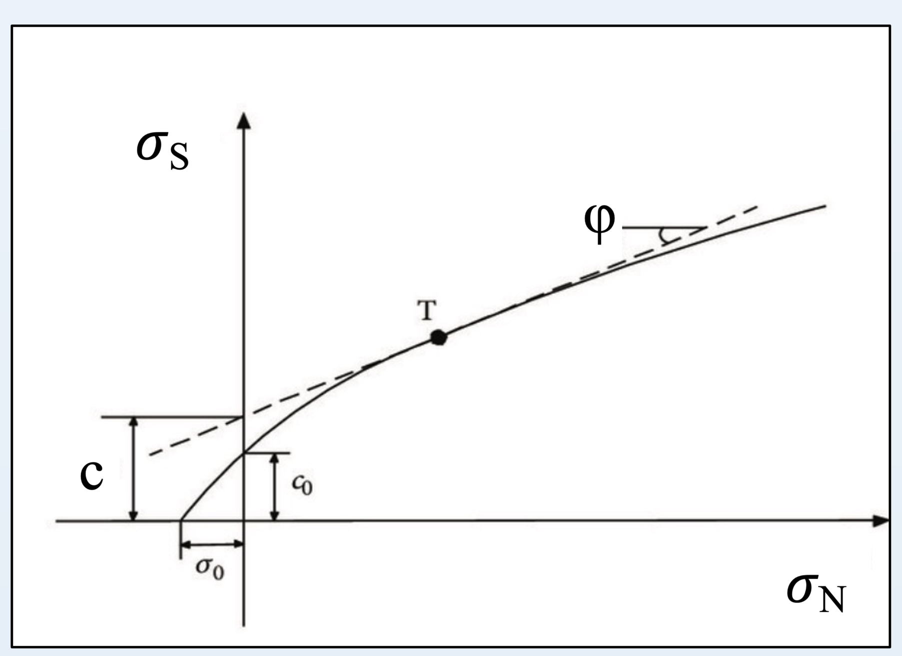
This study examines the effects of bulk density on the **cohesion** and **internal angle of friction** for lunar highlands simulant (LHS-1 and BP-1) using direct shear tests conducted under **vacuum conditions**. Experimental measurements are compared to similar tests in atmosphere, highlighting the impacts of lower ambient pressures on geotechnical properties.

WHY DOES THIS MATTER?

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

A material's shear strength is dependent on the applied normal load (σ_N) and is related to cohesion and internal angle of friction, described by the **Mohr-Coulomb failure criterion** [2]:

$$\sigma_S = \sigma_N \tan \varphi + c$$



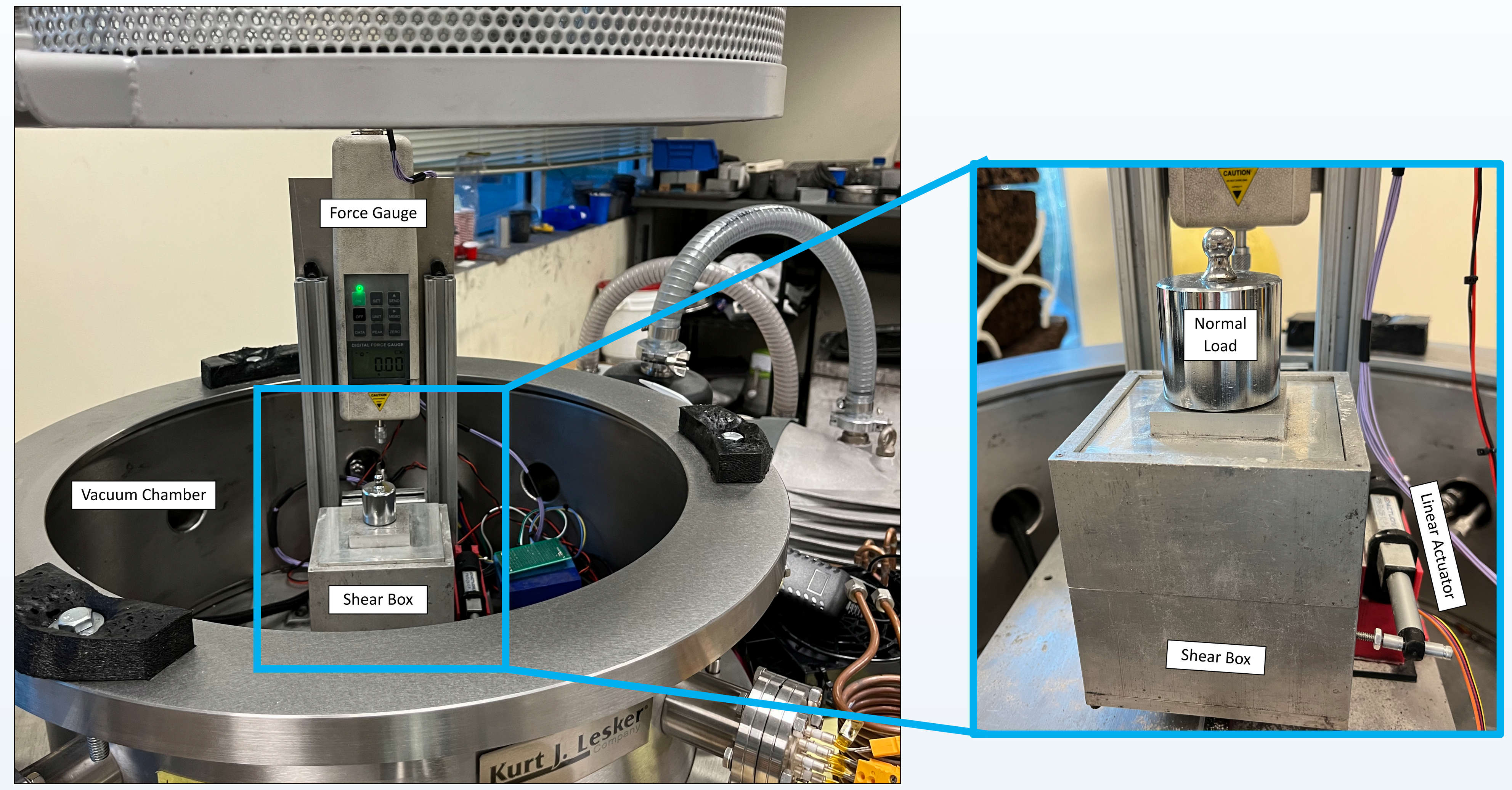
(Image credit: Modified from Wu et al., 2019)

Shear strength (σ_S), a material property that represents the pre-failure, resistive force (per unit area) to a shearing load through constituent particle interactions; may be non-linear for reduced gravity or smaller normal loads, but not considered in this study [3].

Cohesion (c), is a measure of the inherent force holding particles together in a granular material [2]. It reflects the strength of the interparticle bonds and is influenced by factors including particle size, shape, mineralogy, electrostatics, and Van der Wahl's forces.

Internal Angle of Friction (φ), is the calculated angle between maximum shear strength and normal load acting on a granular material at failure. This angle is crucial in analyzing slope stability and overall bearing capacity.

Methods



Direct shear measurements were conducted using a 9 cm x 9 cm x 9 cm aluminum shear box in accordance with ASTM D3080, under vacuum conditions [4, 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.

Key Findings

The geotechnical properties of regolith can vary greatly when exposed to vacuum ambient conditions, including a **decrease in cohesion** and an **increase in internal angle of friction**.

- Decreased cohesion for regolith could result in difficulty during traverse planning (Example: Spirit rover stuck on Mars), failure of instrumented probes (Example: Insight H3 heat probe), or increased plume effects from landing and launching rockets [1, 3, 7].
- Increased internal angle of friction for regolith may result in steeper features on the surface, particularly during rocket plume events, astronaut and rover tracks, or impact craters.
- Significant out-gassing was observed when using BP-1 under vacuum conditions, particularly with ambient pressures between 20-30 mTorr, consistent with the vapor pressure of water at room temperature.

Taken together, the interplay of cohesion and internal angle of friction under vacuum conditions can impact the overall shear strength and bearing capacity of granular materials, including regolith [8]. Additional testing is needed to determine the overall impact on bearing capacity.

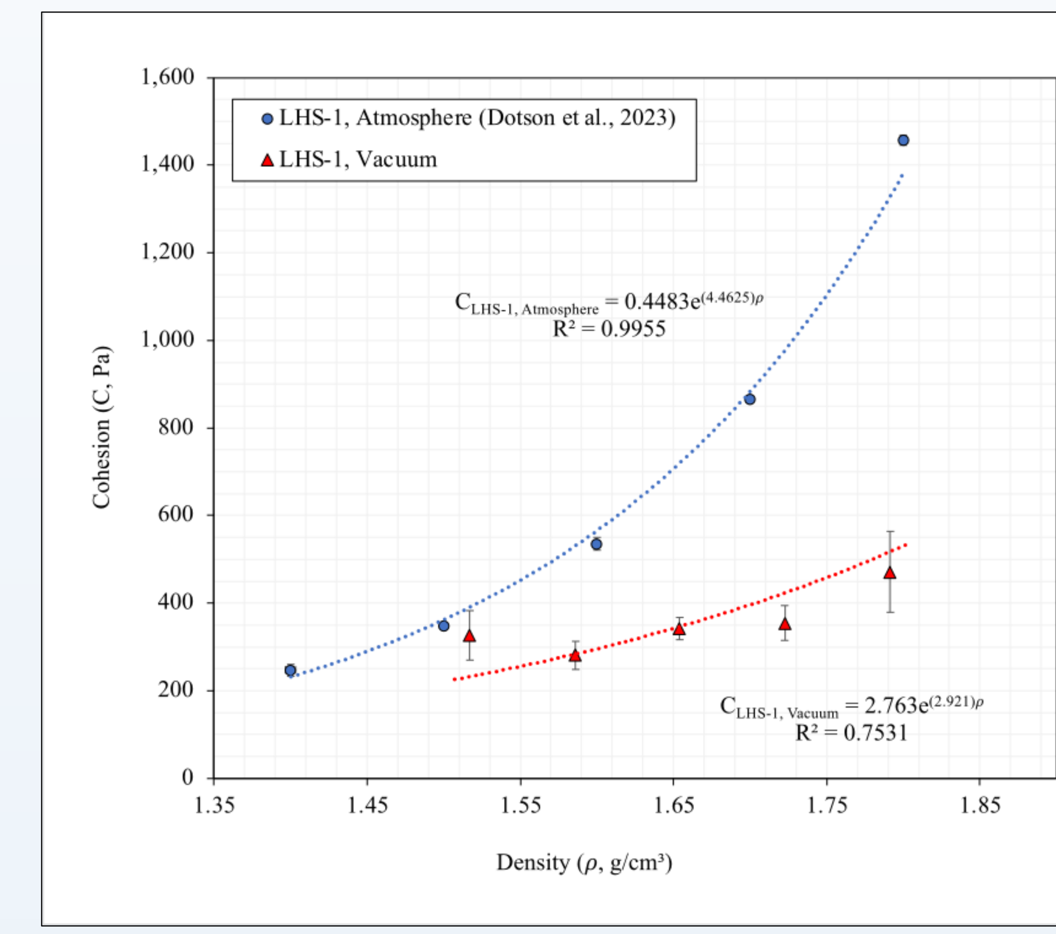
Future studies should also examine the effects on geotechnical properties for other simulants under vacuum conditions, with lower ambient pressures and gravity consistent with the Moon.

A change in geotechnical parameters (including cohesion and internal angle of friction) of granular material when exposed to vacuum should be considered in planning of space missions, particularly during surface construction, instrument design, traverse planning, or while testing and simulating plume surface interactions.

Results

Cohesion Under Vacuum Conditions:

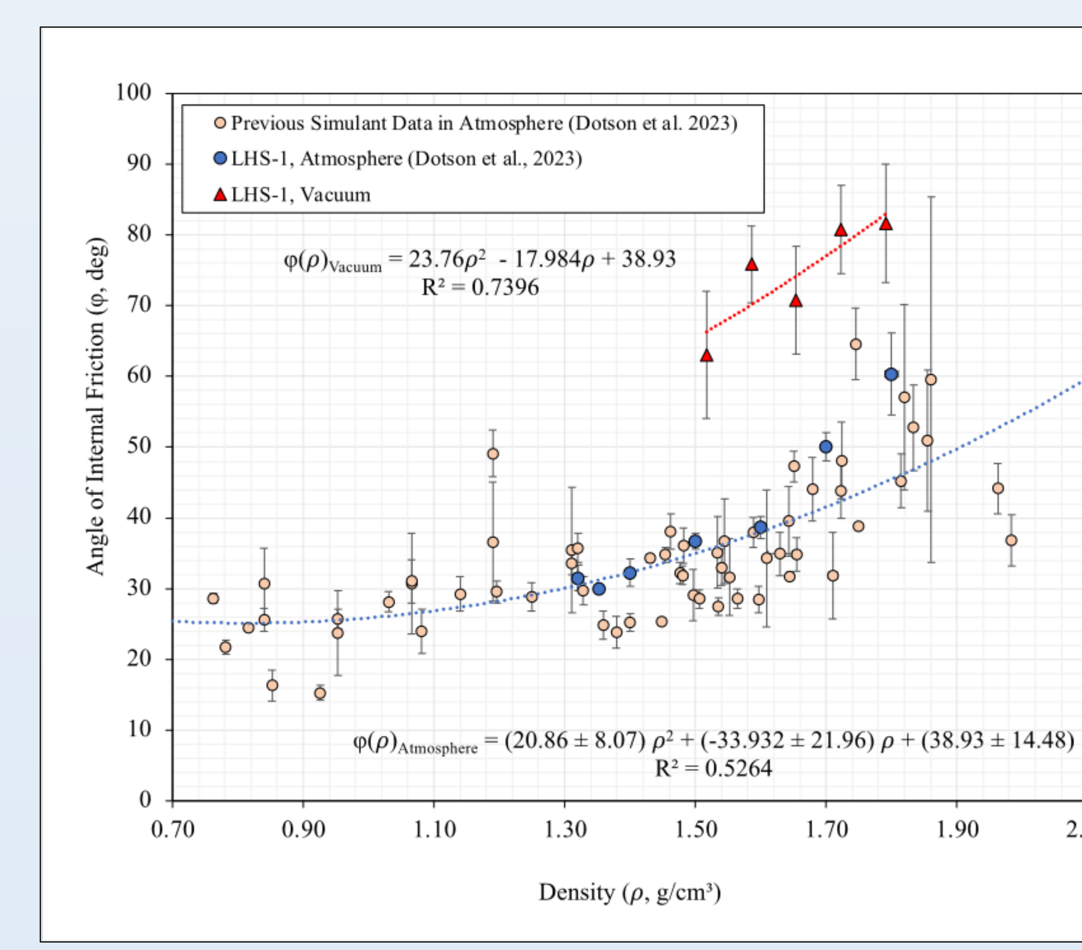
Similar to studies in atmosphere, an increase in sample density corresponds to an increase in cohesion while under vacuum conditions. Yet, the change in cohesion with density appears to be reduced under vacuum conditions [1,4].



Internal Angle of Friction Under Vacuum Conditions:

Consistent with previous measurements, the internal angle of friction for LHS-1 under vacuum conditions increases with higher sample densities. However, these calculated internal angles of friction are roughly 44-50% higher than similar measurements using LHS-1 and other regolith simulants in atmosphere [1]

Initial results for BP-1 also demonstrate a decrease in cohesion and increase in internal angle of friction when exposed to vacuum.



References

[1] Dotson, B. et al. (2023), Icarus (2023). [2] Terzaghi, K., Wiley (1943). [3] Dixit, M. and Patil, K., IGC (2009), 682-685. [4] Dotson, B. et al., LPSC 54 (2023), 2806. [5] ASTM, D3080/D3080M-11 - Standard Test Method (2011). [6] Exolith Lab, LHS-1 Spec Sheet (Jul. 2022). [7] Sapkota, D. et al., DPS 55 (2023). [8] Alshibli, K., Innovative Infrastructure Solutions (2017).