Lunar Regolith Hopper Design and Testing Under Atmosphere and Vacuum Conditions. Jason B. Noe[1], Paul van Susante[2], Laurent Sibille[3], Parker Bradshaw[4], Eli Sierra[5], and Ben Wiegand[6], [1,2,4,5,6]Planetary Surface Technology Development Laboratory, Michigan Technological University, 1400 Townsend Dr, Houghton, MI 49931, USA, (contact: pjvansus@mtu.edu), [3]Southeastern Universities Research Association (SURA), Swamp Works Granular Mechanics and Regolith Operations, NASA Kennedy Space Center, Florida 32899, USA

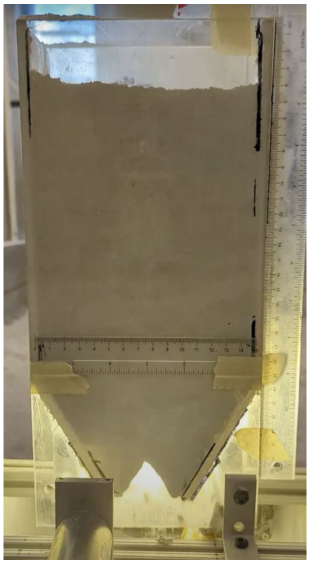
Introduction: Lunar regolith ISRU research is currently a very popular field of research as lunar regolith is a very versatile resource for future missions to the moon [1-2]. However, one aspect of this field that is underdeveloped is that of lunar regolith hopper design. Hoppers act as intermediates between storage areas and other ISRU systems, regulating material flow. Lunar regolith has poor flowability and is prone to arching due to its small particle size and strong cohesive properties [3-4]. Several researchers have already built and used lunar regolith hoppers but have failed to provide information about the hoppers like hopper inclination angle, outlet area, material mass, and hopper mass flow rate [1, 3-4]. Additionally, most of these tests of regolith hoppers were conducted in atmosphere under terrestrial gravity. It is conservatively speculated that the flowability of lunar regolith hoppers will be decreased by a factor of 6 on the lunar environment [3]. However, only a single research group has assessed regolith hoppers at reduced gravity and in vacuum [5]. The objective of their research was to determine hopper geometry for small scale sampling devices, roughly 50 g of regolith. The results from this research may not be scalable for full scale ISRU systems handling tens to hundreds of kilograms of regolith. Additionally, several aspects of this research were not fully explored such as starting and stopping regolith flow, hopper material, wall thickness, and hopper shape. This paper investigates lunar regolith simulant, MTU-LHT-1A, for general ISRU applications. It looks at lunar regolith hopper average mass flow rate as a function of regolith compaction (low-high), hopper inclination angle (40-80°), hopper opening width (2.5–7.5 cm), and the effects of vacuum on flowability. This was done over six experiments with an emphasis on experimental design and statistical analysis.

Hopper Design: Ten hoppers were constructed out of polycarbonate for this research. Polycarbonate was chosen as it was a vacuum rated material that is transparent, allowing for real time observations of regolith flow and arching. Nine of these hoppers were classified as 2.5 D hoppers. The 2.5 D hoppers were cross sections of 3D conical hoppers that were then extruded to a depth of 6.35 cm. 6.35 cm was used as it was ten time larger than the largest particle diameter found in the simulant. This increase in depth was to limit wall effects on the flow of regolith simulant during testing. The 2.5 D design for the hoppers was also chosen as a cost-effective way to determine the optimal hopper inclination angle and opening area that provided the maximum mass flow rate. The tenth hopper was a full 3D box hopper, designed based on the 2.5 D hopper with the highest mass flow rate. Each hopper was designed to accommodate several kilograms of regolith simulant to portray the macro scale regolith mechanics more accurately. Six experiments were conducted to parameterize lunar regolith simulant hopper flow, not all discussed here.

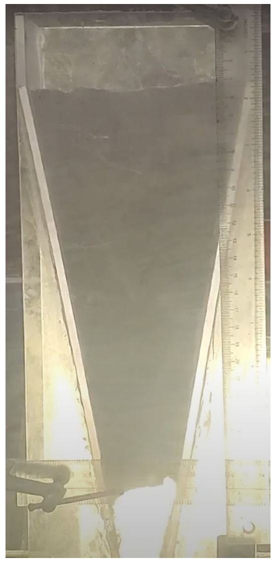
Experiment 1: This experiment used 40°, 60°, and 80° hoppers, all with a 5 cm opening width filled to 29 cm in atmosphere. The angle of repose of the simulant was measured to be 49°. From this, the lowest hopper inclination angle was determined at 40°. The goal of this experiment was to determine hopper inclination angle range where the highest mass flow rate existed and to determine the effects of compaction on flowability. To compact the simulant in the hoppers, a vibration table was used to shake the filled hoppers at 30 hz for 2 minutes. The bulk densities tested for the experiment were 1.3 g/cm^3 for uncompacted and 1.7 g/cm^3 for compacted regolith. An ANOVA was used to determine factor significance, with relative humidity used as a covariate. It was determined that both angle and compaction were significant. All hoppers, regardless of inclination angle, at bulk densities of 1.7 g/cm^3 did not flow. It was found that an inclination angle of 60° produced the highest mass flow rate of the tested hoppers.

Experiment 2: The second experiment tested hopper opening width effect on mass flow rate in atmosphere. Two hopper inclination angles were used, 60° and 80°, and three opening widths, 2.5 cm, 5 cm, and 7.5 cm with all the hopper filled to a height of 29 cm. An ANOVA was used to determine significance of the factors. It was found that hopper inclination angle and hopper outlet width were both significant. The mass flow rate for increasing hopper width followed a linear growth for both the 60° and 80° hoppers, where the 7.5 cm widths had the highest mass flow rate.

Experiment 3 & 5: These are not described here because they tested other parameters not as relevant to the described observations.



(a) 60 deg Hopper, 5 cm Opening, Loose Regolith Simulant, Flowing.



(b) 80 deg Hopper, 2.5 cm Opening, Loose Regolith Simulant, Flowing.

Fig. 1 Hopper Testing in Atmospheric Condition.

Experiment 4: The fourth experiment was an initial test to determine the effects of vacuum on mass flow rate. The 40° and 60° inclination hoppers were filled in atmosphere to 29 cm, moved to a vacuum chamber that was then pumped down. Compaction was also tested. The 40° hopper had bulk density around 1.3 g/cm^3 while the 60° hopper had a bulk density around 1.7 g/cm^3. No statistical analysis was conducted for this experiment as it was exploratory. It was found that both hoppers had a much higher flow rate than their atmospheric counterparts. It took approximately 30 seconds for their atmospheric counterparts to empty while in vacuum it took between 1-5 seconds. It was suspected that this increase was due to trapped air in the regolith itself, a byproduct of the atmospheric filling. This was reinforced by the vacuum chamber pressure increasing during testing and by a dust devil forming in one of the hoppers during a test.

Experiment 6: Experiment six was a continuation of experiment four. A system was developed to fill hoppers in vacuum. A large tray held 2-3 kg of simulant at a 2 cm depth. After pumping down to vacuum, a vibration motor would then shake the bottom of the tray, slowly filling a hopper over 10-20 minutes. It was determined through testing that the vibration system did not compact the regolith simulant in the hopper. The 60° hopper, filled to 29 cm at a bulk density of 1.3 g/cm^3 was used for this experiment. The first test was a control that filled the hopper by hand, and then measured the mass flow rate in atmosphere. The second test filled the hopper via the tray and measured the mass flow rate in atmosphere. It was found that the tray filled hopper had a slightly higher mass flow rate. Finally, two tests were conducted where the hoppers were filled, and their mass flow rates were measured in vacuum. The mass flow rates of the vacuum hoppers were roughly 17 times higher than atmospheric counterpart. Because of the method of filling, and the 10-20 minutes it took for the hoppers to be filled in vacuum, it was determined that trapped air was not a factor in the increased mass flow rate. It was concluded that this 17 times increase was due to the absence of air.

To determine the effect of air on the simulant, a simple drag force calculation was done. It found that the drag force for an individual 70 micron regolith particle was on the order of 10^{-10} Newtons whereas the force of gravity was on the order of 10^{-36} Newtons. From this, it was concluded that even small currents or eddies in the air would have a significant effect on regolith simulant flow. It was observed in experiments 1-3, that the regolith simulant flowed in chunks, not a continuous stream. This chunky flow was not observed in experiments 4 and 6. This has led to speculation that the chunky flow was a direct result of the force imparted on the simulant by the ambient air.

Future Work: To continue this work, more vacuum testing of each hopper is required. Specifically, multi-level factorial experiments with statistical analysis. Additionally, simulation of the hoppers in both atmospheric and vacuum conditions to more accurately model and understand the forces at play in the flowability of the hoppers is planned.

References: [1] Cannon, K. M., Dreyer, C. B., Sowers, G. F., Schmit, J., Nguyen, T., Sanny, K., & Schertz, J. (2022). Working with lunar surface materials: Review and analysis of dust mitigation and regolith conveyance technologies. Acta Astronautica. [2] Roman, M., Yashar, M., Fiske, M., Nazerain, S., Adams, A., Boyd, P., Bentley, M., & Ballard, J. (2020). 3D-printing lunar and martian habitats and the potential applications for additive construction. International Conference on Environmental Systems. [3] Walton, O. (2012). Challenges in Transporting, Handling and Processing Regolith in the Lunar Environment. In V. Badescu (Ed.), Moon: Prospective Energy and Material Resources (pp. 267-293). Springer Berlin Heidelberg. [4] Kring, D. A. (2006). Parameters of Lunar Soils. [5] Reiss, P., Hager, P., Hoehn, A., Rott, M., & Walter, U. (2014). Flowability of Lunar Regolith Simulants Under Reduced Gravity and Vacuum in Hopper-Based Conveying Devices. Journal of Terramechanics, 55, 61-72.