# PRESSURE-SINKAGE TESTING OF LUNAR REGOLITH SIMULANTS IN AMBIENT PRESSURE AND VACUUM.

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**Introduction:** Regolith is the blanket of unconsolidated fragmented rock and related dust material covering the surfaces of extra-terrestrial bodies that has been created by high energy impact ejecta, pyroclastic deposits or by other environmental phenomena such as thermal cycling or accretion. On the Moon, the regolith consists of fine sharp rock particles whose physical behavior is dominated by electrostatic forces, van der Waals forces and the friction created by the complex and convoluted morphology of the granular rock materials interacting with each other through compressive and shear forces [1]. The geo-mechanical characteristics of lunar regolith have been studied by analyzing samples of actual lunar regolith that have been sampled and returned via Soviet Union and Chinese robotic lander missions as well as the United States of America (USA) Apollo program where human astronauts were able to excavate and drill regolith samples and bring them back to Earth in the return capsule. The 6 Apollo missions that landed on the lunar surface returned 2196 samples comprised of 382 kilograms of lunar regolith materials which are curated at the National Aeronautics & Space Administration (NASA) Johnson Space Center [2]. However, the scarcity and value of these lunar samples means that very small quantities are loaned to qualified researchers for experimentation, characterization and analysis. There is a need for larger scale testing to understand the geo-mechanical performance of lunar regolith and the determination of its geotechnical properties. Geotechnical engineering is a branch of civil engineering that applies principles of geomechanics to the design, construction, and maintenance of infrastructure and structures involving soil and rock. It focuses on the safe and effective use of soil and rock materials in engineering projects.

To address this need for larger quantities of lunar regolith for geotechnical testing, the space community has developed lunar regolith simulants during the past 20 years [3]. There are two main types of regolith on the Moon as determined by the minerology of their rock origin: lunar mare regolith (basalt based) and lunar highlands regolith (plagioclase-rich anorthosite based). The lunar regolith was primarily formed by high energy impacts over the Moon's 4.5 billion year history which resulted in ejecta that partially went into orbit and then rained down across the Moon's surface. Succesive layers of ejecta deposition have formed a regolith covering. The regolith is approximately 4 meters thick in mare regions and 10 to 15 meters thick in the highlands [1] and the particle sizes and particle size distribution are remarkably consistent due to repeated and successive impact events from comets and meteorites. These lunar regolith simulants have been engineered by sourcing mineralogically similar rocks from terrestrial mine sites and then these rocks have been crushed or ball milled into fine particles that have then been separated into various size fractions, and then mixed together to obtain particle size distributions that are analogous to the actual lunar regolith.

**Pressure-Sinkage Behavior of Lunar Regolith:** In order to create civil engineering structures, a strong and consistent load bearing foundation is needed, and in order to enable robotic mobility the amount of sinkage that corresponds to a known pressure load acting perpendicular to the regolith surface is one of the fundamental properties that must be measured to account for its geomechanical behavior.

For terramechanics applications, the classical engineering mathematical analysis models depend on a semi-empirical approach where measurements of the regolith must be made to determine constants that are then used to predict regolith geotechnical performance for civil engineering structures or mobility applications. The original Bernstein-Goriatchkin model is an empirical pressure-sinkage single-parameter equation, expressed as follows:

$$p = k \cdot z^n \qquad (1)$$

where, z is the sinkage depth of the plate subjected to a vertical pressure p, k is a modulus of inelastic deformation, and n is the exponent of sinkage (Bernstein 1913; Bekker 1969) which varies between zero and one. Bekker improved the Bernstein-Goriatchkin model by replacing $k = k_c / b + k_\phi$ with new parameters $k_c$ and $k_\phi$ as follows:

$$p = \left( \frac{k_c}{b} + k_\phi \right) z^n \qquad (2)$$

where, b is the width of a rectangular plate or the radius of a circular plate; $k_c$ and $k_\phi$ are the deformation modulus of cohesion and friction, respectively; and n is the parameter that determines the shape of the pressure-sinkage curve.

The first widely used planetary terramechanics methods were pioneered in the 1950's and 1960's by Dr. Mieczyslaw Bekker. This method requires using a Bekker Values Meter (Bevameter) to push two different size plates (either square / rectangular or circular shapes) into the regolith to use the results to calculate the moduli which are denoted by $k_c$ and $k_{\phi,}$ representing the respective influence of regolith cohesion and internal friction. These plates are pushed into the regolith surface from above in a directly perpendicular direction and the force is measured as well as the vertical displacement of the plate in relation to its initial position flush with the surface of the regolith. Since the areas of the plates are known their pressures can be calculated and plotted against the corresponding sinkage displacement of the plate as a function of time.

**Pressure-Sinkage Testing of Lunar Regolith Simulants in Ambient and Vacuum Environments:** Two lunar regolith simulants were selected for pressure sinkage testing : Lunar Highlands Simulant (LHS-1E) from the University of Central Florida Exolith Lab [7] and Black Point-1 (BP-1) [8] a basaltic mechanical lunar mare simulant, sourced as fines from a quarry at the Black Point lava flow near Flagstaff, Arizona. A Bevameter pressure-sinkage test rig (Figure 1) was used that consisted of a frame made of aluminum modular extrusions that were bolted together, an electromechanical linear actuator with various sizes of square and rectangular plates mounted to it and a simulant test bin which was made out of 0.95 cm thick acrylic and is 40 cm tall with horizontal dimensions of 30.48 x 30.48 cm. The linear actuator was controlled by an Arduino microprocessor programmed in C+ language. The time, actuation distance and force measured with a sandwiched load cell were data logged for analysis.

The regolith simulant was tested at various bulk densities ranging from 1.42 grams/cm$^3$ to 1.86 grams/cm$^3$. The simulant was carefully prepared by sieving it into the test bin and then if compaction was required, a 1.91 cm thick plywood board cut to the size of the simulant bin wrapped in landscape fabric, with a 90 W vibration motor bolted to the board, was placed on top of the regolith simulant and vibrated. Recent work by others [9] has indicated substantial differences between ambient and vacuum properties and a high sensitivity to the bulk density. The results of these ambient and vacuum tests will be presented with a full analysis to follow in a journal publication.

Figure 1. Pressure Sinkage Test Rig in a NASA Vacuum Chamber

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