A Method of Measuring Bulk Density of Regolith Simulants In-Situ. E. Skirde[1], B. Kemmerer[2], E. A. Bell[3]
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Introduction: In recent years there has been an emphasis on technology development to enable a civil, structural, and geophysical engineering understanding of regolith mechanics and properties. These characteristics of regolith are essential in the space resources and lunar innovation communities' for applying terrestrial construction concepts to the lunar surface.

The density (rho) of a soil greatly affects essential properties such as the internal friction angle (phi) which is used to determine the soils Mhor-Columb failure envelope, bearing capacity, and settlement [1].

For lunar construction technologies being tested terrestrially, a proper starting regolith simulant density and, in some cases, measurement of the final regolith density post technology testing are needed to verify operation. Preparation and measurement of regolith simulant bins can be difficult work depending on their volume and mass. Verifying the density is challenging without affecting the density of the bin through sample collection itself.

Correlating density to a pressure-sinkage result, in this case a Humbolt H-4205 pocket penetrometer, is an effective means of measuring surface bulk density without significant perturbation of the prepared simulant bin.

The discussion and justification of the procedure used to create a curve correlating a collected pressure reading to a prepared density sample will be shared. Results from this testing is shared in relation to the Granular Regolith Mechanics and Operations lab's Big Bin ambient proving grounds and potential for future work is discussed.

Procedure: A Humbolt Split Compaction mold (H-4159) and a Humbolt Aggregate Tamper (fig 1) were used as a regolith container and impact weight to prepare each sample tested. The mold has a height of 203.2 mm (8in) and a diameter of 152.4 mm (6in). The drop mass on the aggregate tamper weighs 4.2 kg with the total mass of the tamper, including the drop mass, weighing 8.3 kg.

To prepare densities roughly less than 1.5 g/cc the regolith was carefully poured into the sample container through a 6.3 mm sieve plate. Once the desired mass was reached the sieve plate was removed and the surface was carefully leveled. Three equidistant height meas-

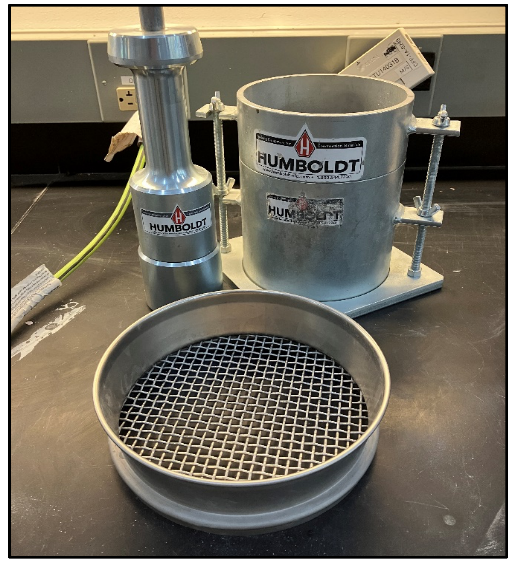

Figure 1 - Test Procedure Tools

urements were then taken along the edge of the sample container, and a penetrometer reading was taken from the center of the sample.

For densities greater than 1.5 g/cc the sample was prepared in the same way, however after gently leveling the surface a thick aluminum plate was then placed on top of the sample. Depending on the desired density to be tested, a number of impacts from the Humbolt Aggregate Tamper were imparted on the surface of the lid on top of the prepared sample. Then a penetrometer reading was taken after the lid was removed.

A sample of the number of impacts and corresponding densities can be seen in Table 1. This variation of impacts and weights allowed for the creation of a wide range of densities to be tested and measured.

Table 1 - Sample Data Collection Table

Goal Density (g/cc)	Pene-trometer head	# of hits	Calculated Density (g/cc)	Pene-trometer Reading
1.6	20mm	Static load only	-	-
1.65	20mm	2	-	-
1.7	20mm	4	-	-
1.5	60mm	0	-	-
1.55	60mm	lid	-	-
1.6	60mm	Static load only	-	-

A Humbolt H-4205 pocket penetrometer was used to record the applied pressure with a 20 mm diameter foot and a custom 60 mm diameter foot. The 60 mm foot was used for lower density samples to get better readings when applying lower pressures. The penetrometer provides a reading in kg force imparted by the user to press the cylindrical foot 15 mm into the soil, so that the soil surface is flush with the top of the foot. This force can be converted to a pressure applied to the surface based on the area of the foot used in the test.

To properly interpret these recorded results, curves were created to correlate the penetrometer readings and the applied pressure to the goal density. Using the calculation of pressure applied allows for comparison of multiple different diameter feet to be overlayed with each other. These correlation curves can then be used to get an estimation of density of a sample that is measured with a H-4205 penetrometer. Figure 2 shows the results of testing in the form of penetrometer reading vs. the calculated density of the sample. The resulting curve of pressure vs. density is seen in Figure 3. Testing was completed with the simulant within the GMRO Big Bin BP-1 ambient proving grounds for analysis of both the simulant and the discussed procedure.

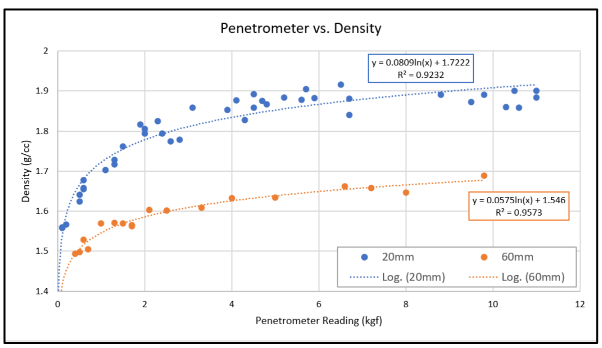

Figure 2 - Penetrometer Reading vs. Calculated Density

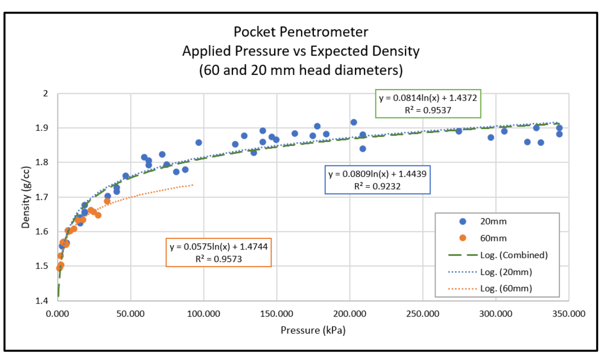

Figure 3 - Calculated Pressure vs. Calculated Density

Discussion: ASTM standards were consulted when making the procedure, however they were not used in their full scope. Standards such as the standard proctor test (D968) or the modified proctor test (D1557) were determined to be unfit for the purposes of creating the desired density range. These standards use a method of compaction that layers soil within a mold like the Humbolt Split Compaction Mold. A layer of soil is placed within the mold and then is compacted, then the next layer is placed on top of and compacted on top of the previous layers. This part of these procedures is the reason why they were deemed unfit, because of the desire to achieve a range of densities from low to high, there was a concern of not being able to achieve a range of 'medium' densities to test. Other standards such as ASTM D5195, D2937, D4564 can potentially enable a better understanding of a desired density range, however were found to either require extensive complex equipment, are not suited for easily molded granular materials, or require previous soil specific calibration equations.

The procedure and curves developed have informed testing including work in [2] as well as continuing work within the Swamp Works lab.

Process Development and Future Work: Throughout the process of testing, locations for improvement of this procedure were identified. An area of development being perused for future work and testing of this procedure include using the technique of multiple prepared layers of compacted material as seen in ASTM standards D968 and D1557. This would further align this procedure with standard geophysics based density test methods and ASTM standards.

Current and future planned efforts to quantify the accuracy of correlating density to pocket penetrometer results will be included in the final documents for conference. Planned testing will include the use of x-ray Computed Tomography (CT) scanning to measure density homogeneity throughout a prepared cylinder of regolith. Initial results and preliminary conclusions from the CT scanning will be shared.

Finally, plans to adapt this test procedure to be performed in vacuum are being created for further development of the understanding of atmosphere on compaction efforts.

References: [1] Braja M. Das *Principles of Geotechnical Engineering, 7th Edition*; Cengage Learning (2006). [2] Bell, Kemmerer, et al (2025) https://ntrs.nasa.gov/citations/20250005172.