Vibratory Plate Compaction of BP-1 & LHS-1 Utilizing the Planetary Automated Compaction Tool (PACT).

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Introduction: The Multi-Purpose End Effector for Regolith Construction, Acquisition, and Transfer (MEERCAT) is a robotic arm end effector developed by the Swamp Works Granular Mechanics and Regolith Operations (GMRO) lab [1]. This system has several capabilities including excavation, trenching, regolith size screening, compaction, and geotechnical property measurement.

The NASA Tipping Point Project, Mason, led by Redwire Space in partnership with the Swamp Works GMRO lab has continued development and refinement of the MEERCAT system's compaction capabilities, specifically, under the new moniker Planetary Automated Compaction Tool (PACT). A test campaign in ambient laboratory conditions was conducted using Black Point-1 (BP-1) and Lunar Highlands-1 (LHS-1) simulants in the GMRO's Big Bin test facility utilizing the Excavation Test Stand (ETS) 2-axis gantry. Along with this work a correlation curve was developed to estimate bulk surface compaction based on surface pocket penetrometer readings of penetration force into simulant.

Compactor Configuration: Compaction testing was performed using the ETS 2-axis gantry system in the BP-1 Big Bin at the Swamp Works GMRO laboratory at Kennedy Space Center. The PACT system was tested using two excentric mass motor configurations for vibratory motion during compaction. Figure 1 shows these two configurations. The dual-mass motor produced vibratory frequencies of 71 Hz and 48 Hz (based on tachometer readings of the excentric mass rotation rates) in the Y-Z plane. The single mass motor, utilizing a smaller excentric mass, produced a frequency of 158 Hz in the X-Y plane. The single-mass motor was used for ambient testing using LHS-1 simulant to recreate previous work performed under vacuum conditions with LHS-1 and the single-mass motor.

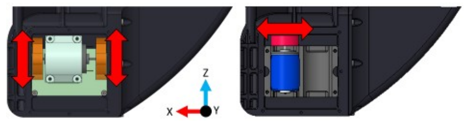

Figure 1. PACT with dual-mass motor (left) and single-mass motor (right) configurations.

The PACT system utilized two methods of compaction for testing, Spot and Raster. The "Spot" compaction method consists in applying a static vertical load to the compaction plate while vibratory motion is induced. Compaction forces are measured during test and sinkage into the regolith simulant is measured after the test. The "Raster" compaction method consists in placing PACT at 1-5 mm below the surface grade of the regolith and moving it along the X-axis of the ETS system, building a surcharge while vibration is applied. The travelling speed along the X-axis is controlled, and pass-depth is fixed throughout the test while compaction and surcharge reaction forces are recorded.

A test matrix of Spot and Raster tests that vary the vibratory frequency, surface contact time, a static compaction pressure of 7 or 70 kPa (Spot only), and pass depth of 5 or 1 mm (Raster only) was developed to test each parameter's effect on compaction effectiveness.

Regolith Preparation: Regolith simulant was prepared with the goal of achieving the lowest possible density with the methodologies described herein. For BP-1 testing, a 0.3-m deep pit was dug into the BP-1 surface with outer dimensions of 0.6 x 0.6 m for Spot tests and 0.6 x 1.6 m for Raster tests. The manual excavated material was then gently shoveled onto a 9-mm hole size mesh placed over the pit to allow the BP-1 to fall through the mesh to obtain a low bulk density. This produced bulk densities (based on surface pocket penetrometer readings) of approximately 1.55 g/cm^3. The surface was then graded with a surface preparation grader blade that was affixed to the ETS along with PACT. The final surface finish, PACT, and the grader blade can be seen in Figure 2.

Figure 2. PACT and surface preparation grader blade on the ETS above a prepared, low-density, graded surface.

The LHS-1 simulant was prepared in a smaller, trapezoidal bin (35.5-cm deep, top surface area of 79 x 45 cm and a bottom area of 38 x 45 cm with a resultant volume of 93,454 cm^3). Regolith was prepared by fully emptying the bin and then re-filling via sprinkling from a shovel. This produced bulk densities (based on surface pocket penetrometer readings) of approximately 1.54 g/cm^3.

Density Measurement Methods: Measurements taken of the prepared, uncompacted regolith and of the compacted region post-test included: surface pocket penetrometer measurements, using a Humbolt HS-4205, cone penetrometer (CPT) readings, using a Humbolt HS-4210, and, in some tests, a direct core sample measurement using a 60-mm diameter x 25-mm deep core sampling cylinder. Measurements were then used to indicate the change in compaction of the regolith simulant pre- and post-compaction test at several depths.

A correlation curve was created to link pocket penetrometer measurements (using a 60-mm or 20-mm diameter head) to the surface bulk density of the BP-1.

Figure 3 displays the obtained data with fitted curve, and the best-fit equation.

The data required for the correlation curve was obtained with BP-1 samples prepared in a Humbolt split compaction mold cylinder and compacted by repeated tamping via an aggregate tamper tool. Densities of BP-1 samples ranged from 1.48 to 1.74 g/cm^3. Pocket penetrometer measurements with the 20-mm and 60-mm heads were taken (one reading per prepared cylinder of regolith). Additional pocket penetrometer measurements performed in the Big Bin on higher density BP-1 (1.76 to 1.86 g/cm^3, as measured using the core sampling tool) were added to the curve to extend it beyond the range of testing performed in the split compaction mold.

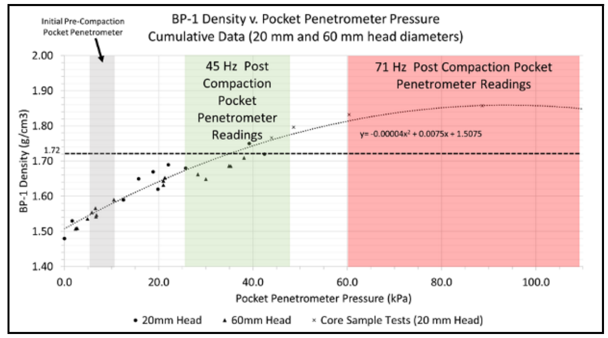

Figure 3. Pocket penetrometer correlation curve with curve fit trendline with polynomial equation.

Relative densities were calculated based on a minimum density of 1.27 g/cm^3 and maximum density of 1.86 g/cm^3 for BP-1 [2]. Similar values of 1.27 g/cm^3 to 1.86 g/cm^3 were used for LHS-1 [3].

Results: The tests revealed the PACT system to be capable of achieving 80% relative density (%RD) in BP-1 and LHS-1 using the dual-mass motor. shows some of the test results. Testing showed that the Spot compaction method was more capable of compaction at depth (below 51 mm) than the Raster method. Several other conclusions were made including that higher static compaction pressure improved compaction at depth, and that longer surface contact times provided diminishing returns on compaction performance. A consistent correlation between the ambient testing in LHS-1 performed as part of this test campaign and previous work performed in-vacuum conditions using LHS-1.

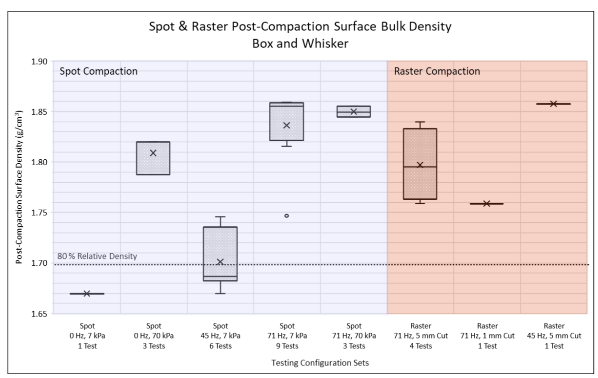

Figure 4. Spot and Raster post-compaction surface bulk density for dual-mass motor 71 and 45-Hz frequencies in BP-1 tests.

References: [1] Bell, Eduardo, et al ntrs.nasa.gov/citations/20240004381 [2] Suescun-Florez, Eduardo, et al. (2015) J. Aero. Eng., 28.5, 04014124. [3] Long-Fox, Jared M., et al. (2023) Adv. Space Res., 71.12, 5400-5412.