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DEVELOPMENT AND TESTING OF A LOW MASS VIBRATORY LUNAR COMPACTOR

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DEVELOPMENT AND TESTING OF A LOW MASS VIBRATORY LUNAR COMPACTOR

By

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A REPORT

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This report has been approved in partial fulfillment of the requirements for the Degree of MASTER OF SCIENCE in Mechanical Engineering.

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List of Abbreviations

NASA – National Aeronautics and Space Administration

LuSTR – Lunar Surface Technology Research

MTU-LHT-1A – Michigan Technological University – Lunar Highland Terrain – Version 1A

Abstract

NASA and other agencies are working to return to the moon, with the Artemis Program [1]. As a part of this new effort, an emphasis is being placed on having a sustained presence, building lunar bases and other permanent structures. The development of such infrastructure will require the development of civil engineering structures, and site preparation becomes a necessity. The Planetary Surface Technology Development Laboratory is developing a low mass lunar compactor as part of an autonomous site preparation vehicle in partnership with Colorado School of Mines, funded by NASA’s 2021 Lunar Surface Technology Research grant. The low mass lunar compactor utilized vibrated pins which allow for compaction at depth.

This report will discuss the development of this compaction method and hardware through multiple prototype test devices and the relevant results.

1 Background

Terrestrially, site preparation is a fundamental step in most construction efforts, be it roads, buildings, or launch pads. As NASA and other space agencies return their focus to the moon building infrastructure on the moon is an important step in making this new effort sustainable, and it will require site preparation. The lunar environment poses physical and logistical challenges requiring existing technologies developed for use on earth to be adapted or overhauled to remain effective. This is also true for compaction tools; common compaction methods on earth rely on surface compaction and utilize high energy vibration to increase the compaction near the surface. The mass necessary for such systems are costly to launch, and the moon also has 1/6 the gravity of earth reducing the reaction forces available from mass. The need for lightweight efficient systems rules out these devices as they are used today, and a lightweight energy efficient method is called for.

While common terrestrial compaction techniques are inadequate for a lunar application, inspiration can still be drawn from terrestrial techniques. The proposed design is similar in principle to vibroflotation, a compaction technique that uses a large vibrating probe that pushes several meters into soil under its own weight. During the process the compactor is raised in steps and backfilled with additional material [2]. This method is used to create compacted columns as a part of foundations, notably not typically used for surface compaction. Another source of inspiration comes from the Netherlands delta project, where specialized compaction equipment was developed in the form of the “Mytilus” ship, which was used to create an underwater foundation. The Mytilus compactor consists of a row of large, vibrated needles creating a compacted surface rather than singular columns [3].

This need is called for in NASA’s LuSTR 21 grant [4], which is funding this project. The call requires that 90% relative compaction be reached to a depth of 30 cm on a 10 m diameter site, simulating a lunar launch pad. Apollo mission data (Table 1-1) has given a glimpse at the existing density profile on the lunar surface and 90% compaction is achieved naturally at only 30 cm depth [5]. The grant calls for the total vehicle mass of 83 kg to simulate a 500 kg vehicle in 1/6 g.

Table 1-1 Summary of apollo data [5]

Depth Range [cm]	Average Bulk Density [g/cc]	Average Relative Density
0 - 15	1.50 ± 0.05	52 ± 7%
0 - 30	1.58 ± 0.05	64 ± 7%
30 - 60	1.74 ± 0.05	88 ± 7%

2 Design

The explored design utilizes long pins which are vibrated into the soil, like vibroflotation, and like the Mytilus ship uses an array to compact a larger area at once. The scale of the design is considerable smaller, only needing to reach approximately 30 cm depth. This method also demands more attention be given to the surface to avoid loosening the top surface when needles are retracted. A plate applies a downward force to provide a bounded surface to aid in compaction, without it the regolith near the surface would fluff and remain uncompacted. A practical lunar compactor would also require independent pins, allowing the compactor to compact surfaces with uneven starting compaction profiles or buried obstacles.

The expected duty cycle of this design is shown in Figure 2-1 Design concept of operation: (1) System stowed at distance from surface, (2) system moves down and pressure plate engages with surface, (3) needles are vibrated and pushed into regolith, (4) obstacle stops individual pin but allows other pins to continueBeginning from a stowed position on a rover (1), the system would then move down and engage with the regolith (2). The surface pressure applied at this point is low to allow the pins to move to depth more easily. The needles are then pushed to the target depth while vibrating (3). The system then moves upwards in a stepwise fashion, the pin tip collapsing the walls so that the compactor can periodically move down to compact the whole surface.

The demonstration and optimization of this design concept has been explored through a series of test setups in the following sections.

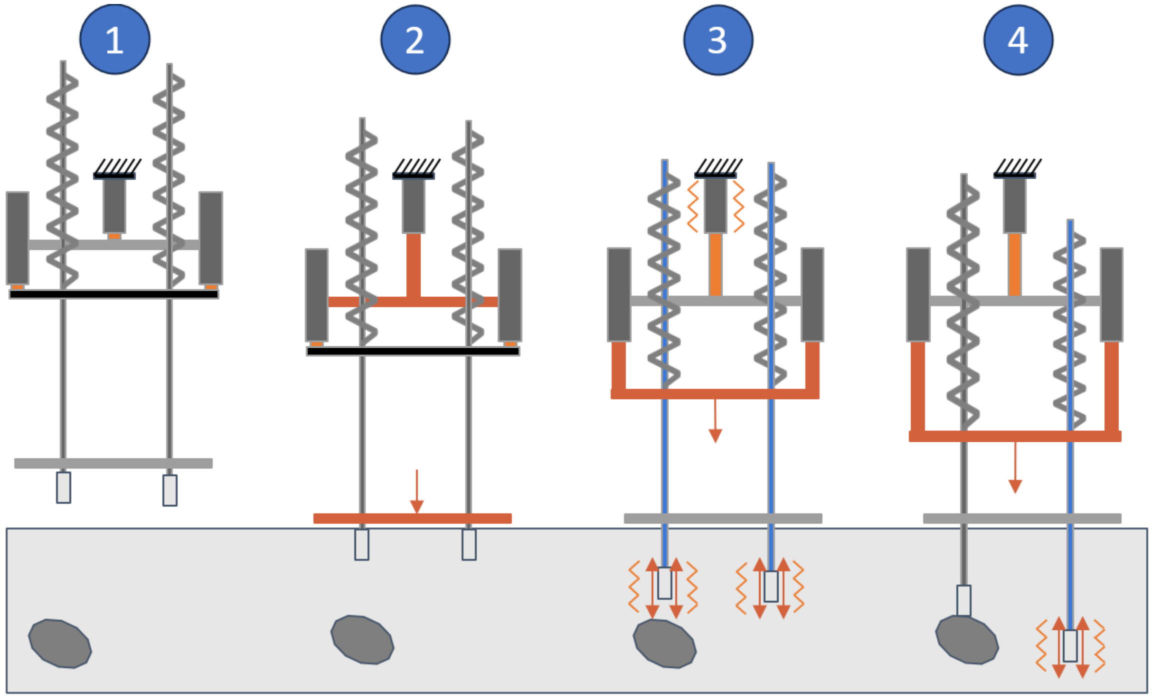

Figure 2-1 Design concept of operation: (1) System stowed at distance from surface, (2) system moves down and pressure plate engages with surface, (3) needles are vibrated and pushed into regolith, (4) obstacle stops individual pin but allows other pins to continue

3 Methods

To accurately reflect the compaction of lunar regolith most testing is conducted with the regolith simulant MTU-LHT-1A [6]. This lunar highlands simulant consists of anorthite, and basaltic scoria produced in house and has a particle size distribution similar to lunar samples. It has a maximum bulk density of 1.87 g/cc and minimum bulk density of 1.28 g/cc, which is used to calculate relative density from measured bulk density.

3.1 Concept Prototype (V1) Testing

The first test setup used, was made of a line of ¼ inch needles with an off the shelf eccentric mass vibrator (Figure 3-1 2D Testing Set-up). This system was held manually and pressed into a narrow test box with transparent windows. This system was initially used to investigate the feasibility effectiveness of the compaction technique. Tests were also conducted with layered colored sand to give a visual indication of the pin's effected radius.

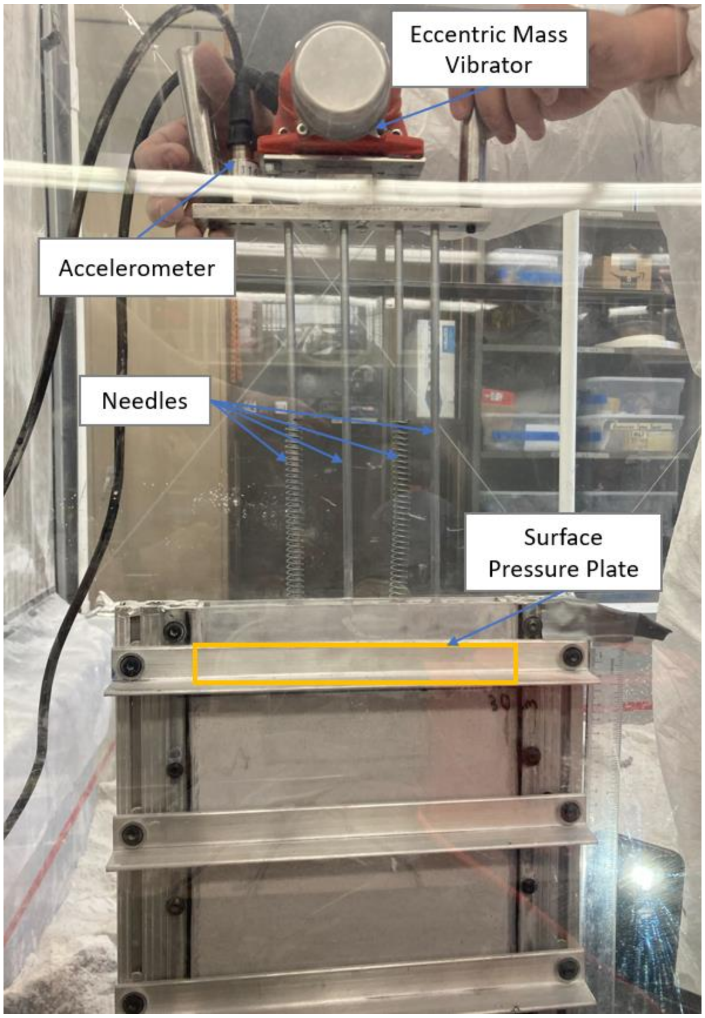

Figure 3-1 2D Testing Set-up

3.2 Surface Compaction Testing

With the limited mass of the system the compaction area will be limited by the reaction forces in the system. A review of sources [5] indicated that static pressure of 100 kPa would be required to compact the regolith to 90% relative density, allowing for only 81cm^2 of compaction area. With a dynamic system increasing the compaction area was thought to be possible so testing was conducted to find the necessary pressure when a vibrating compactor was used. The test rig shown in Figure 3-2 used a simple eccentric mass vibrator sized for a 5-gallon bucket, with a mounting surface to apply increasing levels of mass. For each test the bucket contained 2.4 kg of regolith which was stirred to reduce the compaction state resulting in a layer height of approximately 3 in. The tests used a measured load applied to simulant surface and vibrated for 60 seconds. The resulting surface level was measured and averaged to calculate the achieved compaction. The mass was increased each load until 90% was consistently achieved. The simple system did not allow for the measurement of driven frequency or the amplitude of vibration.

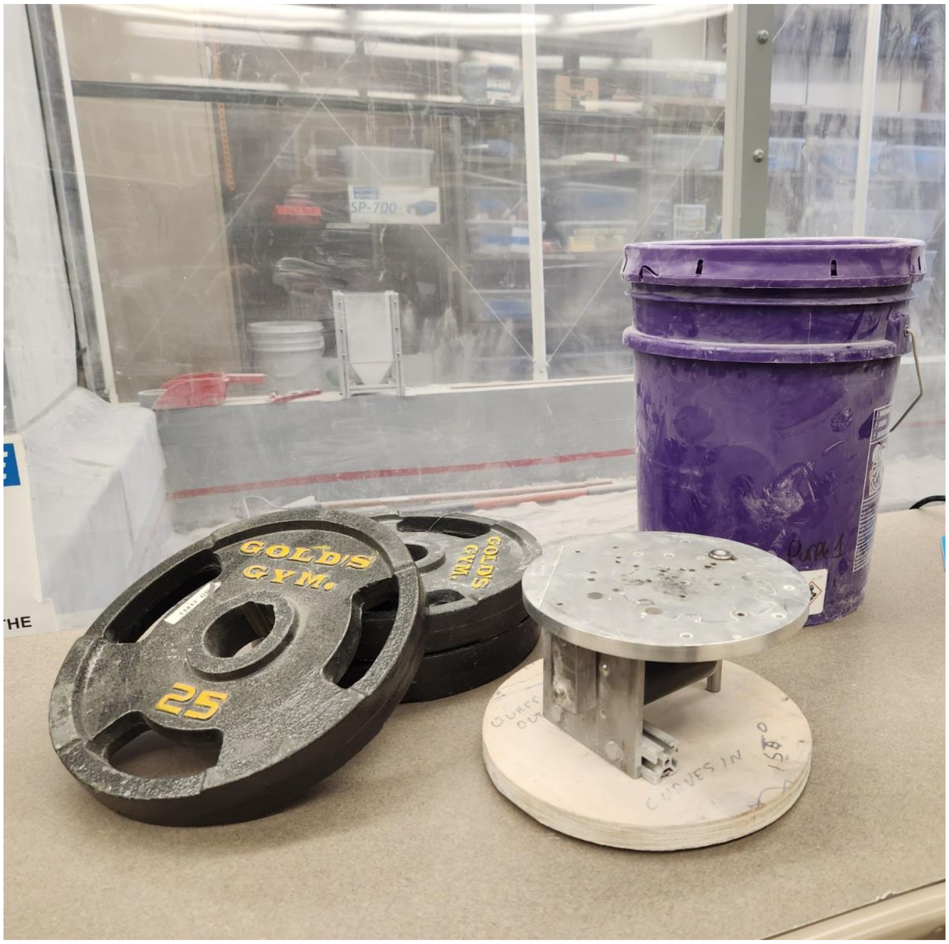

Figure 3-2 Surface pressure testing equipment

3.3 Single Pin Prototype (V3) Testing

The final test stand is a single pin prototype which has been used to optimize operation parameters and test features of a fully realized system (Figure 3-3). This system is again driven by eccentric masses which are embedded in 3D printed gears. The vibration box is fixed to a support bar which limits non-vertical motion. This V1 prototype also included a test for the independent pin concept with the use of a spring, however this feature did not work as expected and inhibited compaction so was removed for the primary test campaign conducted with the system.

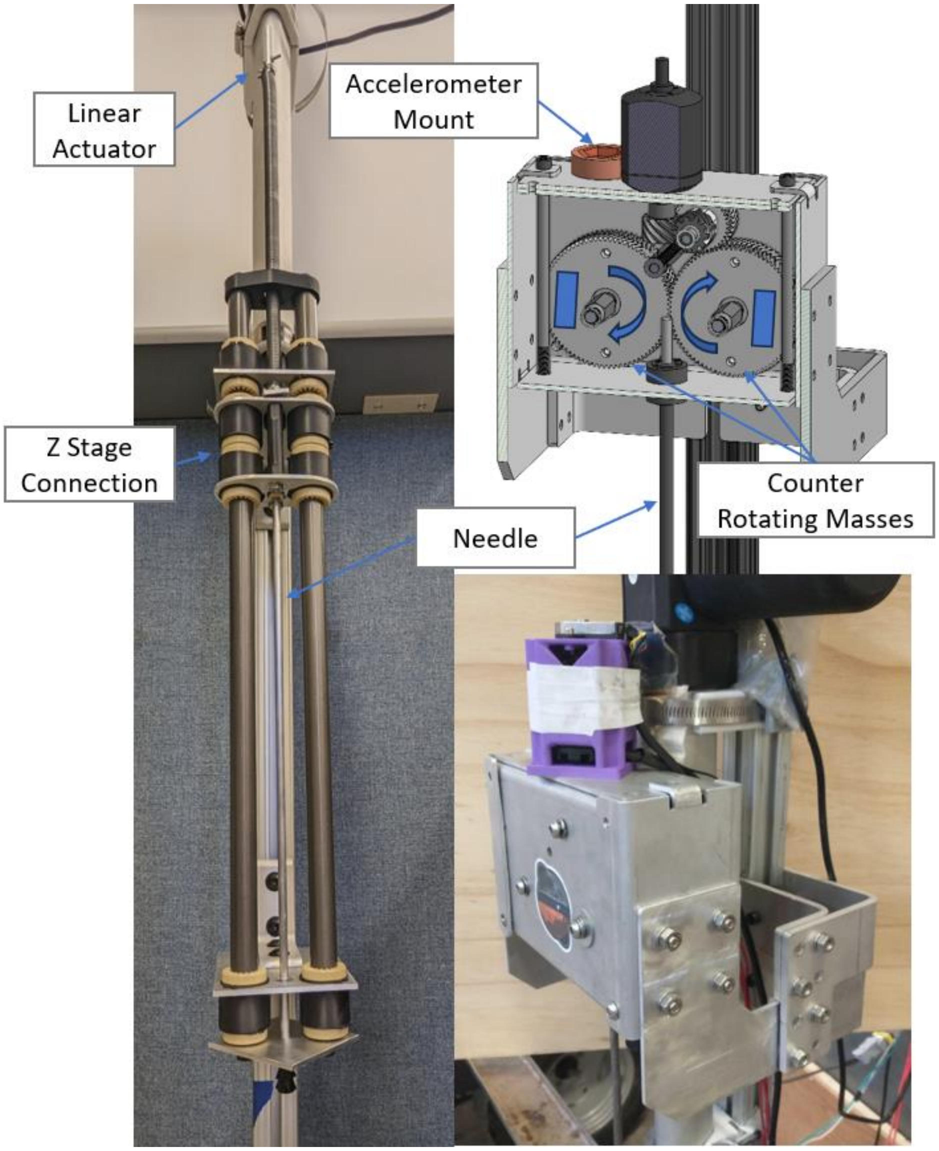

Figure 3-3 Single pin test stand, z-stage (left) vibration unit design (upper right), and vibration unit (lower right)

The primary data of interest is the compaction state. To measure this, tubes of known diameter and mass are filled and pre-compacted to 60% relative compaction as shown in Figure 3-4. After a test run, the mass and column height are measured to determine the bulk density of the test. In addition to compaction data the system has sensors that allow for collection of additional data of interest: an accelerometer mounted to the top of the vibration box sampled at 6400 Hz to collect data on the vertical acceleration; an ac logger attached to the input power line collecting data on power consumption; and system telemetry is outputted from the controller. This additional data is used to optimize the control systems for better results.

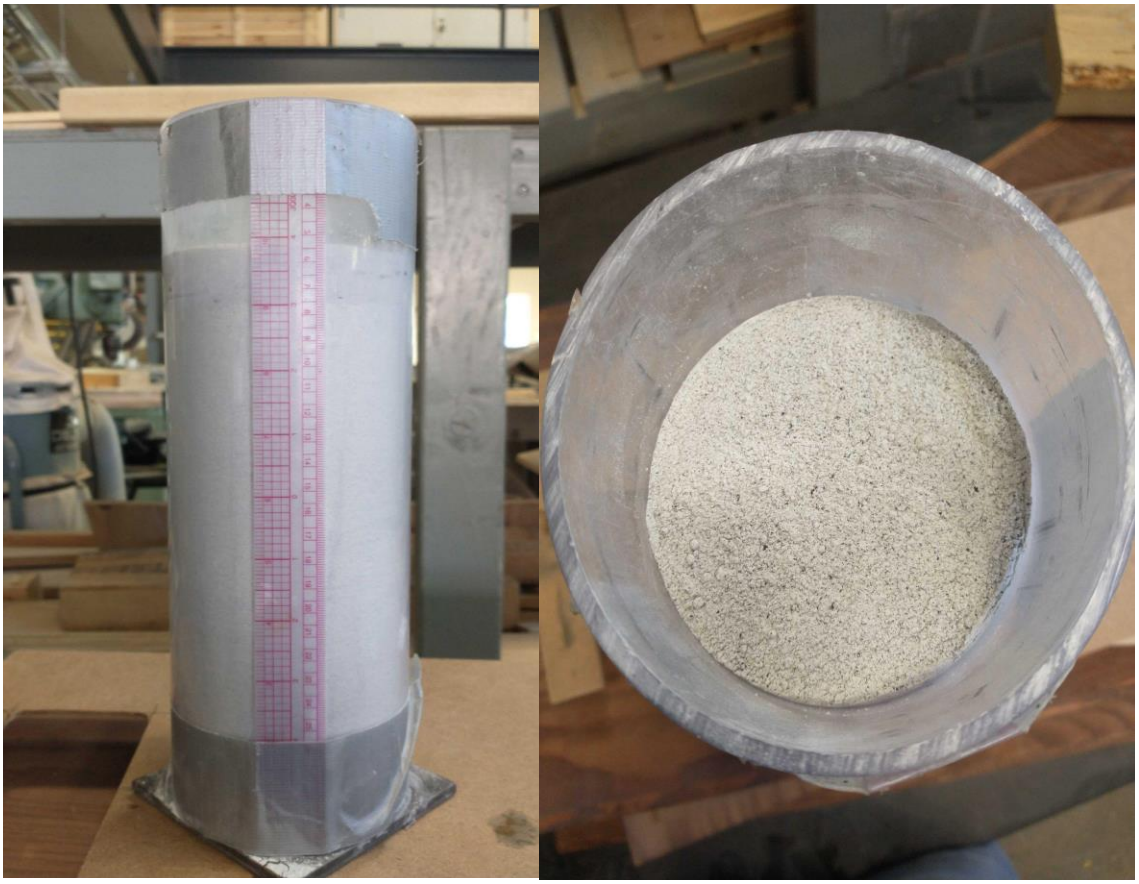

Figure 3-4 Uncompacted regolith sample

3.4 Other Testing Devices

The V2 prototype (Figure 3-5) is notably absent from the discussed prototypes, this device was built to test pin interactions as well as act as a first full scale prototype. However, this prototype has several fatal problems that did not allow for meaningful results. Prototype V2 lacked the space to allow for large enough eccentric masses to make an impact on regolith. In addition, insufficient vibrational isolation led to a significant amount of energy lost to the structure. Finally, the attempted damping to the system provided a weak point in the vertical column which caused the system to buckle when pin was pressed into the regolith. As a result, prototype V3 was built, addressing these concerns, and simplifying the goals to better understand the system fundamentals.

Figure 3-5 Prototype V2

Other compaction efforts have been undertaken in the PSTDL for test bed preparation. Hand-tamping, surface compaction in lifts, and container vibration have been used to prepare regolith for testing. These methods are not feasible for the intended application but are a useful point of comparison.

4 Results

4.1 Prototype V1 Test Results

Initial testing with the 2D test setup resulted in the data shown in Figure 4-1. This device produced compaction only 30-40% overall, and manual probing of the samples indicated that the top surface was consistently less compact than the deeper parts of the sample.

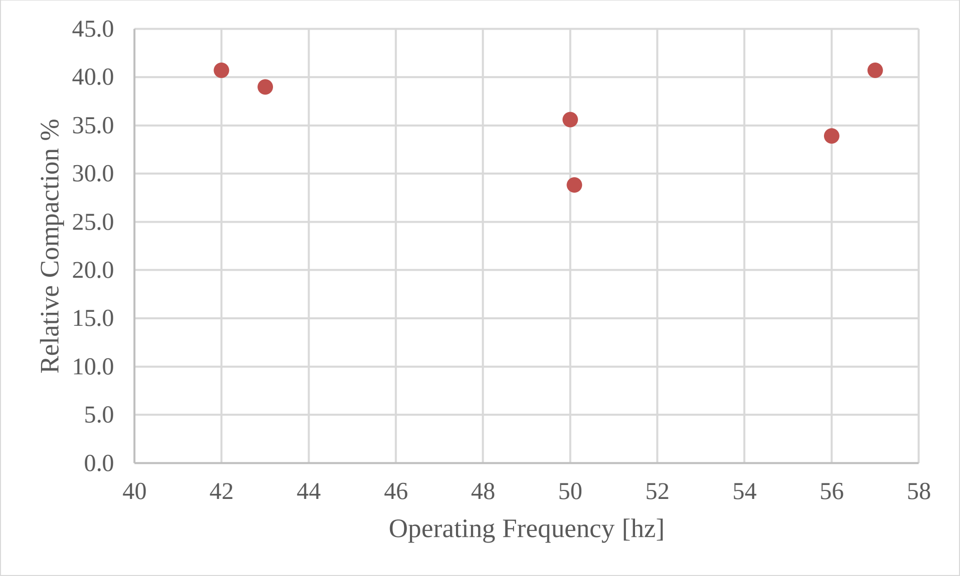

Figure 4-1 2D testing initial results

The second testing campaign for the 2D test setup allowed for a visual analysis of compaction effects on a granular media. Figure 4-2 shows a test sample before and after a test run, it should be noted that the sand had low compressibility and most of the apparent compaction is from bowing of the polycarbonate wall. Testing was afterwords conducted with additional support added to the sides, however no additional effect was seen in the sand during this test.

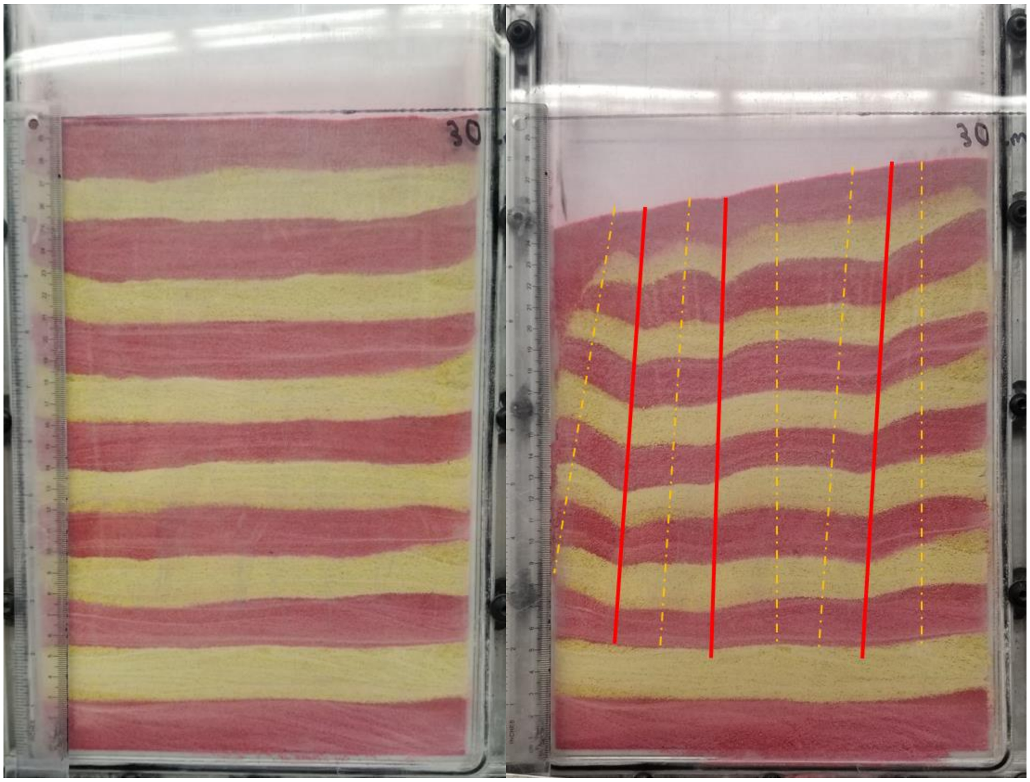

Figure 4-2 Colored sand test sample before (left) and after (right) test

4.2 Surface Vibration Test Results

Table 4-1 indicates the results from the surface vibration testing. After increasing to a pressure of 5493 pascals, the compactor was able to produce 90% compaction on 3 trials and was considered successful.

Table 4-1 Surface testing results

Weight [N]	Compaction Pressure [pa]	Final Density [g/cc]	Final Relative Density [%]
137.2	3596	1.60	55.4%
137.2	3596	1.58	52.9%
230.3	5493	1.83	93.2%
230.3	5493	1.81	89.9%
230.3	5493	1.82	91.5%

4.3 Single Pin Prototype V3 Results

The frequency testing with the single pin test setup is summarized in Figure 4-3. The frequencies of interest are between 20 and 40 Hz, the typical range for terrestrial compaction. Testing was only performed from 20 - 32.5 Hz due primarily to limitations of the driving motor and inefficiencies in the mechanical design, resulting in breaking components. Figure 4-4 shows a typical test tube after a test run. The mounting hardware can clearly be seen as well as divot where the pin had been inserted. This suggests that the pin tip is effectively collapsing the hole until it is near the surface and indicates design changes that could be made to reduce the noise in the surface finish.

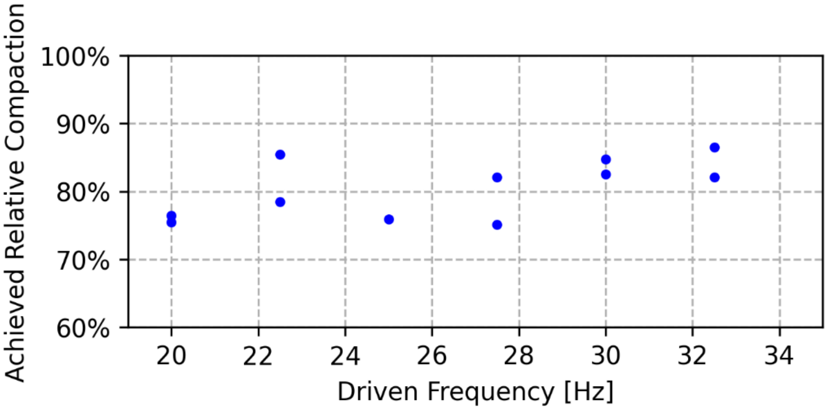

Figure 4-3 Single pin frequency testing results

Figure 4-4 Compacted regolith cylinder (1.76 g/cc or 82.1%)

5 Conclusions

Many of the key take aways from the testing process have been operational and design optimization through iteration in test setups.

The 2D test stand indicated that vibrated pins effectively compact at depth but the top layer remained uncompacted. The arrangement of springs in this design provided the most spring force at depth, and the least near the surface. This indicated that in future design the pressure plate would likely need the most force to be applied at the end of the compaction cycle, which led to separate motion stages on future design iterations. The colored sand testing with the 2D test stand does not give a direct correlation to expected compaction range and effectiveness due to the difference in material, but there is great benefit in understanding the nature of pin effected radius and interaction at depth.

The surface pressure test was specifically made to investigate a single design parameter: surface pressure. The test results indicated that only 5% of the originally indicated pressure would be needed to achieve the target compaction, and thus a much greater area could be used in the final design increasing efficiency of the compaction effort.

The final frequency testing with the single pin test stand has given the best results towards our NASA set goal of 90% relative compaction. Over the course of 11 runs compaction of 80% or greater was consistently reached for frequencies above 30 Hz. While this has not yet reached the target, it is important to compare it to some expected loading conditions. For an apollo sized human landing system (HLS), a landing pad of 90% would expect to experience 1.63 cm of settling where an 80% would lead to 2.62 cm of settling [7]. This suggests that the tool in its current state can bring the lunar surface to a significantly more compact state, that may be effective for many applications. Additionally, this system was not fully optimized and 90% is expected to be possible with appropriate optimization of the run parameters.

Operating the single pin test stand also gave many insights into longevity concerns of some initial design ideas. The motor was not equipped to deal with extended periods of intense vibration it was subject to attached directly to the vibration box. Several mechanical elements initially included to save mass were also found to be problematic under the speed and force of the system namely the screw gear that transferred the motion to the necessary axis.

Table 5-1 summarizes the results of all testing conducted to date. Prototype V3 indicates the best results achieved with this system design and is on par with results seen from hand tamping with 8 times the depth possible. Surface compaction still achieves higher compaction levels, but the timing benefits from triple the depth indicates that the design has great value and will be expected to provide further benefit as it is optimized to achieve higher compaction levels.

Table 5-1 Summary of compaction results

Best Compaction Achieved	Prototype V1	Prototype V3	Hand Tamping	Surface Compaction	Container vibration
Bulk Density [g/cc]	1.51	1.79	1.78	1.83	1.59
Relative Density [%]	41.3	86.5	84.7	93.2	61.4
Layer height [cm]	30	25	3	7	28

6 Future Work

The limitations of the V3 prototype have led to the design and manufacture of a new design iteration (Figure 6-1). The new design implements vibration isolation from the frame as well as the driving motor, reducing energy loss. The design includes similar sensing capabilities as the single pin test setup: power data, acceleration, force, and telemetry data. In addition, the control system is being updated to allow the acceleration to be monitored in real time, such that the changing dynamics of the system can indicate when a target compaction is achieved.

This new test setup has not yet been used for any testing, but plans exist to use this system for a number of test campaigns including investigations of dynamic amplitude with different amounts of off-center mass; effectiveness of spring isolators; system dynamics-based control with the integrated accelerometer; multiple pin arrangements and interactions; and vacuum testing of all parameters. The data collected will allow for the optimization of these parameters on the basis of effectiveness and power efficiency.

Figure 6-1 Variable pin test stand

Additionally, the LuSTR grant requires demonstration of the technology onboard a single lunar construction vehicle. The design and manufacture of a final system for this purpose is underway and will use the results from testing to produce an optimal design.

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