Lunar Site Preparation via Rocket Terrain Autonomous Multi-pulse Preparation (TAMP) Regolith Compaction. J.H. Slavik, E.C. Luken[1] and D. Cortes[2], [1]Astrobotic Technology (1570 Sabovich St. Mojave, CA 93501, Jonathan.slavik@astrobotic.com), [2]New Mexico State University (3035 S Espina St. Las Cruces, NM 88003, dcortes@nmsu.edu).

Concept: Initial lunar landings for upcoming programs such as Artemis and large CLPS missions will require landing pads for dust mitigation [1]. While much effort has been invested in landing pad development, such as sintering and binders, the underlying civil engineering of landing site preparation, including soil compaction, is a prerequisite for the functionality of any landing pad system. To provide a near-term, economical solution for compacting regolith for upcoming lunar missions, Astrobotic's Propulsion and Testing group is developing the Rocket Terrain Autonomous Multi-pulse Preparation (TAMP) system. Rocket TAMP employs a fundamentally different approach to lunar soil compaction than traditional mass-based compactors: namely the reaction force of a rocket engine, fired away from the surface, to impart a compaction force to the lunar soil. Because the reaction force of a rocket engine is not dependent on gravity in the same way as traditional mass-based compactors, the full compaction force developed by a "rocket tamper" can be applied in reduced lunar gravity. This approach provides high performance per unit mass, making Rocket TAMP a practical, near-term, economical solution for compacting regolith for upcoming lunar missions. This mass efficient performance will allow for the future delivery of low energy but high mass equipment for further site development.

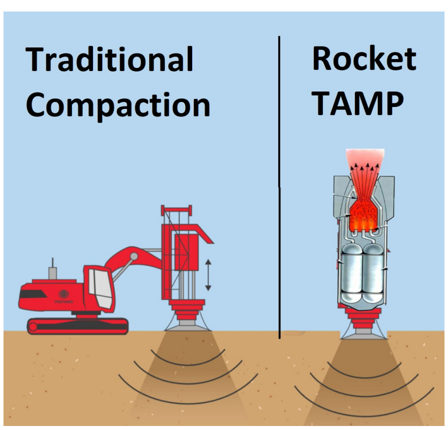

Figure 1: Oscillating mass compactor (left) and Rocket TAMP concept (right)

State of the art: Currently, most lunar construction proposals assume site preparation following terrestrial analogs. involving a sizeable mass to impart a large weight-force to the soil to increase its density by reducing the free-space between soil particles. This force can be static, like a "steamroller," or oscillatory using a vibratory or dropped mass. However, this approach is less advantageous for lunar construction and site preparation. The reduced gravitational acceleration on the Moon means any mass used for compaction will impart 1/6th the compaction force of the same mass on Earth. This has obvious implications for the cost effectiveness of site preparation hardware launched from Earth, but even hardware which uses lunar materials (i.e., using lunar regolith as mass for site prep hardware) will have diminishing returns due to the lower gravity environment. These diminishing returns may be acceptable for long-term applications, but for early construction projects like the Artemis Basecamp, it presents a serious challenge. Rocket TAMP is well suited for early lunar missions as it trades down-mass for fuel consumption and rapid deploy-ability.

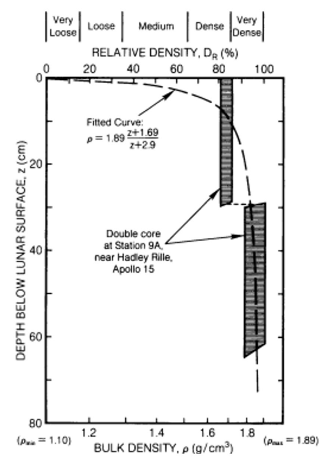

Figure 2: Lunar regolith density vs. depth as measured during the Apollo missions.

Compaction depth: The relative and bulk densities of lunar regolith were measured with in-situ processes during the Apollo missions. A graph of a typical density curve compared to depth measured during Apollo 15 is shown in Figure 2. The relative density of the top 15 cm changes quickly from very loose to dense. From 15 cm to 30 cm, the relative density moves from dense to very dense. Below 30 cm, the relative density increases to more than 85%, meaning the regolith is very dense. This is unique to lunar regolith compared to terrestrial soils. Terrestrial soils typically meet their relative density maximum around 70% [5]. The high relative density on the Moon is achieved from millions of years of impacting, which shift and shake the regolith. Due to this unique density profile, ideally only the top 15 centimeters will need to be compacted on the lunar surface.

Improvements provided by new concept: On earth, soil is compacted with relatively high compaction energy from heavy rollers. Liquid water is also added to aid in the densification process, but this is obviously impractical for lunar applications. The soil type, target density, and depth dictate the type of equipment needed for compaction. The compressive stresses within the soil that arise in response to the static compactor weight decrease with depth. Thus, a surface compactor can only densify a layer of soil immediately underneath it. In general, a 120 kN (12-ton) compactor is only able to densify the uppermost 15 cm of soil. Neglecting the unavailability of liquid water, using a similar target compaction depth of regolith on the lunar surface would require the mobilization of a 75 ton compactor. A more realistic compactor mass for NASA's Artemis Program would be on the order of 0.5 ton. A major challenge in using a light weight compactor on a rover platform is that the effective densification layer may be in the same order of magnitude as the rover-disturbance depth. The interaction between a rover's tires and the surface regolith results in regolith disturbance. Thus, the depth of compaction needs to be sufficiently larger than the disturbance depth.

While the comparison of early lander payload capacity versus required compaction force may seem daunting, it should be noted that first-stage rocket engines routinely produce thrust-to-weight ratios in excess of 100:1, with cutting-edge designs claiming performance over 150:1. While the smaller engine designs appliable to this concept will necessarily have lower thrust-to-weight performance, the required force to compact a sufficient depth of regolith to avoid disturbance by surface operations and construction seems well within the realm of possibility.

Additionally, lack of applied shear force would give Rocket TAMP an advantage compared to a wheeled compaction system, such as a steam roller. This is because a shear force is applied to lunar regolith causes the regolith to dilate, increasing its volume by 20%, thereby lowering its relative density [3]. After the regolith has been dilated, the relative density becomes 30-40%, which is similar to the relative density on crater rims. This dilatancy, or fluffing, is problematic for wheeled systems. This was observed in the Apollo and Luna missions. For example, the Lunar Roving Vehicle (LRV) had to be moved by astronauts after being stuck during Apollo 15, and Lunokhod sank nearly 20 cm near a crater [2]. Mechanical compaction, on the other hand, may return the relative density to 65-75%, similar to terrestrial compaction limits [2]. Dilation for lunar regolith is not thoroughly studied; the only information available is that gained through the Apollo and Luna missions.

Development: The Rocket TAMP system is currently under development via a partnership between Astrobotic Technology's Propulsion and testing group in Mojave, CA, and Dr. Cortes' lab at New Mexico State University. The team at Astrobotic is developing and bespoke rocket system for tamping applications and will integrate a future system onto an Astrobotic rover system for technology demonstration. The team at NMSU is using their MUREP Advancing Regolith-Related Technologies and Education (MARTE) lab to characterize the compaction performance of the Rocket TAMP system in a dirty vacuum environment.

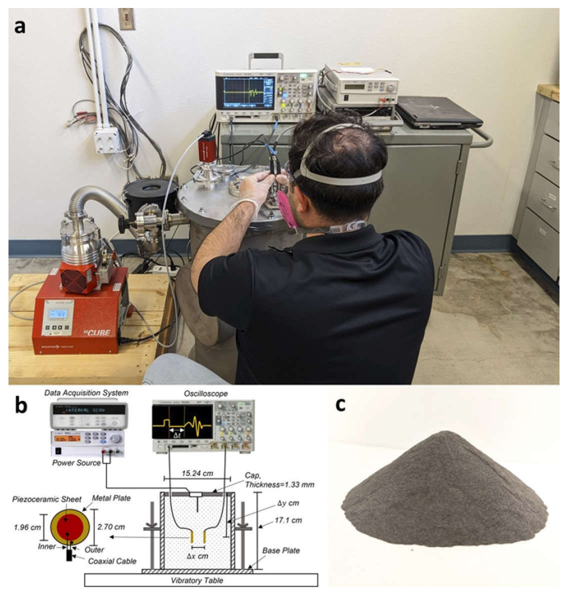

Figure 3:NMSU MARTE Dusty Thermal Vacuum Chamber (a), non-destructive regolith characterization test setup schematic (b), and MARTE Lunar Mare Simulant (c).

References

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