

Compaction trial on lunar regolith simulant

Brendan Scott, Yien Lik Kuo, Mark Jaksa & Akshay Kumar Agarwal

School of Architecture and Civil Engineering, The University of Adelaide, Australia, Brendan.Scott@adelaide.edu.au

ABSTRACT: NASA's Artemis program involves inhabiting the Moon's south pole, which consists of lunar highlands regolith. For successful long-term habitation on the Moon, resilient infrastructure built on lunar regolith will be required. Therefore, it will be essential that the geotechnical characteristics of lunar regolith are quantified and improved, where required, using surface compaction techniques. This study investigates whether lunar highlands simulant could be compacted using a 1:13 scale model impact roller. Surface settlement and density measurements were undertaken to quantify improvement with increasing compactive effort. The results of laboratory testing conducted on lunar highlands simulants are also presented in this paper. The results from this compaction trial indicate that this surface compaction technique can improve the density of lunar highlands simulant, despite it having no moisture.

KEYWORDS: Moon, impact, roller, highlands, simulant.

1 INTRODUCTION

The National Aeronautics and Space Administration (NASA) is planning to return humankind to the Moon and establish the first long-term presence on the lunar surface as part of the Artemis program. As part of the program, permanent bases will be established on the lunar surface in highlands regions near the Moon's south pole (NASA 2019) that were not investigated during previous missions. Long-term habitation will require resilient infrastructure to be built and maintained. To be able to achieve this, the geotechnical properties of the lunar surface need to be quantified and improved as required. The suitability of terrestrial surface compaction techniques requires investigation to determine if they could potentially improve the density of the lunar surface, particularly within the top 0.3 m, which is known to be loose.

Heiken et al. (1991) emphasise that it is crucial to understand the differences between the Earth and the Moon to be able to develop and adapt terrestrial processes for lunar application. Unlike the Earth, which has an abundance of oxygen and more than 60% of its surface covered by water, the Moon is barren of both compounds, and the surface of the Moon is subject to a bombardment of meteoroids due to the lack of any atmosphere (Heiken et al. 1991). Other significant differences include that the lunar surface is subject to much greater thermal changes between day and night, and the Moon's gravitational pull is approximately 1/6th of that of the Earth.

The material that covers the surface of the Moon is referred to as lunar regolith, formed from the unique impact dominated environment of the lunar surface, which can be broadly classified into lowland (mare) and highland regions, formed on basaltic and anorthosite bedrock, respectively (Anbazhagan et al. 2021). Lunar highlands regolith covers approximately 83% of the lunar surface, including the Moon's south pole. Due to the need to preserve the scarce quantities of lunar regolith that were returned to Earth from the Apollo missions for future generations, the development of lunar simulants is essential to facilitate lunar investigations (Taylor et al. 2016).

The Andy Thomas Centre for Space Resources at the University of Adelaide features a unique lunar simulation laboratory that contains a collection of lunar simulants of varying quantities, including those that simulate lunar soils from the highland regions: Lunar Highlands Simulant (LHS-1) and Mixed Anorthosite and Basalt (MAB-1). A comparison of these simulants against actual lunar soil is beyond the scope of this paper but is included in Agarwal et al. (2023).

The purpose of this study is to determine if a lunar highlands simulant can be compacted using an impact roller via the use of a 1:13 scale model compaction trial. An impact roller imparts

energy to the ground via the use of a non-circular module that rotates as it is towed, causing it to fall to the ground and compact it dynamically. This compaction trial is being undertaken at scale, as the test rig is readily available and the quantities of lunar simulant needed are not insignificant. Terrestrial soils with wide ranging gradings and properties have been successfully densified using impact rolling, hence this compaction trial was considered worthwhile to determine if the density of a lunar simulant could also be improved.

2 LUNAR SIMULANTS

The Mixed Anorthosite and Basalt (MAB-1) simulant and the Lunar Highlands Stimulant (LHS-1) are 99% similar in terms of their mineral composition. The 1% difference can be attributed to MAB-1 missing ilmenite, olivine and pyroxene. Further detail on the lunar simulants used in this study, and others, is provided by Agarwal et al. (2023). Both simulants are sourced from the University of Central Florida in the United States; however, the cost to obtain the LHS-1 simulant is nearly 6 times that of MAB-1. The compaction trial that is described in this paper required the use of a large quantity of material (nearly 1-tonne), and it was deemed that the difference in mineralogy between the two simulants was not significant given the scope of the compaction trial and the cost premium involved. It was decided to undertake geotechnical tests of relevance to the proposed compaction trial to confirm the similarity between the two simulants.

2.1 Particle size distribution

Particle size distribution testing was undertaken in accordance with AS 1289.3.6.1 (Standards Australia 2009) and AS 1289.3.6.3 (Standards Australia 2020), on coarse- and fine-grained sized particles, respectively. The test results in Figure 1 confirm the physical similarities between the MAB-1 and LHS-1 simulants. Both the LHS-1 and MAB-1 simulants can be classified as a Silty Sand (SM) in accordance with AS 1726 (Standards Australia 2017a).

2.2 Density and specific gravity

The minimum and maximum densities of both the LHS-1 and MAB-1 simulants were obtained in accordance with AS 1289.5.5.1 (Standards Australia 1998). The specific gravity of solids for both simulants was determined in accordance with AS 1289.3.5.2. (Standards Australia 2002). As shown in Table 1, the minimum and maximum densities, and specific gravity, for the MAB-1 and LHS-1 simulants are comparable, which can be

attributed to their similar particle size distributions and mineral composition.

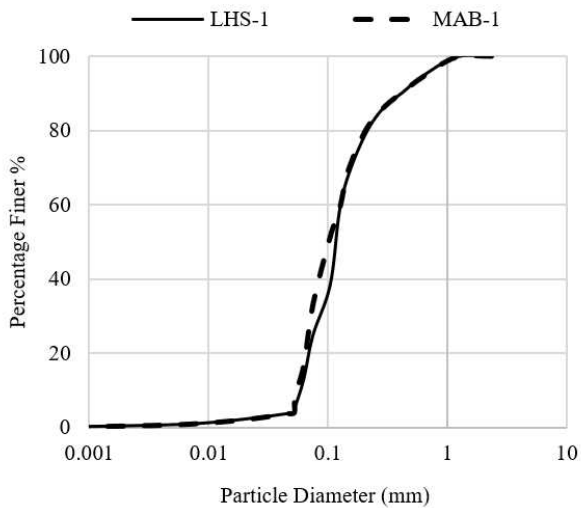


Figure 1. Particle size distribution curves for LHS-1 and MAB-1.

Table 1. Simulant properties.

Simulant	Min. Density (t/m ³)	Max. Density (t/m ³)	Specific Gravity
LHS-1	1.47	2.02	2.81
MAB-1	1.45	2.00	2.79

Standard Proctor compaction testing was undertaken in accordance with AS 1289.5.1.1 (Standards Australia 2017b) on the LHS-1 and MAB-1 simulants. In addition to the Standard Proctor test, a reduced energy Proctor test with a drop height of 50 mm (i.e. 1/6th of the standard drop height of 300 mm) was also undertaken on each simulant to simulate the Moon’s gravity (1.62 m/s²) being approximately 1/6th of that of the Earth (9.81 m/s²). The results in Table 2 indicate that similar densities were achieved for both simulants, indicating that MAB-1 would exhibit similar compaction properties to LHS-1.

Table 2. Proctor compaction test results.

Simulant	Drop Height (mm)	Max. Dry Density (t/m ³)
LHS-1	50	1.82
LHS-1	300	1.87
MAB-1	50	1.78
MAB-1	300	1.85

3 COMPACTION TRIAL METHODOLOGY

Two different placement densities were adopted in this trial to determine the extent to which this surface compaction technique could improve the density of lunar simulant. Two bins, each 0.75 m wide by 1.06 m long by 0.35 m deep were used in this trial. The MAB-1 simulant was placed at two different initial densities of 1.65 and 1.72 t/m³, corresponding to simulant masses of approximately 459 and 479 kg, in each bin respectively. When comparing to the results in Table 1, the initial placement densities correspond to approximately 60% and 73% relative density, respectively.

The placement of the MAB-1 simulant into each bin was undertaken using 10 litre buckets, such that the exact mass of simulant was known in each bin. The simulant was placed in nominal layers of no greater than 50 mm thickness, so that a uniform placement density (or as close to it as possible) could be achieved. This was a slow and tedious task, and one that was made more difficult by dust that was generated from the placement process. Unlike a typical earthworks project on Earth, the material had to be placed completely dry, consistent with the absence of moisture on the Moon. Appropriate personal protective equipment (safety glasses, masks, coveralls and gloves) was needed for this task. Placement of the material and tamping (as shown in Figure 2) was undertaken below a plastic sheet for dust suppression.



Figure 2. Placement of MAB-1 simulant prior to compaction.

Figure 3 shows the 1:13 scale model impact roller used for this compaction trial. The scale model used in this trial is a replica of the 4-sided, 8-tonne Broons BH-1300 impact roller, which at 1:13 scale has a mass of 3.64 kg. The model is towed around the test rig using a chain-driven carriage that is powered by a variable speed motor. More information on the scale model test rig used in this compaction trial is described by Chung et al. (2017).

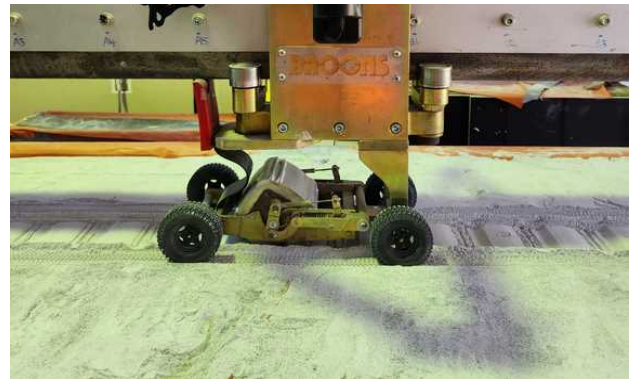


Figure 3. 1:13 scale model of the 4-sided, 8-tonne impact roller.

To quantify improvement with increasing compactive effort, surface settlements and density measurements were both undertaken. Two different techniques were used to quantify surface settlements, the first involved a simple physical technique of measuring surface settlement using a tape measure relative to a datum as shown in Figure 4. This technique was undertaken after every pass with five measurements taken within each bin, from which a median value was adopted.

The second technique involved the use of a hand-held 3D surface scanner (EinScan Pro+) as used by Jaksa et al. (2019) and Chen et al. (2021) to provide measurements of the compacted surface in high resolution, with the distance between points being

only 0.2 mm in high resolution mode (Shining 3D 2019). As shown in Figure 5, this technique involved a 3D scan of the compacted test lane, surrounded by flat plates at each end and reference mats top and bottom (with markers on them) to help determine orientation during post-analysis. Each scan typically collected thousands of data points that captured the undulating surface left by the impact roller (as typically shown in Figure 3). A software program, *LS PrePost*, was used to align all the scans to a single reference plane to enable scans of incremental passes to be overlaid on top of each other and compared. The 3D scanner technique was able to capture the low and high points of the ground surface, as typically shown in Figure 6, which were then averaged to obtain a single value. The 3D scanner technique was undertaken at regular pass intervals so that a relationship between surface settlement and number of passes could be generated using this technique.



Figure 4. Surface settlement monitoring using physical measurements.

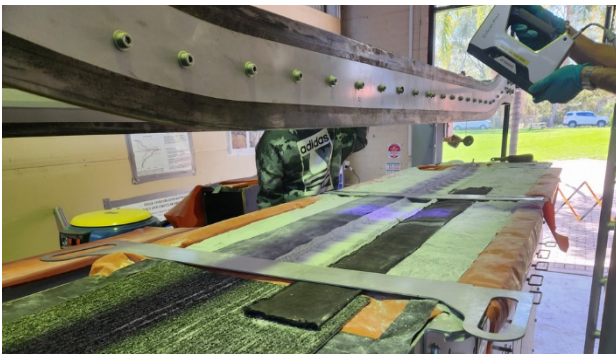


Figure 5. Surface settlement monitoring using 3D scanner.

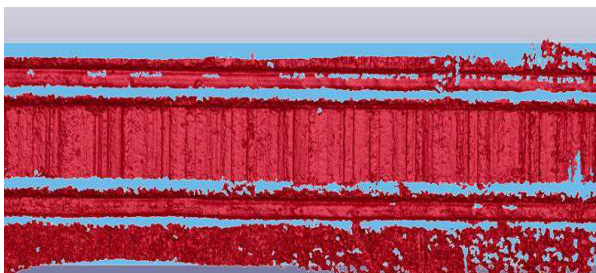


Figure 6. Scanned surface in software program *LS PrePost*.

A Humboldt HS-5001SD nuclear density gauge, as shown in Figure 7, was used to quantify changes in density in accordance with AS1289.5.8.1 (Standards Australia 2007). The gauge was

calibrated for test depths of 50, 150 and 300 mm, and was used to measure density after intervals of 0, 10, 30 and 60 passes.



Figure 7. Nuclear density testing at 0 passes.

4 RESULTS

Figure 8 shows a plot of settlement versus number of passes for the soil bin with an initial placement density of 1.65 t/m³. It can be observed in Figure 8 that the changes in settlement reduced with increasing passes for both the 3D scanner and physical measurement techniques used. The greatest change in settlement occurred within the first 20 passes. As explained by Scott et al. (2016), plotting settlement versus number of passes helps to identify a point on the graph (pass number) beyond which effective refusal is reached and that the time and cost involved with imparting greater compactive effort would not be worthwhile. From Figure 8, it can be observed that regardless of which technique is considered, the majority of surface settlement occurred within the first 40 passes, suggesting that this would be an appropriate number of passes to adopt given the 350 mm thickness of material tested in this trial.

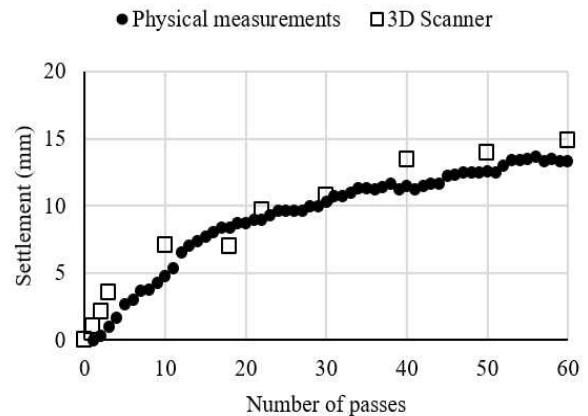


Figure 8. Surface settlement versus number of passes using both physical and 3D scanner measurement techniques.

Density test results are shown in Figure 9 for the soil bin with an initial placement density of 1.65 t/m³. The 0 pass results vary between 1.63 and 1.66 t/m³, indicating that a uniform placement density (or as reasonably close as practical to it) was achieved. The results at 50 and 150 mm depths indicate improvement in density with increasing passes, however, at 300 mm depth, there is no distinguishable improvement, suggesting that this is beyond the depth of influence of the 1:13 scale model impact roller.

As per the work of Chen et al. (2021), it is possible to upscale the results obtained from the 1:13 scale model testing to the full-

size impact roller. However, the focus of this trial was to test proof-of-concept for this type of surface compaction, with the test results indicating that an impact roller is able to improve the density of lunar simulant, despite it having no moisture.

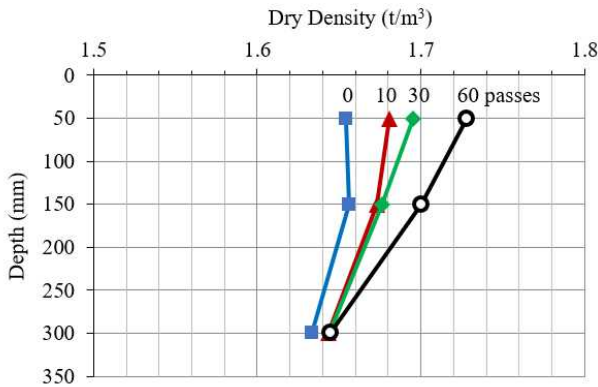


Figure 9. Dry density versus depth for varying passes.

5 CONCLUSIONS

The results from this study indicate that the MAB-1 simulant has similar physical and compaction properties and is a cost-effective substitute for the LHS-1 simulant.

The results from this compaction trial confirm that impact rolling, a terrestrial ground improvement technique, is able to compact completely dry lunar simulant. The authors chose not to upscale the results from this trial to the full-size (BH-1300) impact roller because it would not be practical from a payload perspective for an 8-tonne concrete filled, steel encased module to be transported to the Moon. A shell of a module that could be filled in situ with lunar regolith may be a more realistic option. However, a factor that is more likely to determine if impact rolling has off-world application will be dictated by the capabilities of rover towing units. Innovations are continuing to evolve and are likely to govern the physical characteristics of any surface compaction technique that may be used in an off-world lunar environment in the future. It is planned to undertake further comparative research studies on alternative surface compaction techniques to determine their efficacy for improving the density of lunar simulants.

The relatively large quantity of simulant used in this compaction trial highlighted the issue of dust control. Unlike terrestrial earthwork projects where water is used for dust suppression, it was found that working with a completely dry lunar simulant required thin layers to be adopted during placement. Additionally, the use of a plastic sheet to cover the simulant during placement and tamping was an effective dust control measure, combined with the use of personal protective equipment.

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7 REFERENCES

- Agarwal, A. K., Kuo, Y. L., Jaksa, M. B. and Scott, B. T. 2023. Density, strength and compressibility characteristics of lunar regolith simulant. *Proc. 14th Australia and New Zealand Conference on Geomechanics*, Cairns, Australia.
- Anbazhagan, S., Venugopal, I., Arivazhagan, S., Chinnamuthu, M., Paramasivam, C.R., Nagesh, G., Kannan, S.A., Shamarao, Chandra Babu, V., Annadurai, M., Muthukkumaran, K. and Rajesh, V.J. 2021. A lunar soil simulant (LSS-ISAC-1) for the lunar exploration programme of the Indian Space Research Organisation. *Icarus*, <https://doi.org/10.1016/j.icarus.2021.114511>.
- Chen, Y., Jaksa, M., Kuo, Y. and Airey, D. 2021. Experimental Analysis of Rolling Dynamic Compaction Using Transparent Soils and Particle Image Velocimetry. *Canadian Geotechnical Journal*, <http://dx.doi.org/10.1139/cgj-2020-0573>.
- Chung, O.Y., Scott, B., Jaksa, M., Kuo, Y.L. and Airey, D. 2017. Physical modelling of rolling dynamic compaction. *19th Int. Conf. Soil Mech. Geo. Engrg.* Seoul, Korea, 905-908.
- Heiken, G.H., Vaniman, D.T., & French, B.M. 1991. *Lunar Sourcebook, a user's guide to the Moon*.
- Jaksa, M. B., Airey, D. W., Scott, B. T., Kuo, Y. L., Ranasinghe, R. A. T. M., Bradley, A. C., Chung, O. Y., Li, Y. and Chen, Y. 2019. Quantifying the Effect of Rolling Dynamic Compaction. *Proc. 4th World Congress on Civil, Structural, and Environmental Engrg.* Rome, Italy. doi: 10.11159/icgre19.1.
- NASA. 2019. Moon's South Pole in NASA's Landing Sites. Available from <https://www.nasa.gov/feature/moon-s-south-pole-in-nasa-landing-sites> accessed 2 February 2023.
- Scott, B.T., Jaksa, M.B. and Syamsuddin, E. 2016. Verification of an impact rolling compaction trial using various in situ testing methods. *Proc. 5th Int. Conf. Geotechnical and Geophysical Site Characterisation*. Australian Geomechanics Society, Gold Coast, 735-740.
- Shining 3D. 2019. EinScan-Pro series user manual version 3.3.0.0. Available from <https://it3d.com/wp-content/uploads/download-files/manual/en/EXScan-Pro-User-Manual-V3.3.0.2.pdf> accessed 29 August 2022.
- Standards Australia. 1998. Methods of testing soils for engineering purposes, Method 5.5.1: Soil compaction and density tests - Determination of the minimum and maximum dry density of a cohesionless material - Standard method, AS 1289.5.5.1. Standards Australia, Sydney, Australia.
- Standards Australia. 2002. Methods of testing soils for engineering purposes, Method 3.5.2: Soil classification tests - Determination of the soil particle density of combined soil fractions - Vacuum pycnometer method, AS 1289.3.5.2. Standards Australia, Sydney, Australia.
- Standards Australia. 2007. Methods of testing soils for engineering purposes - Soil compaction and density tests - Determination of field density and field moisture content of a soil using a nuclear surface moisture-density gauge - Direct transmission mode, AS 1289.5.8.1. Standards Australia, Sydney, Australia.
- Standards Australia. 2009. Methods of testing soils for engineering purposes, Method 3.6.1: Soil classification tests - Determination of the particle size distribution of a soil - Standard method of analysis by sieving, AS 1289.3.6.1. Standards Australia, Sydney, Australia.
- Standards Australia. 2017a. Geotechnical site investigations. AS 1726. Standards Australia, Sydney, Australia.
- Standards Australia. 2017b. Methods of testing soils for engineering purposes, Method 5.1.1: Soil compaction and density tests - Determination of the dry density/moisture content relation of a soil using standard compactive effort, AS 1289.5.1.1. Standards Australia, Sydney, Australia.
- Standards Australia. 2020. Methods of testing soils for engineering purposes, Part 3.6.3: Soil classification tests - Determination of the particle size distribution of a soil - Standard method of fine analysis using an hydrometer, AS 1289.3.6.3. Standards Australia, Sydney, Australia.
- Taylor, L.A., Pieters, C.M. and Britt, D. 2016. Evaluations of lunar regolith simulants. *Planetary and Space Science*. <http://dx.doi.org/10.1016/j.pss.2016.04.005>.