LUNAR LOW-DENSITY (LLD-1) REGOLITH SIMULANT DEVELOPMENT. K. Šļumba[1,*], W. Foster-Hall[1], K. Farries[1], R. Muir[1], Y. L. Kuo[1], D. J. Harvey[1], and B.T. Scott[1], [1]Andy Thomas Centre for Space Resources, Adelaide University, SA 5005, Australia, [*]karlis.slumba@adelaide.edu.au

Introduction: A well-known limitation for large scale gravity offloaded experiments is that it is extremely challenging to offload regolith. The most obvious technique for gravity offload of regolith simulant is parabolic flight testing, e.g. [1], which is expensive and has significant testing time limitations. Another novel option is using a magnetic simulant in a strong magnetic field that is opposite to the gravity field, but this technique has not been tested on a large scale, and there are concerns that it does not produce homogeneous effects in large areas [2].

There have been previous attempts to capture some properties of gravity offloaded regolith simulant, either by having the regolith simulant less compacted to capture frictional properties [3] or to make regolith simulants with reduced particle density [4].

The goal of this research was to develop a lunar regolith simulant capable of producing a representative response for dynamic testing of a gravity offloaded rover. The new regolith simulant was made to have six times lower bulk density than other lunar regolith simulants while keeping the particle size distribution in the Apollo range [5]. This would be a new category of regolith simulants with reduced bulk density that could be used in gravity offload testing on Earth, where the rover would be gravity offloaded, and the regolith simulant would be reduced density. The hypothesis being that such a regolith simulant would behave similarly to regolith in lunar gravity. The new lunar low-density (LLD-1) regolith simulant is shown in Figure 1.

Figure 1. Lunar low-density (LLD-1) regolith simulant.

Several lightweight granular materials were tested, and the best candidate was empirically selected based on the minimum density achieved. Materials were sourced from Australian suppliers. The LLD-1 regolith simulant was produced from exfoliated perlite grains, which were milled down to a desired minimum bulk density and particle size distribution. LLD-1 particles fall through a 1.32 mm sieve.

Results: Some of the results from the geotechnical testing campaign are presented here: min-max density, particle density, particle size distribution using both sieves and laser dispersion, and angle of repose. The same tests were also performed with other well-known regolith simulants: LHS-1E and LHS-1 [6,7].

Minimum and maximum densities were measured according to AS 1289.5.5.1 [8] results are in Table 1. The minimum density of LLD-1 was measured as 229 kg/m^3, while LHS-1E was measured as 1450 kg/m^3 ny Agarwal et al. 2023 [7], resulting in a minimum density ratio of 6.33 as calculated with Eq. 1.

$$r = \frac{\rho_{LHS-1E}}{\rho_{LLD-1}} \quad (1)$$

The maximum density of LLD-1 was measured as 396 kg/m^3, and LHS-1E was measured as 2000 kg/m^3 [7], resulting in a maximum density ratio of 5.05.

The minimum densities of Apollo 14, 16, and Luna 20 lunar highlands 5-10 gram samples were between 1040 - 1200 kg/m^3, while the maximum densities were between 1700 - 1800 kg/m^3 [5]. It should be noted that these measurements were made on very small sample sizes and using test methods which are not directly comparable with this study.

Table 1. Bulk density and ratio of LLD-1 and LHS-1E.

Simulant	ρ_{min} kg/m^3	$\rho_{10\%}$ kg/m^3	$\rho_{25\%}$ kg/m^3	ρ_{max} kg/m^3	ρ_{grain} kg/m^3
LLD-1	229	239	256	396	1940
LHS-1E	1450	1491	1557	2000	2770
Ratio	6.33	6.24	6.08	5.05	1.43
Relative density	0%	10%	25%	100%	*n/a*

It is challenging to place regolith simulant in a large rover test bed at its minimum density because it gets compacted as it is being placed. Realistically, the lowest relative density (*RD*) in large scale experiments is between 10 and 25%, as calculated from Eq. 2 [5], which gives a density ratio between 6.08 and 6.24.

$$RD = \frac{\rho_{max}}{\rho} \cdot \frac{\rho - \rho_{min}}{\rho_{max} - \rho_{min}} \cdot 100\% \quad (2)$$

Taking the gravity acceleration on Earth from definition at 45° latitude of 9.806 m/s^2, and lunar average gravity acceleration of 1.625 m/s^2 from Hirt et al. [9], the average ratio between Earth's and Lunar gravity accelerations is around 6.035.

Particle density was measured according to ASTM D854-23 [10] with a pycnometer by saturating particles with water. LLD-1 and LHS-1E particle densities were

1940 ± 12 and 2770 ± 10 kg/m^3, respectively. For comparison, Apollo samples from the lunar highlands were in the range of 2200 to 2810 kg/m^3 [11].

The ratio between LHS-1E and LLD-1 particle densities is 1.43. Macroporosity of LLD-1 is between 0.80 and 0.88, void ratio is between 3.90 and 7.47. Macroporosity of ~1 gram Apollo 14 samples was 0.47 - 0.70, and the void ratio was between 0.90 and 2.33 [5]. More measurements on lunar samples would be necessary for the results to be comparable, but it seems that LLD-1 has higher porosity.

Particle size distribution was measured with a Malvern Mastersizer laser diffraction instrument. The results of LLD-1, LHS-1, and LHS-1E are shown in Figure 2. The particle size distribution of LLD-1 is in good agreement with other regolith simulants and Apollo samples.

Particle size distribution of LLD-1 cannot be measured using dry sieving techniques, as the light particles clump together and do not fall through fine sieves under their own weight, this is shown as the purple dashed line in Figure 2.

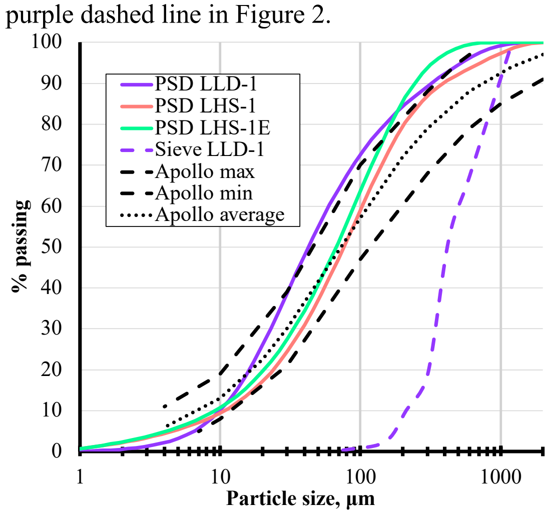

Figure 2. Particle size distribution

Angle of repose was measured using a similar setup to Easter et al. 2024 [12]. Tests on LHS-1 and LHS-1E were done with 500 gram samples. Tests on LLD-1 were done with 50, 100, and 200 gram samples, as 500 gram samples would take too much volume for this setup. All samples were oven dried. Three different values were recorded as shown in Table 2 and Figure 3. The average angle of repose is the average slope of the pile. Static and dynamic angles are the steepest angles formed before and after an avalanche, respectively. LHS-1 results show good agreement with Easter et al. 2022 and 2024 [12,13], given the stated error ranges. LLD-1 results show slightly steeper angles for all sample sizes than LHS-1 or LHS-1E. All results are comparable to Apollo findings [5].

Table 2. Angle of repose results. LHS-1 from Easter et al. 2022 and 2024 [12,13].*

Simulant	Mass, g	Average, °	Static, °	Dynamic, °
LLD-1	50	43.8 ± 1.7	49.5 ± 4.0	39.8 ± 5.0
LLD-1	100	41.0 ± 1.4	48.0 ± 1.4	38.3 ± 2.9
LLD-1	200	39.5 ± 1.3	47.8 ± 1.7	38.3 ± 1.3
LHS-1E	500	39.3 ± 0.5	44.3 ± 0.8	37.3 ± 0.5
LHS-1	500	38.6 ± 1.1	43.0 ± 1.8	35.5 ± 3.0
LHS-1*	500	39.8 ± 0.6	41.2 ± 3.9	30.9 ± 4.8

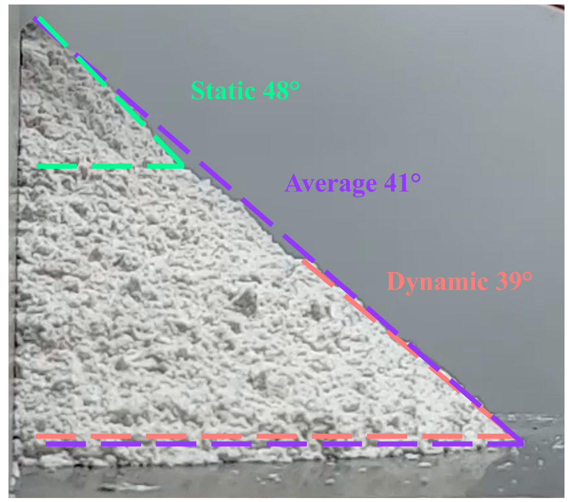

Figure 3. Static, dynamic and average angle of repose of a representative LLD-1 sample.

Conclusions: A lunar low-density (LLD-1) regolith simulant was developed with hypothesis that it will effectively emulate the effects of lunar gravity on regolith for large scale terrestrial dynamic trails with gravity offloaded rovers. The minimum density of LLD-1 is 229 kg/m^3, or 6.33 times lower than minimum density of other lunar regolith simulants. The maximum density of LLD-1 is 396 kg/m^3, or 5.05 times lower than maximum density of other lunar regolith simulants. The particle size distribution and the angle of repose are comparable to Apollo samples and other regolith simulants.

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