Project: CMPCTR

Executive Summary Report

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CHANGE LOG

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CHANGE RECORD

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1   Summary of the achievement

Within this project we have designed, developed and tested the compaction device Breadboard in a regolith simulant Testbed. The experimental test campaign verified that the compaction device can be successfully used to improve the surface geotechnical properties of two different regolith simulants: GreenSpar-250 analogous to lunar Highlands, and AGK-2010 analogous to lunar Mare regions.

The activity verified the compaction as a viable large-scale horizontal construction method on the Moon, as previously proposed in Phillips et al. (1992), and utilized terrestrial analogies (Chen & Fang, 2008) along with best practices (Kwaśniewski et al., 2022) for compaction performance monitoring. The current improved design of the device (TRL 4) is proposed to be further studied and developed for a lunar use-case scenario, as lunar surface exploration capabilities and needs intensify within the following decades.

Design and testing

The device is designed for two modular versions with interchangeable components: CMPCTR-FR-LAB, which is focused on laboratory measurements of compaction performance and categorization of various regoliths based on their acceleration response, and CMPCTR-FR, which is focused on the use-case scenario for lunar large-scale surface construction and site preparation.
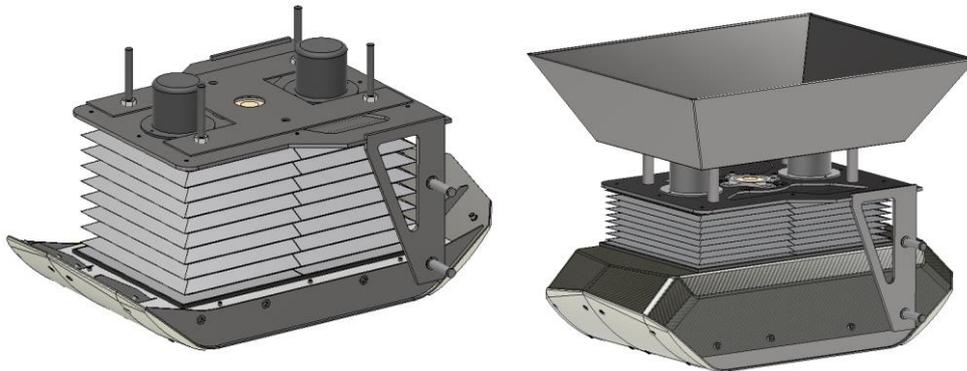

Figure 1. Compactor laboratory (left) and in-situ (right) models.

The laboratory device model was tested in a Testbed equipped with: a regolith sandbox, push-pull capability for mimicking rover mounting and movement, electric box for control and power supply of the BB and TB, Data acquisition computer, and a weather station for monitoring of particulate matter, temperature, humidity and light conditions in the test room.
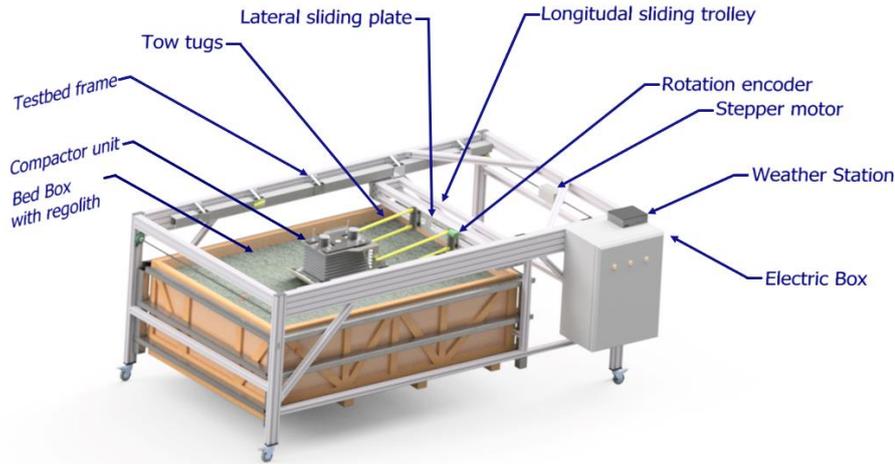
Figure 2. Final design of the BB-TB assembly.

The critical parameter that was measured during the study was the Q-parameter. The Q-parameter is a result of integration of acceleration data in the frequency domain (Kwaśniewski et al., 2022):

$$Q = \int_a^b A(f)df$$

where:

Q – total acceleration response of the material in the frequency range a to b [g Hz or ms^{-2} Hz],
A(f) – Fast Fourier Transform of the measured acceleration data
a, b – integration range: for Q-parameter 1 a = 1 Hz and b = 1500 Hz, while for Q-parameter 2 a = 1500 Hz and b = 4000 Hz

Q-parameters can be assigned to specific known regolith parameters, such as their bulk density, by gathering data from number of tests and categorizing the Q-parameter-regolith relations. That said, this method may be used in general regolith geotechnical measurements in situ

In general, different regoliths were subject to different compaction performance. In average terms this may be summarized as shown in Table 1.

Table 1. Key differences in compaction of tested regoliths.

GreenSpar-250	AGK-2010
The post-test Q1 parameter values increased 2 to 3-fold. Post-test penetration typically yielded values up to 6 to 9 times higher than the initial, e.g. increasing from 4.73 N to 42.43 N.	The post-test Q1 parameter values increased 1.5 to 5-fold. Post-test penetration typically yielded values up to 30 to 100 (!) times higher than the initial, e.g. increasing from 0.75 N to 74 N.
Higher passive compaction on the sides of the Testbed	Lower passive compaction on the sides of the Testbed
Up to 40% density increase near surface (1.25 to 1.75 gcm^{-3})	Up to 46% density increase near surface (1.30 to 1.90 gcm^{-3})
	Differences mainly caused by larger distribution of particle size of the AGK compared to GS-250, resulting in more effective porosity fill and grains interlocking

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Key experimental outcomes

Compaction depth and near surface reaction forces were higher during tests with AGK-2010, which translated to higher Q-parameters. This was attributed mostly to the Particle Size Distribution characteristics between the different simulants.

For lower frequencies (e.g. 15 Hz), higher Q-parameter values can be observed. This is largely attributed to higher impact energies at lower frequencies of vibrations, which result from higher strokes of hammerings.

Higher force settings (amplitude) resulted in higher Q-parameter values, which is expected.

Tests performed with sine profile resulted in lower Q-parameter values than in the corresponding square profile tests. This is attributed to a much smoother stroke characteristics in sine vibrations than in sharp movement of coil in square profiles.

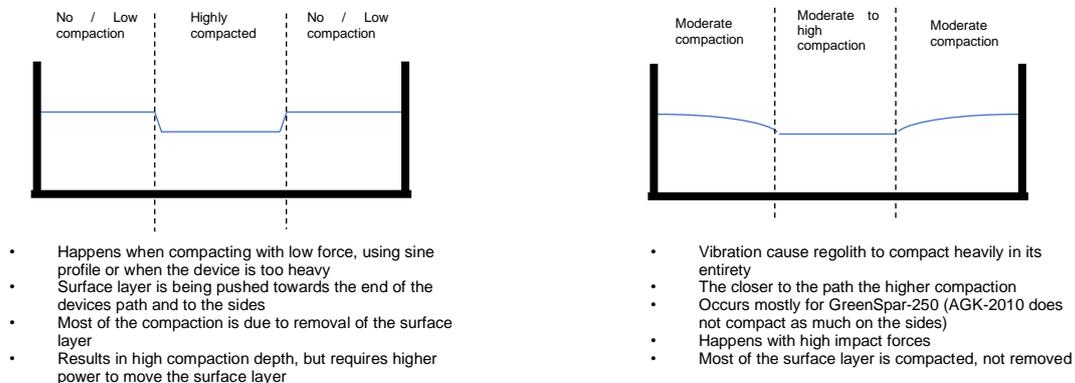The key differences are summarized in Figure 3.

No / Low compaction	Highly compacted	No / Low compaction

- Happens when compacting with low force, using sine profile or when the device is too heavy
- Surface layer is being pushed towards the end of the devices path and to the sides
- Most of the compaction is due to removal of the surface layer
- Results in high compaction depth, but requires higher power to move the surface layer

Moderate compaction	Moderate to high compaction	Moderate compaction

- Vibration cause regolith to compact heavily in its entirety
- The closer to the path the higher compaction
- Occurs mostly for GreenSpar-250 (AGK-2010 does not compact as much on the sides)
- Happens with high impact forces
- Most of the surface layer is compacted, not removed

Figure 3. Key differences in compaction.

Numerical model

Based on the device performance and experimental test results, a numerical model was developed to (1) recreate the acceleration data, (2) compare the test results with the model, (3) develop a tool for replication of regolith densification and surface indentation data, and (4) provide an assessment for device functionality in lunar low gravity.

The simplified numerical model exhibits a satisfactory qualitative correlation with the test results (Figure 4). Specifically, the increase of the accelerations on the body mass is visible as expected, concluding that the assumption for regoliths stiffness increase and damping decrease during compaction is correct and possibly can be fine-tuned accurately in the future if needed.

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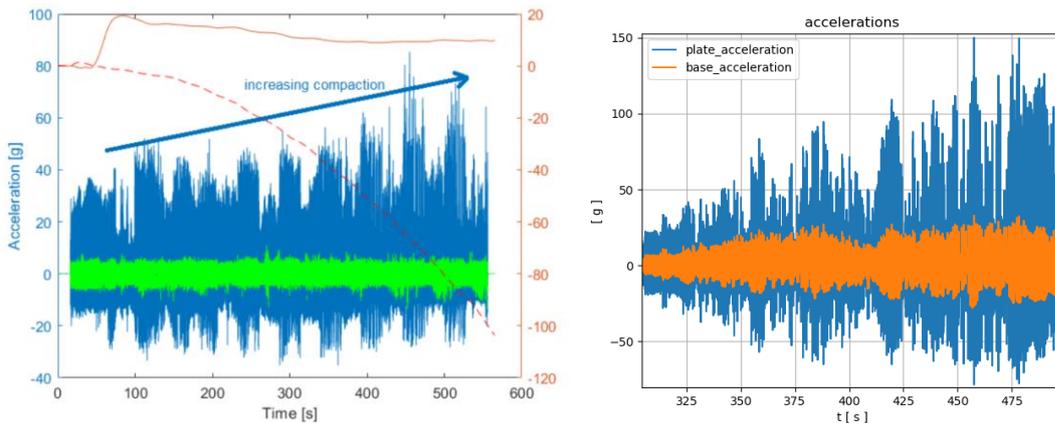Issue   1.0
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Figure 4. Comparison of experimental data (left) and numerical recreation of the data (right).
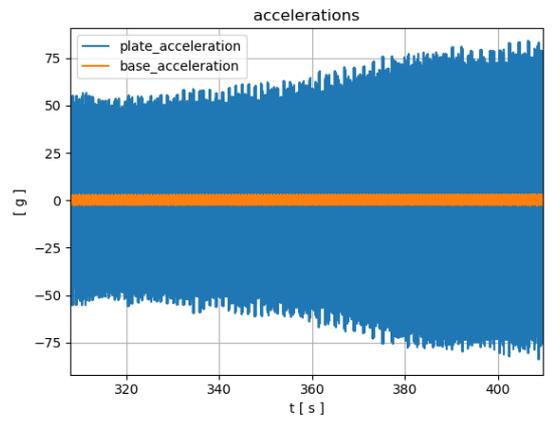

Figure 5. Expected lunar compaction acceleration data with visible increasing compaction.

The compaction process densifies the regolith by its plastic failure resulting in the sinkage of the surface. Densification and sinkage are therefore related. A typical spring-damper model of the reaction with the soil needs to be supplemented by consideration of: (1) elasto-plastic behaviour of the regolith compression, and (2) deformed soil "added mass" below the plate.
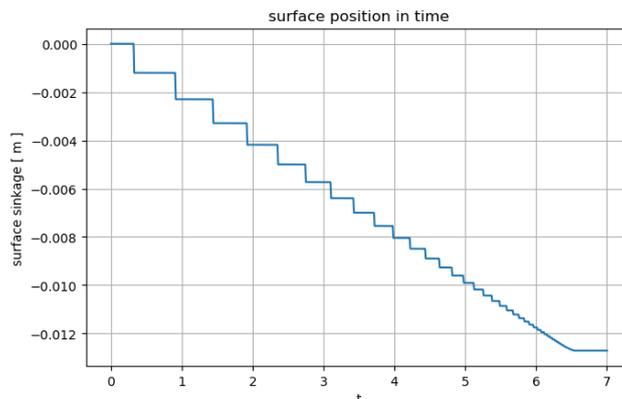

Figure 6. Surface sinkage during compaction.

In its simplified form, the model allows for achieving the sinkage effect, as shown in Figure 6. The dropped mass m_p bounces on the surface and creates indentation until the reaction forces are low enough to stop creating further progress. At the same time, the added mass of the accumulated soil increases until the value is settled.
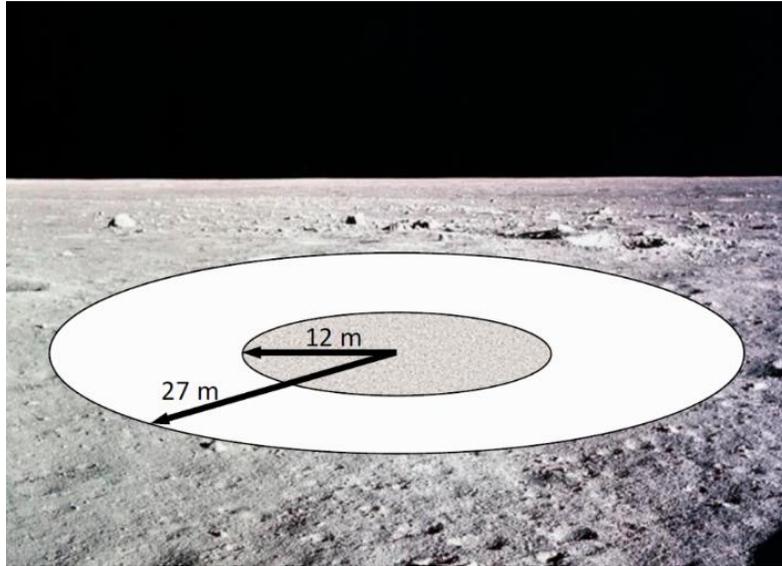
Horizontal construction

Figure 7. A typical layout of the lunar landing pad with the inner and outer zones (Metzger et al., 2022).

Based on the results of the activity and other studies, we anticipate that the horizontal construction on the Moon will heavily rely on site preparation techniques like compaction, while more complicated surface construction techniques will utilize compaction for their performance improvement.

Compactor can contribute to site preparation and horizontal construction by:

- Preparation of horizontal constructions (e.g. landing pads) via compaction with:
    - Increased regolith cohesion
    - Increased bearing capacity
    - Surface levelling
- Surface and subsurface properties via:
    - Surface data acquisition
        - By comparing acceleration data and Q-parameters to catalogued parameters, such as density
    - Seismic measurements
        - By acting as an active seismic source for geophones

The currently established performance of the Compactor device is based on its average rate of operations at a value of 0.0017 m^2s^{-1} until the effective compaction of a work patch after 10 round trips. As a first iteration of estimates, a landing-launch pad with 54-meter diameter (2,290 m^2) will be fully compacted and levelled after approximately 370 hours of operations, which is approximately in line with a duration of sunlight at the lunar Equator, and leaves a large room for manoeuvres within the Polar highly illuminated crater peaks.