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GRC-3b-DST, a Geotechnical Simulant For Cohesive Mars and Moon Mobility and Excavation Testing with Reduced Respirable Silica

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Abstract

This study presents the development and evaluation of a modified version of the GRC-3b lunar soil simulant designed to address both geotechnical performance and operator safety in terrestrial mobility and excavation testing. While GRC-3b is widely used due to its cost-effectiveness and similarity to extraterrestrial regolith, its fine silica content poses significant health risks during handling. To mitigate this, a dust-suppressing additive was introduced, producing GRC-3b-DST. The modified simulant maintained the original particle size distribution and classification as a well-graded silty sand but exhibited increased cohesion and a lower minimum density, enhancing its ability to replicate compacted regolith conditions. Laboratory testing, including modified Proctor compaction, simple shear tests, and cone penetrometer correlations, confirmed that the geotechnical properties of GRC-3b-DST are consistent and predictable, making it suitable for high-fidelity terrain simulations. Safety testing using OSHA-compliant air sampling showed respirable silica concentrations remained well below permissible exposure limits during soil preparation, indicating a significant reduction in airborne hazards. These findings suggest that GRC-3b-DST offers a safer, more versatile alternative for use in large-scale test environments where repeatable geomechanical properties and minimized health risks are essential.

Introduction

To investigate sample retrieval architectures options for a Mars Sample Return mission, a soil simulant was developed to replicate the compacted and cohesive soils of the Three Forks River Delta region. This region is of particular importance because it is the location of a Mars sample tube depot, a region where ten sealed sample tubes containing rock core were dropped by the Perseverance rover to be potentially recovered for return to Earth. One of the architectures examined for such a mission was a small-wheeled helicopter equipped with a robotic arm, which would pick up the tubes [Mier-Hicks 2023]. Given this platform needed to drive, large areas of prepared simulant were necessary to test critical detection and perception algorithms, particularly in relation to the vehicle's locomotion performance.

The GRC-3b simulant was chosen for this testing. Originally designed for lunar geotechnical studies, its low cost enables the purchase of large quantities needed for mobility and excavation testing. Through empirical testing it was found that this lunar simulant could represent the compacted soil regions of Mars if it was properly compacted. Dirt strength preparation techniques we developed on earth using GRC-3b to match the wheel sinkage data sent back from the Perseverance rover. The relative density of the prepared simulant was varied until the wheel sinkage matched the images coming back from Mars ($D_r \approx$ 70-75%). Additionally, GRC-3b has previously been subjected to numerous geotechnical evaluations [He 2010, 2013, Dewoolkar 2018, Frost 2018]. This larger body of knowledge is critical for comparing data collected on this simulant vs in-situ lunar data, which will inevitably be different.

A significant challenge with GRC-3b, as with most lunar simulants, is the presence of silica particles smaller than 15 µm, which pose a respirable hazard. This necessitates the use of filtering facemasks by operators when handling the simulant. Due to the plasticity (memory) of GRC-3b, it must be reconditioned to its desired state before each test, requiring prolonged use of personal protective equipment (PPE). Additionally, the dust generated during handling eventually settles throughout the lab and can be re-suspended by foot traffic when personnel are not wearing PPE, posing an ongoing risk.

A decision was made to collaborate with Covia (https://www.coviacorp.com/), the GRC-3b manufacturer, to incorporate a dust-suppressing additive (0.7% by weight) into the original GRC-3b formulation. This modification aimed to mitigate silica dust generation while minimally affecting the simulant's geotechnical properties. The additive also enhanced the cohesion of GRC-3b, which originally lacked this characteristic. The optimal ratio of additive to bulk material was determined through testing at JPL, after which Covia implemented the formulation and produced 22 tons of the modified material. Geotechnical and safety tests were conducted on the new simulant, named GRC-3b-DST, with the results detailed in the following sections.

Geotechnical Laboratory Test Summary

The original formulation for GRC-3b was not altered for this Dust Suppression Technology (DST) variant meaning the Particle Size Distribution (PSD) as well as its classification as a well-graded silty sand (SM, using unified soil classification system) were not changed. Geotechnical tests were done on the new DST soil to characterize it as well as on the new batches of unmodified GRC-3b to ensure the batches currently being produced still match the data from literature.

Minimum and Maximum Densities

The soil strength in lunar regions surveyed by the Apollo missions is often expressed in terms of relative density (D_r) and ranges from 60-80% at depths up to 20cm [Heiken 2005]. However, this is not a direct measurement, but a calculated value based on specific gravity, as well as minimum and maximum density measurements of samples [Mitchell 1974]. Relative density represents where a soil sample lies between its minimum (loosest) and maximum (densest) conditions (eqn. 1). Therefore, determining these values for the DST simulant was crucial. Since the DST additive introduced cohesion into the soil, the standard [ASTM D4253] method for determining minimum and maximum densities was unsuitable. Instead, a modified Proctor test [ASTM D1557] was used to establish the maximum density of the DST simulant.

$$D_R = \frac{\rho_{max}}{\rho} \times \frac{\rho - \rho_{min}}{\rho_{max} - \rho_{min}} \times 100\%$$

Equation 1: Relative density

Where ρ is the bulk density (in kg/m^3), ρ_{max} is the maximum density, and ρ_{min} is the minimum density. The tests done on the unmodified new batches of GRC-3b yielded a min and max density of 1581 and 1972 kg/m^3 respectively. These are in family with the reported literature values of GRC-3, which are 1520 kg/m^3 and 1939 kg/m^3 for the min and max densities respectively and the max density for the lunar samples [He 2013, Heiken 2005]. When the DST soil was tested, the min and max densities were found to be 1352 kg/m^3 and 1971 kg/m^3 respectively.

Table 1: Minimum and maximum densities for lunar regolith, GRC-3b, and DST simulants

SOIL	MINIMUM DENSITY (kg/m^3)	MAXIMUM DENSITY (kg/m^3)
Moon	870	1930
GRC-3b (literature)	1520	1939
GRC-3b (new batches)	1581	1972
GRC-3b-DST	1352	1971

Cohesion and Internal Friction Angle

Single simple shear testing [ASTM 3080] was performed on both the unmodified and DST soils. In this test, the soil samples were placed into a rectangular cavity divided at the midpoint. A mass was applied on top to introduce a surcharge load, after which the cavity was sheared laterally. The peak and ultimate shear forces were recorded during the process for different normal loads. These tests were conducted on both soil types, prepared to varying relative densities, to evaluate their shear strength characteristics.

The Mohr-Coulomb failure criterion was used to determine the cohesion and internal friction angles of the DST soil. The normal stress (σ) was calculated based on the applied surcharge mass and surface area of the shear box, and the shear strength (τ_f) was measured using a load cell (eqn. 2). Twenty tests were conducted across five different densities, allowing for a system of equations with variables for cohesion (c) and internal friction angle (φ) (eqn. 2). Once solved, the system of equations revealed that the internal friction angle of the DST soil ranged from 32° to 35°, while cohesion values ranged from 5 kPa to 11 kPa, both increasing with bulk density. The cohesion and internal friction angle are all determined as a function of bulk density, so the results reported in the table below aim to provide that data at approximately the same bulk density conditions for the different soils [He 2013, Heiken 2005].

Table 2: Cohesion and internal friction angle for lunar regolith, GRC-3b, and DST simulants

SOIL	Test Relative Density	Cohesion - Ultimate [kPa]	Internal Friction Angle
Moon		0.1 – 1	30° - 50°
GRC-3b (literature)	84%	0	47.8° (at 1839 kg/m^3)
GRC-3b (new batches)	79%	0	33.4° (at 1792 kg/m^3)
GRC-3b-DST	81%	11.5	35.5° (at 1816 kg/m^3)

$$\tau_f = c + \sigma \times \tan\varphi$$

Equation 2: Mohr-Coulomb failure criterion

Cone Penetrometer Testing

Determining the relative density of soil is important for mobility and excavation testing. However, in-situ measurements of relative density can be invasive or require consumables and specialized equipment. To address this, testing was conducted at JPL to establish a correlation between relative density and cone index gradient [McRae 1965]. Soil samples were prepared to minimum, maximum, and intermediate densities using the ASTM D1557 standard method. A cone penetrometer was then used to penetrate the soil, recording the force exerted during penetration. The collected data produced a curve whose equation provides an approximate value for the soil's relative density based on the cone index gradient (G). This allows for the acquisition of relative density with a more portable and easier to use cone penetrometer.

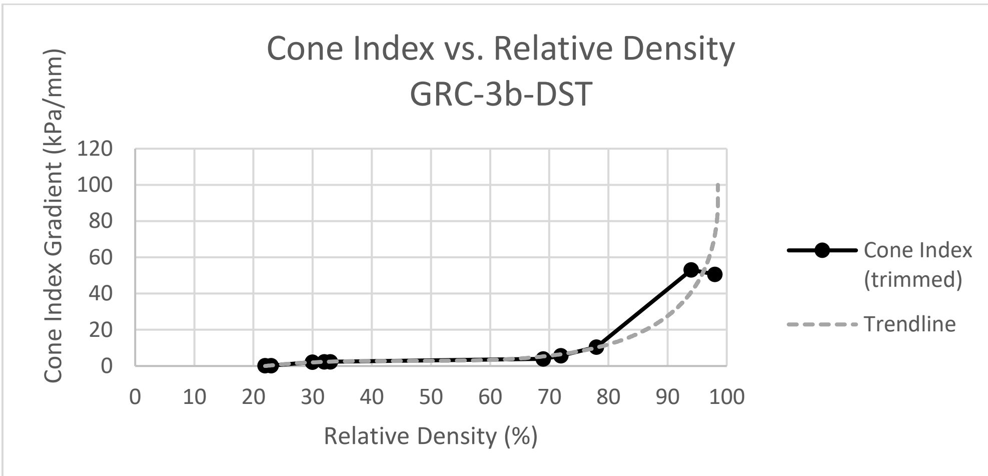

Figure 1: Cone index vs. relative density for GRC-3b-DST using ASTM 1557 and 0.5in² tip cone penetrometer

$$D_{r,DST} = 14.3 * (\frac{G}{.54} - 5.26)^{1/3} - .157\left(\frac{G}{.54} - 5.26\right) + 46$$

Equation 3: Correlation between relative density to cone index gradient for GRC-3b-DST, G = cone index gradient acquired from cone penetrometer

Safety Testing

One of the primary objectives in developing the GRC-3b-DST soil was to create an extraterrestrial simulant that generates less airborne silica when disturbed. To validate this, a DustTrak DRX air sampler and a personal air cartridge sampler were used. For the test, a 10 m x 3.5 m bed of GRC-3b-DST soil was prepared to a moderately compact condition (D_r≈53%) and disturbed three times. During the entire test, an operator wore a personal air sampler, which collected air samples near their face. The particulate meter captured samples on a filter cartridge, which was sent to a laboratory to quantify the respirable silica content. The DustTrak air sampler, placed on a table, continuously recorded data throughout the test period, measuring the total amount of respirable particles, not limited to silica, generated during the tests.

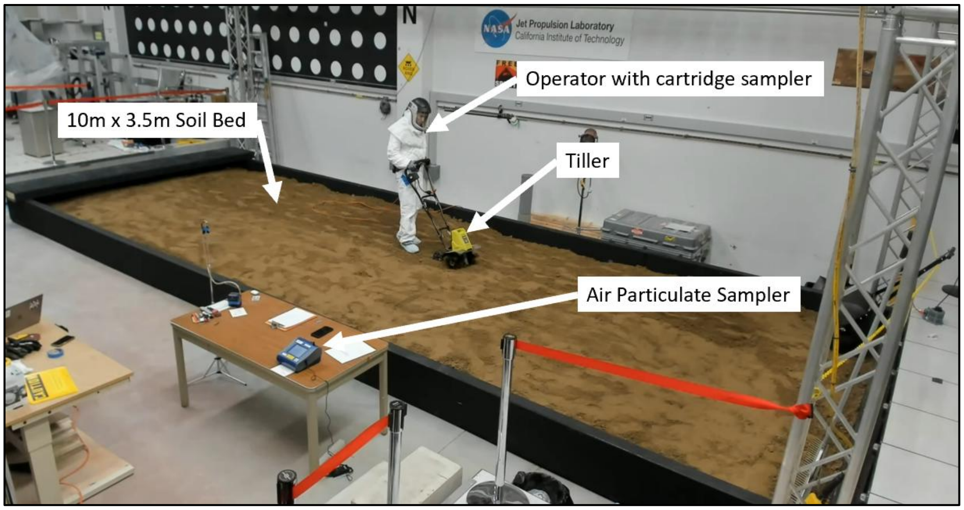

Fig 2: GRC-3b-DST soil bed with electric tiller and safety monitoring equipment

The soil preparation process was designed to replicate the conditions typically used for rover mobility testing, where the soil is fully loosened and recompacted before each run. Loosening was performed using an electric tiller with an 8-inch blade diameter, which was passed over the entire soil surface. After tilling, the soil was leveled with a flat blade rake. A water-filled soil roller was then used to compact the soil with a single pass. The level of compaction could be adjusted by increasing the number of passes or the water volume in the roller, although precise compaction was not critical for the safety testing conducted. This process was repeated three times, with data collected on an operator wearing a Powered Air Purifying Respirator (PAPR) for protection.

The results from these safety tests indicated that the cumulative respirable silica concentration for the soil preparer ranged between 9.1 and 12 μg/m³, well below the OSHA-defined Personal Exposure Limit (PEL) of 50 μg/m³ over an 8-hour workday, as outlined in standard 1926.1153, subsection 1926.1153.d.1 [OSHA 1926]. These findings suggest that the airborne silica generated by the DST soil during this preparation method is low enough that operators would not require a filtering facepiece, provided they limit their activities to three preparations per day. Additionally, a qualitative observation noted the minimal dispersion of dust in the lab space surrounding the soil bed.

Conclusion

A modified version of GRC-3b was developed to add cohesion and reduce the airborne silica risk for operators. The PSD of the original GRC-3b was not altered, and geotechnical testing demonstrated that the minimum density of the new GRC-3b-DST soil decreased from the unmodified value of 1581 kg/m^3 up to 1352 kg/m^3 meaning that a less dense, fluffier, soil could be prepared. While not as low as the 870 kg/m^3 minimum density of lunar samples, this GRC-3b-DST soil can provide a good geotechnical analogue for mobility and excavation testing.

The results from personal and static sampling pump safety testing concludes that the DST dust reduction additive has reduced the airborne respirable silica levels. With the use of certain soil preparation techniques in concert with appropriate safety screenings, the airborne silica levels may be low enough to create a safe environment per the OSHA requirements. This reduction may result in less engineering, administrative, and PPE controls for the test conductors, resulting in faster and less expensive test campaigns.

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