LUNAR REGOLITH: SMALL SCALE ROBOTIC SITE PREPARATION AND GEOTECHNICAL EXPERIMENTS WITH SCOOPS

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Space Resources Roundtable, XXII Meeting
June 7-10, 2022
Colorado School of Mines
Golden, Colorado USA

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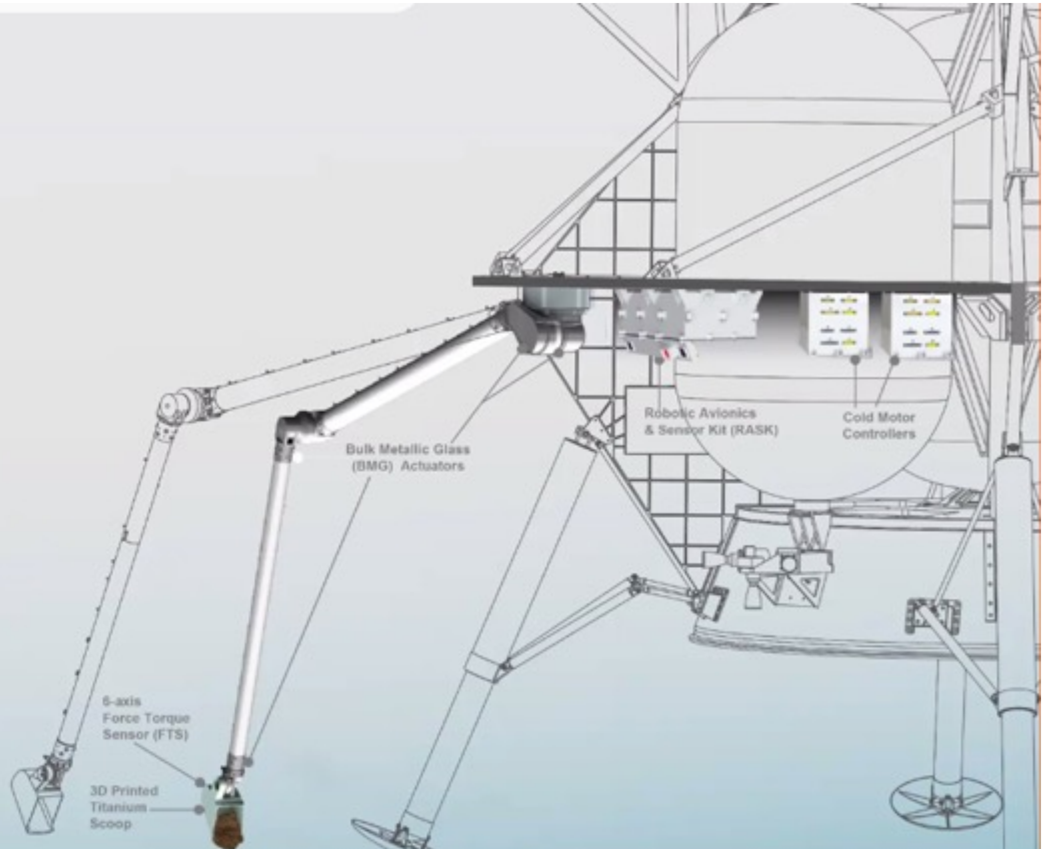
Introduction

- NASA's Moon-To-Mars Planetary Autonomous Construction Technology (MMPACT) project seeks to research, develop, and demonstrate lunar surface construction capabilities.
- Quantification of lunar regolith's geotechnical properties allows for effective prediction of forces and displacement during excavation and construction and is critical to facilitating regolith sintering capabilities all of which benefit lunar infrastructure plans.
- Knowledge of shear strength, Mohr-Coulomb cohesion, angle of internal friction, bearing strength, bulk density, etc. is needed.
- The use of ground-based testing of various lunar simulants with relevant hardware (e.g., robotic arm tools) enables validation of technology choices, tool paths, and lunar surface construction activities.
- In addition, the use of Taguchi methods [1] will minimize the number of needed experiments to explore critical input parameters.
- The Jet Propulsion Lab is preparing to fly the COLDarm payload on a CLPS lunar mission with a geotechnical measurement scoop

COLDarm

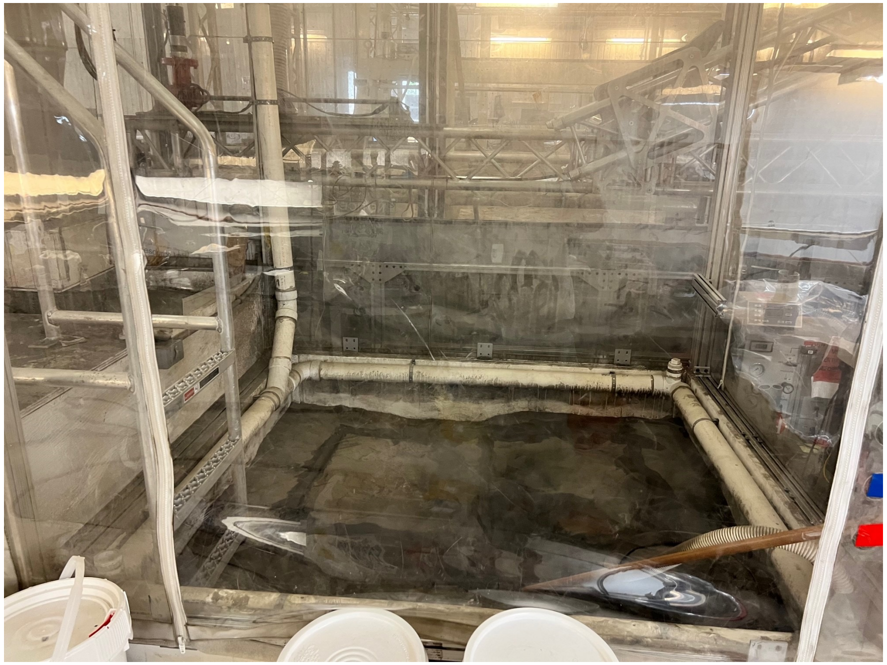
COLDArm Overview

- Industrial Partner: Motiv Space Systems
- Phoenix/InSight Scale
  - 4 degrees of freedom
  - ≈ 2 meter length
  - Initial concept with scoop/geotechnical property feature (3D Printed at MSFC)
  - 40 N Tip Force in Primary Workspace
- Cold operable
  - <100K operation without heaters
  - BMG Actuators/Harmonics
  - Cold Motor Controllers
- Robotic Avionics and Sensor Kit (RASK)
  - Warm Electronics Box (WEB)
    - Located on arm baseplate
    - Leverages Mars Helicopter Avionics
    - Cameras
  - Force Torque Sensor at Wrist

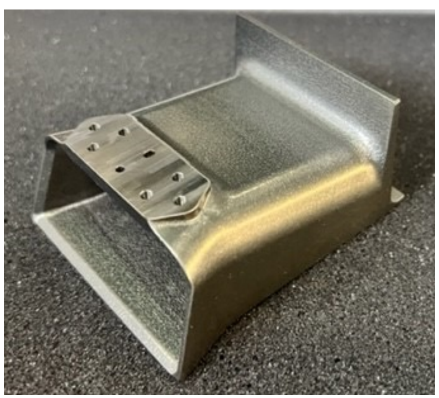


SPACE TECHNOLOGY OFFICE COLDArm Jet Propulsion Laboratory California Institute of Technology motiv space systems

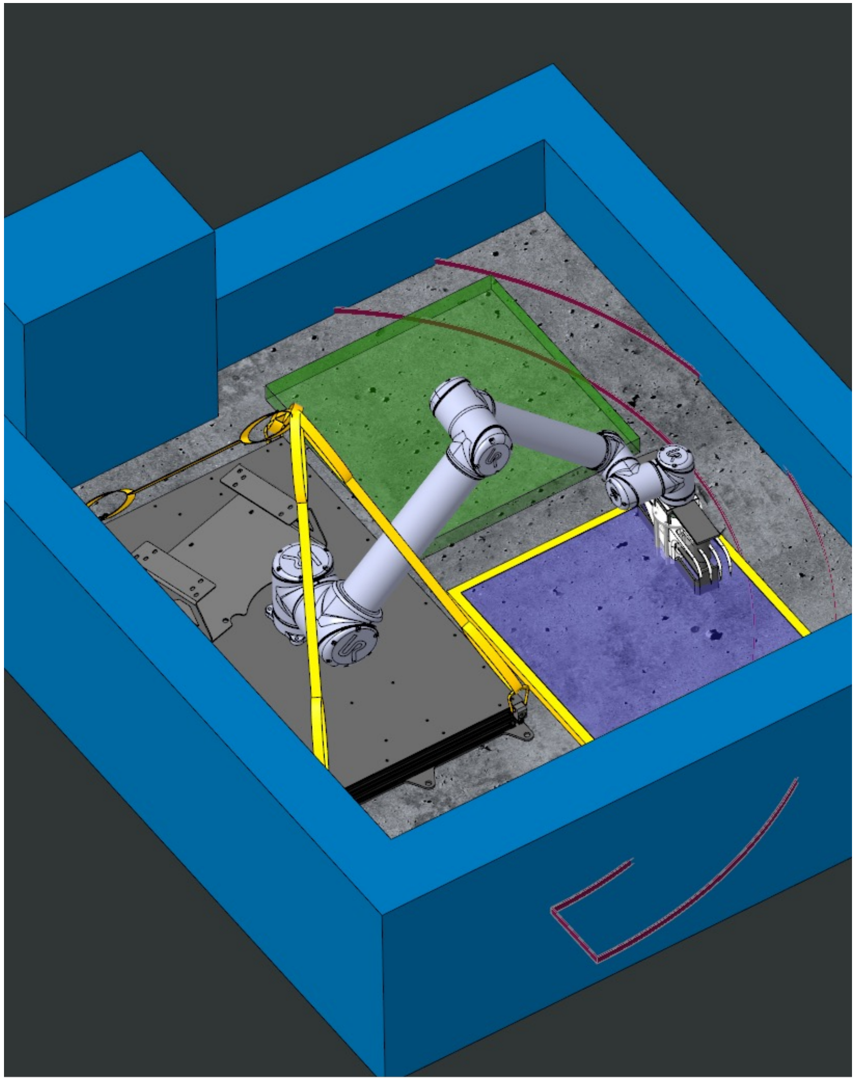
Experimental Tools



KSC Regolith Simulant Bin – 2,000 kg



3D printed Titanium Scoop (JPL)



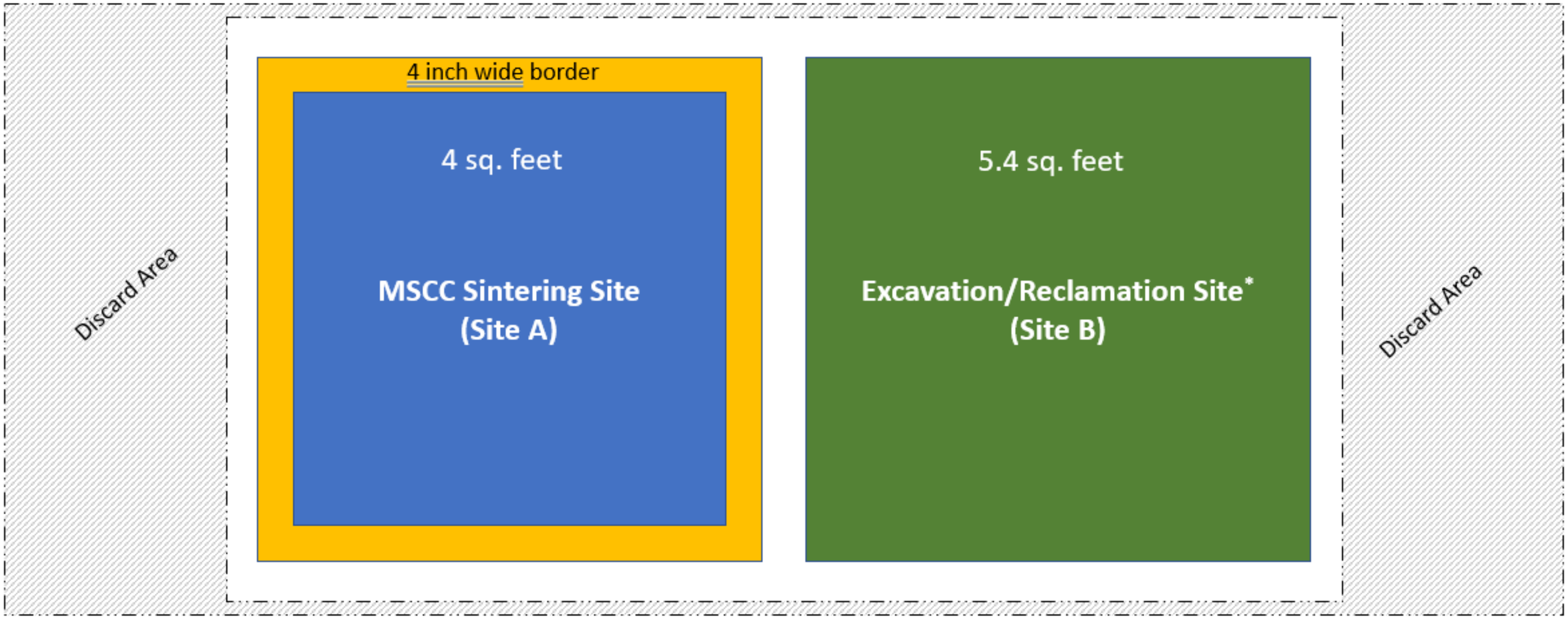
UR-10 robot arm on a pallet in Bin

Site Preparation for Regolith Microwave Sintering

Action: A 2' by 2' pad will be built up with four 1" layers by excavating adjacent material, sorting it, and depositing it on the pad site. A topography scan will be completed after each layer is deposited to measure volume, after which fine grading, compacting, and sintering will occur.

Inputs: VS (Scoop Volume), nS (Number of Scoops)

Outputs: VL (Layer Volume), ρL (Layer Density)

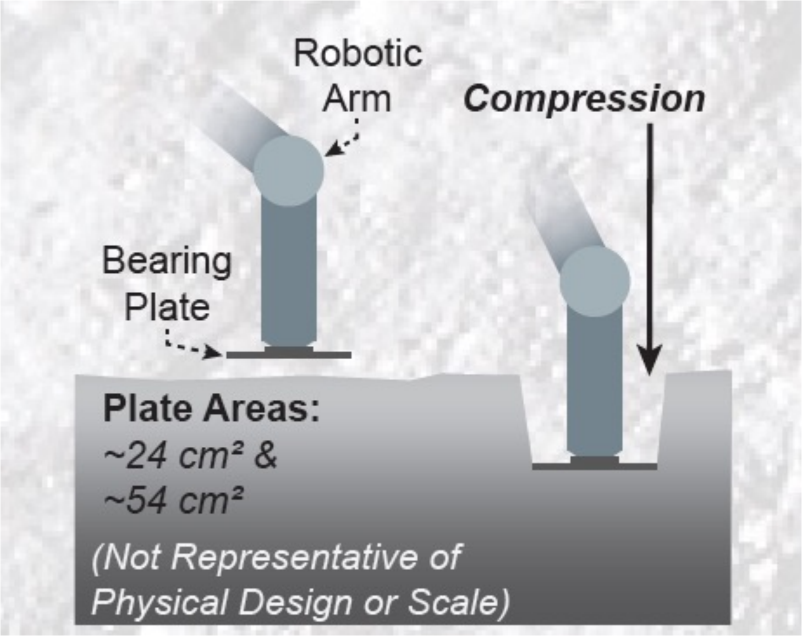


Pressure-Sinkage Test

Action: Slowly press down normal to regolith surface with bearing plate until desired or max allowable force (or max allowable displacement) is reached.

Inputs: P (Applied Pressure), b (Plate Width)

Outputs: z (Vertical Displacement)

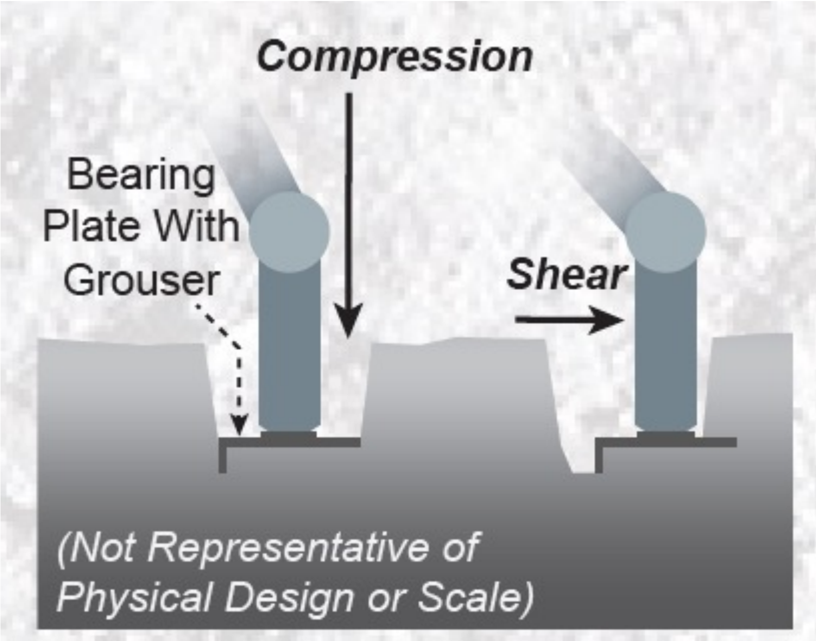


Shearing Test

Action: Slowly press down normal to regolith sur-face with bearing plate with grouser until desired load is reached, then translate horizontally by a set distance.

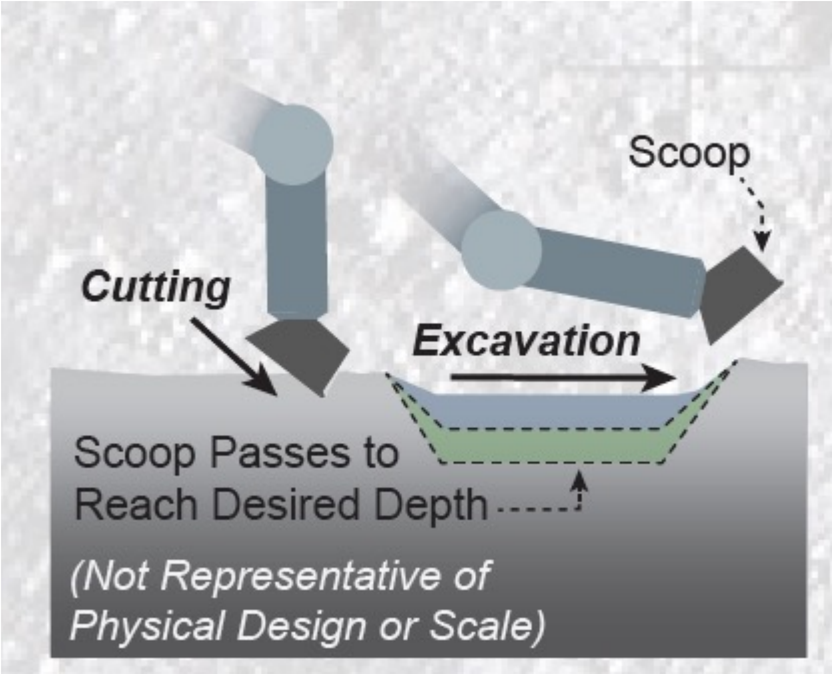
Inputs: A (Shearing Plate Area), σ n (Applied Nor-mal Load)

Outputs: τs (Shear Stress at Failure)



Excavation Test

Action: Approach regolith surface with scoop at desired rake angle, then vertically translate scoop cutting edge down into the regolith to the desired depth. Translate the scoop horizontally as needed (dependent on scoop depth & rake angle) then rotate up to collect sample.
Inputs: β (Rake Angle), DT (Trench Depth), LT (Trench Length)
Outputs: LS (Surface Excavation Length), Ft (Tip Force), Tt (Tip Torque)

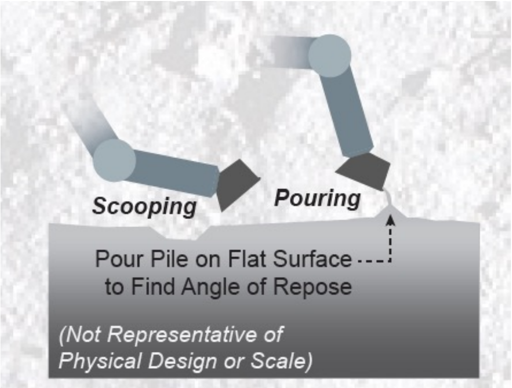


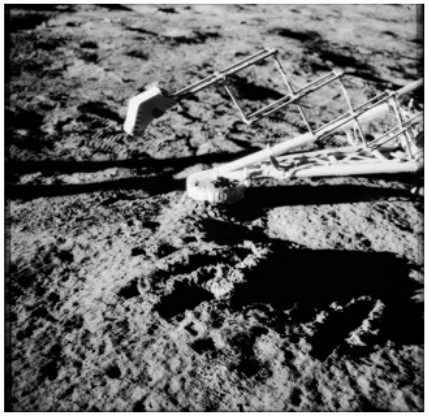
Angle of Repose Test

Action: Excavate desired volume of regolith then translate scoop diagonally over above a flat surface. Slowly angle the scoop to dump contents onto the surface at a relatively constant rate, creating a pile.

Inputs: V (Sample Volume), nS (Number of Scoops), dd (Drop Distance)

Outputs: rp (Pile Radius), hp (Pile Height)





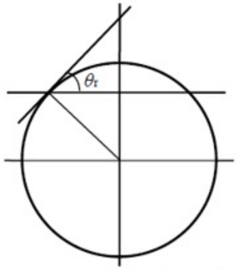


Figure 2. Schematic diagram of the rest angle of repose measurement.

Table 1. Angle of repose of several materials.

Material	θ_r	*Reference*
Glass beads 53-75 µm	32°	[6]
Mojave dune sand <53 µm	31°	[6]
Quartz dust	54°	[6]
JSC-1A simulant <50 µm	37°	This work
Apollo 14 sample 14163	58°	This work

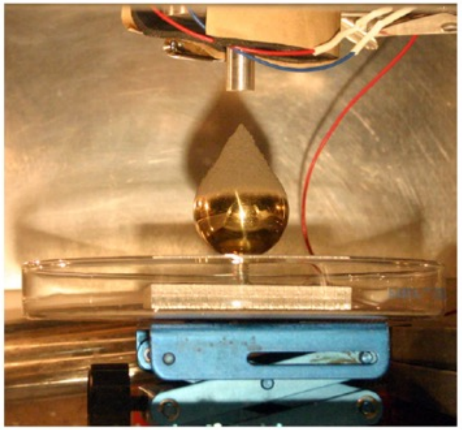


Figure 1. Angle of repose experiment with Apollo 14 sample 14163 at an atmospheric pressure of 10^{-6} kPa.

Notes:

(5) MEASUREMENT OF THE ANGLE OF REPOSE OF APOLLO 14 LUNAR SAMPLE 14163. C. I. Calle and C. R. Buhler, Electrostatics and Surface Physics Laboratory, NASA, Kennedy Space Center FL, 32899, carlos.i.calle@nasa.gov, charles.r.buhler@nasa.gov.

Geotechnical

Data Analysis

Pressure-Sinkage Test

- Results from similar densities for different simulants and different starting densities per simulant will reveal bearing strength sensitivity's to density and composition properties
- Results can be inserted into Bernstein's [5], Reece's [6], and Bekker's [7] pressure-sinkage equations to solve for their constants (**k** and **n** from Bernstein's and k_c, k_ϕ, & **n** from Reece's and Bekker's)

Shearing Test

- (Mohr-Coulomb shear str. at shear failure) $\tau_s = \sigma_n \tan(\phi) + c$
- (Sliding str. after shear failure) $\tau_a = \sigma_n \tan(\delta) + a$
- Results will allow for cohesion (**c**), adhesion (**a**), internal friction angle (**ϕ**), and the angle of external friction (**δ**) to be solved for

Excavation Test

- Results will facilitate calculation of the N_γ, **Nc**, & **Nq** constants and the excavation force's frictional and adhesional components from the fundamental equation of earthmoving (FEE) by Hettiaratchi & Reece [8]. Equations from Luengo et al. [9] which handle shear, remolding and gravitational forces will also be used

Angle of Repose Test

- In line with ASTM standards C1444 and D6393, the inverse tangent of a poured soil pile's height over its radius will produce an angle of repose value for the surface regolith

Regolith Microwave Sintering Site Preparation

- Data from shear vane cone penetrometer tests on the pad easement will reveal design readiness for sintering operations

Conclusions

- In-situ regolith properties need to be measured on the lunar surface for regolith characterization
- The fidelity of regolith simulants in a terrestrial environment is limited
- A series of tests is being performed in a laboratory environment to inform the design of a lunar mission geotechnical measurement
- A small scoop on a robot arm may be able to determine many geotechnical properties

Supported in part by NASA Cooperative Agreement 80NSSC19M0214,
Solar Systems Exploration Research Virtual Institute (SSERVI)
Center for Lunar and Asteroid Surface Science (CLASS)

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