Development of a New Lunar Simulant for Geotechnical Applications

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Introduction: NASA already has several proposed missions to the moon, which will require new process engineering frameworks. This is an important need for detailed characterization of lunar regolith compositions and physical properties critical to many applied areas in lunar science, ISRU, space engineering, and to the operational success of all future science missions involving surface or near surface contact. In order to enable lunar science and the geotechnical investigations, developing a representative lunar simulant is a crucial first step towards understanding the geologic history, origin, and processes that were and/or are active on lunar surfaces. The development of the lunar surface is a direct reflection of the processes associated with the dynamic environment in which it has formed. These are the main motivations for the ongoing development of new simulant for this type of testing and our proposed work will fulfill this important need.

Background: Regoliths are the external ‘skins’ of planetary and moon bodies and therefore understanding their physical makeup and structure is crucial, as well as highly scientific relevant, for current and future NASA missions. In the case of the Moon, the surface and regolith have been severely modified by impactors through time. This includes rocks that have been fractured into small particles, compacted, and in the case of larger events, melted into glass, especially within a few meters of the surface. Impact events create secondary debris that fall ballistically back to the Moon surface. Over geologic time scales, impactors seismically shake the originally loosely packed regolith materials, creating oriented grain fabrics and regions of very high densities. This leads to a complex range of geomechanical behavior, from “fairy castle” structures of low density at the surface, to subsurface densities upwards of 90% **[*1*]**. Also notably, future robotic and human missions will emphasize in-situ exploration in a variety of extraterrestrial surface environments, including the Moon and asteroids **[*2-3*]**. However, a key goal of NASA’s planetary exploration program is to pave the way for astronauts to land and set foot on these planetary soils. However, placing “boots on the ground” and roaming on these unknown surfaces is risky without fully understanding the geomechanical/environmental properties of the materials.

Past lunar simulants (e.g., JSC-1AF, JSC-1AC) [4-5] are primarily designed for chemical analysis. They are not suitable for mechanical/geophysical/mobility testing of hardware that will interact with the lunar surface. The primary reason is that the lunar soils are the result of simple comminution, largely from impact cratering processes, with feldspar and friable mesostasis from regional and local source rocks concentrating in the finest fraction. This finest fraction is supplemented with glass derived from impact cratering. There is strong evidence that agglutinate glass forms preferentially by fusion of the finest soil fractions, thereby providing a strong bonding agent for the finest particles. The presence of this glass component, combined with various rock and mineral fragments, provides a major risk to surface hardware, including protective spacesuits for astronauts. Consequently, the present known simulants do not adequately represent the presence of this glass fraction because it is very difficult to recreate, especially in the quantities needed for adequate testing of flight hardware.

Simulant Development Approch: Currently, the two most viable methods of producing lunar simulants are either mined from the field or synthetically produced in the lab. FJS-1 and MKS-1 were fabricated in Japan and designed specifically for engineering use only due to differences from actual lunar regolith. JSC-1 was mined from volcanic ashes and crushed to proper grain sizes for laboratory and engineering use; this simulant exhibited the approximate geotechnical soil properties of lunar soils. However, availability for distribution to the lunar scientific and engineering community was obviously limited and none is available today. Finally, the lunar simulant CAS-1 was recently discovered in northeast China, but is obviously not available for NASA use due to reasons associated with political and economic rivalry [6].

Our fabrication method seeks to develop new (more optimized) lunar simulant with similar chemical compositions in-house at JPL by the method of microwave sintering process using the most advanced “custom-made” hardware (induction furnace + reduction reactor system). This process includes critical steps of ball milling to refine feedstock materials homogeneity, induction melting at about 1100ºC to produce raw simulants, and hydrogen reduction step at about 1000ºC to remove further impurities and/or chemical volatiles.

Results: The dedicated lunar simulant reactor was successful assembled, functionally tested, and production of lunar simulant variants is underway at JPL. Figure 1 highlights test runs on initial lunar simulants for morphological, micro-structural, and chemical comparisons to those produced at JPL by XRD and microscopy imaging techniques, including JSC-1 for benchmarking purposes; the SEM image provides indications on the presence the of Olivine [(Mg, Fe)$_2$SiO$_4$], Pyroxene [(Ca, Mg, Fe)$_2$Si$_2$O$_6$], and Ilmenite (FeTiO$_3$) by color. We have already performed many production runs in an effort to optimize chemical compostion with particular emphasis infusing glassy materials into the lunar simularnt matrix. Table 1 highlights the increasing glassy phase materials on later production runs (#27 to #31) in terms of atomic percentage (%) using Enegy Desperive X-ray Analysis (EDAX). In Figure 3, a high resolution electronic image confirms the fine-grained lunar simulant was infused with SiO$_2$ producing a desirable amourphous material highly more suitable for geo-technical applications.

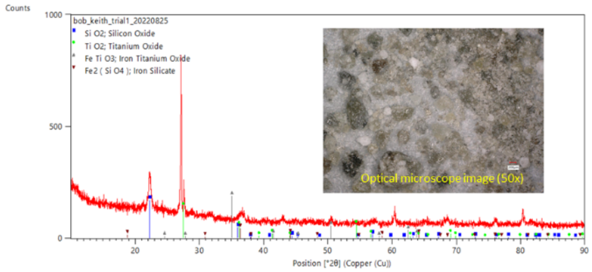

Figure 1. XRD compositional analysis of baseline lunar simulant sample from JPL's reactor testbed. The SEM image highlights the amorphous nature of sintered materials on simulant production runs.

Table 1: EDAX Compositional summary of production runs #27 to #31. All values are in atomic %.

#	O	Mg	Al	Si	Ca	Ti	Fe
27	71.97	0.09	0.42	27.36	0.03	0.14	
28	71.34	1.78	1.08	23.53	1.51	0.09	0.66
29	72.87	2.13	1.47	23.54			
30	63.37	1.36	1.32	29.70	2.92	0.02	1.31
31	72.24	1.10	1.62	21.68	1.91		1.46

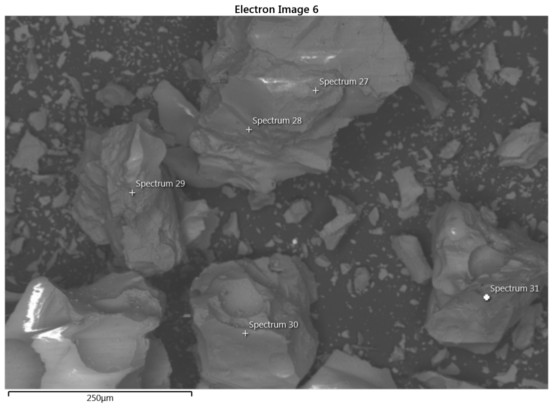

Figure 2. EDAX image validates the presence of glassy phase infused within the lunar simulants developed at JPL.

Future Works: The new lunar simulant reactor testbed developed at JPL is designed for R&D and optimization purposes with production rate of 5-10 mg/run (run = 2-4 hours). We are seeking fabrication techniques and technologies to enhance lunar simulation production the current rate.

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