A COMPARATIVE STUDY OF LUNAR REGOLITH SIMULANTS IN RELATION TO TERRESTRIAL TESTS OF LUNAR EXPLORATION MISSIONS.

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Introduction: Lunar regolith simulants (hereafter referred to as "simulants") have been used in various kinds of terrestrial tests to prepare for future lunar expeditions. However, among dozens of simulants produced internationally, comparisons between them are limited. Not knowing the fidelity of a simulant will result in inaccurate test results and may lead to equipment and astronaut health damages during a lunar surface mission.

This study compares some fundamental properties on a selected set of simulants produced in different countries by a combination of academic, governmental, and commercial organizations. Most of them are representative product(s) of their country of origin that have been, or are intended to be used for a wide range of tests.

Table 1. Summary of selected simulants.

Sample	Target	Type	Country
CAS-1	Apollo 14	Mare (Low-Ti)	China
EAC-1	General		Germany
FJS-1	Apollo 14		Japan
OPRL2N	General		USA
OPRH2N	Apollo 17	Highland	
OPRH2N Agglutinates	N/A		

The objectives of this study are (1) to obtain first-hand data to compare the simulants directly with each other, (2) to discuss how the property differences will affect their intended purpose(s), and (3) to suggest considerations when designing, producing and evaluating future simulants.

Expected properties: Lunar regolith grains are generally irregular, sharp and angular, and will easily abrade materials that come into contact with them [1,2]. Simulants with similar grain shape features can therefore help with the testing of anti-abrasive materials, such as rover wheels.

Mineralogy and moisture content will affect the results when testing in-situ resource utilization (ISRU) applications [3], as well as control some physical properties of the simulant. Ideal simulants should at least replicate the correct mineral contents from olivine, pyroxene and plagioclase feldspar groups, with zero water content unless intentionally introduced with moisture (i.e. icy regolith simulants).

Lunar regolith is much denser than terrestrial soil, with a typical specific gravity value of 3.1 and is unconsolidated [2,4]. These physical parameters in simulants could control several test outcomes including landing module design, surface material sample retrieval, lunar base construction and more [2].

Early simulants were mostly made without agglutinates, a unique component of lunar regolith but challenging to simulate. However, their importance such as reddening the spectra of lunar soil due to rich nanophase-iron content [3], and the complex particle shapes that may affect mechanical strengths of the simulants [4,5], are being more recognized recently and several organizations have been developing agglutinate products to simulate these features.

Figure 1. Simulant samples collected for this study.

Methodologies: Each simulant sample was analyzed for its particle shape and morphology with an

LEO (Zeiss) 1540XB Field Emission Scanning Electron Microscope. The mineralogy of each sample was measured using a Rigaku powder X-ray Diffractometer and processed with the Bruker DIFFRAC.SUITE EVA software. The bulk density of each simulant was determined using the Proctor compaction test under both loose and compact states. Porosity and void ratio values were calculated with their respective specific gravity.

A few other characterizations and analyses are currently underway, including mineral content quantification using the Rietveld Refinement method, moisture content calculation by oven-drying the samples, particle size distribution with a laser diffractometer and oedometer tests for consolidation and shear wave velocity.

Characterization Results: Originally produced at the Chinese Academy of Sciences to study lunar regolith microwave properties, CAS-1 is the least dense simulant (specific gravity 2.74 [6]). Although non-agglutinated, CAS-1 contains olivine, plagioclase and pyroxene minerals and has a significant glass content. The particles appear to be very angular.

EAC-1 is a basaltic simulant sourced from the Eifel region in Germany, and is intended to be used in the European Astronaut Centre's 900m^2 lunar surface simulation facility, LUNA [7]. EAC-1 contains olivine, pyroxene and plagioclase minerals, has a high specific gravity (3.07, measured at UWO) and density that are very close to the typical values of lunar regolith. However, as a low-fidelity simulant [7], it is non-agglutinated, may contain excessive clay minerals, lacks glass and its particle shapes appear to be less angular.

FJS-1 is one of the earliest lunar simulants, developed by Shimizu Corporation of Japan in the 1990s. FJS-1 simulates the Apollo 14 mare soil and is produced by crushing basaltic rocks sourced from the Mt. Fuji area [8]. This non-agglutinated simulant also appears to be less angular, lacks glass but does contain olivine, pyroxene and plagioclase minerals. Due to an insufficient sample quantity available, it was not characterized by Proctor and oedometer tests this time but its specific gravity was previously reported as 2.94 [8].

OPRL2N is the general-use mare simulant produced by Off Planet Research (OPR) of the USA. By mixing the basaltic feedstock from Arizona and Archean anorthosite from Ontario, Canada to a 9:1 ratio, this configuration of this non-agglutinate simulant is based on the average values obtained from the Apollo missions [9]. OPRL2N contains olivine, pyroxene and plagioclase minerals but does not contain much glass. Its particles are mostly angular. A commercial product for rental or purchase, this simulant is slightly less dense (specific gravity 2.9 [10]) than the representative value of lunar regolith but is customizable upon clients' requests.

OPRH2N is the general highland simulant developed by OPR, made from mixing the same anorthosite and basalt feedstocks to a 7:3 ratio but simulates the samples from the Apollo 17 mission [9]. XRD result shows that it is mostly composed of olivine and plagioclase minerals. Since it is likely processed using the same equipment as its mare counterpart, their specific gravity, density and porosity are very close.

A small quantity of OPRH2N Agglutinates (i.e. agglutinate simulant designed to mix with OPRH2N) was included in this study to examine its particle shape and mineralogy. Although the inner structures of the particles were not observed this time, nanometer-sized features that contain some iron were discovered on some particle surfaces, implying the possibility to re-create nanophase-iron in future agglutinates. This product is almost entirely made of plagioclase minerals.

Summary and Future Work: The simulants selected for this study were developed over two decades. Using different source materials and manufacturing processes, each simulant has its strengths and weaknesses. Current users should thoroughly understand these characteristics before employing them for testing lunar exploration technologies. Additional comparisons of other properties of the selected simulants or including other proper candidates could also contribute to the improvement of future simulants.

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