

# Developing an Anorthositic Lunar Regolith Simulant

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**Abstract.** We must increase our understanding of the regolith, as future human missions to both the Moon and Mars will rely on it for insitu resource utilization (ISRU) to produce fuel, water, and other life support and construction materials. ISRU will be more cost effective than shipping required materials from Earth. Because regolith will be the zone of contact for both human and robotic exploration, it is important that we learn how to work with it before returning to the Moon. There are no natural lunar regolith analogues on the Earth, and supplies of existing lunar simulants are currently limited or running out. To prepare for upcoming robotic ISRU missions, equipment must be tested on the Earth, in a good physical/mechanical simulant. To date, all major lunar simulants produced have been basalt based, however ~ 80% of the lunar bedrock - including some potential ISRU landing sites - is composed of anorthosite-norite-troctolite (ANT) suite rocks (Heiken et al., 1991). The goal of this study is to develop an anorthosite-based physical/mechanical lunar regolith simulant, to assist Electric Vehicle Controllers (EVC) Ltd. and the Northern Centre for Advanced Technology (NORCAT) Inc. with lunar drilling and excavation equipment design.

## BACKGROUND

Lunar regolith is an unconsolidated material covering the entire surface of the Moon. It is about 4 to 8 m thick over the Mare regions, and 10 to 30 m thick over the older Highland regions (Heiken et al., 1991). Lunar bedrock consists mostly of the anorthosite-norite-troctolite (ANT) suite rocks of the Highlands, and Mare basalts account for approximately 17% of the bedrock. Lunar regolith is a complicated substance unlike any material found on the Earth, due to the lack of an atmosphere and atmospheric weathering processes on the Moon. Regolith is composed of particles that were derived either from lunar bedrock, or from older regolith, which was formed when repeated meteoroid impacts pulverized the lunar bedrock, over-turning and mixing it, until it became a fine powder. Regolith is still undergoing modification and evolution today, and thus it is a dynamic material (Korotev, 2004). It consists of five components: mineral fragments, rock fragments, breccia fragments, glasses, and agglutinates (smaller particles, bonded together by vesicular glass). Particles are heterogeneously mixed, and can range in size from microscopic to several meters or more in diameter, averaging between 60 and 80  $\mu\text{m}$ . Particles are very angular in shape, which has implications for regolith physical properties (e.g., abrasive to machinery and damaging to the human respiratory system).

## RATIONALE

The specific goal of this project is to enable validation of EVC/NORCAT designs for lunar drilling and excavation equipment, and therefore this study is not concerned with lunar regolith *chemical* properties. On a broader scale, the community needs a new *physical/mechanical* regolith simulant, requiring first that we understand physical/mechanical properties of the regolith, and then learn how to replicate behaviours with a simulant. As there are no natural lunar regolith analogues on the Earth, and supplies of existing lunar simulants are nearly exhausted, equipment must be tested here on Earth utilizing a representative simulant in order to prepare for upcoming robotic ISRU missions.

## **PREVIOUS WORK**

Several lunar regolith simulants have been created. The most widely used are the Minnesota Lunar Simulant (MLS-1) and the Johnson Space Center simulant (JSC-1), as well as several Japanese simulants. However, supplies of these are insufficient for large-scale testing. MLS-1 consists of mechanically crushed, ground, and sized high-Ti basalt (Batiste and Sture, 2005). JSC-1 is made up of low-Ti basaltic volcanic ash from the San Francisco Mountains of Arizona, which has been ground, and sized (McKay et al., 1994). Both have similar chemical and basic engineering properties to the Apollo lunar regolith samples, however, they lack agglutinates and therefore do not display representative inter-particle interaction properties. Thus MLS-1 and JSC-1 do not simulate physical properties sufficiently for testing drilling and excavating equipment. In addition, both MLS-1 and JSC-1 are basaltic, whereas only 17% of the lunar crust is basaltic. Regolith at potential ISRU mission sites may well be anorthositic.

## **OBJECTIVES**

The objectives of this study are to (1) characterize the lunar regolith based on Apollo reports, and studying the physical and mechanical properties of selected samples returned from the Apollo missions using optical and electron microscopy; (2) based on the physical parameters derived from the natural regolith, strive to replicate these using terrestrial analogue rocks and other materials; (3) Test EVC/NORCAT drilling, excavation and processing equipment, enabling EVC/NORCAT to learn how to best operate in lunar regolith.

## **METHODS**

The following methodology has been followed: (1) appraise Apollo samples; (2) study remote sensing data from Lunar Prospector, Clementine, and SMART-1, in order to interpret the mineralogy and large-scale textural properties of the lunar surface; (3) choose suitable source materials for simulant (rocks, glass, etc.); (4) create simulant components through crushing and other procedures; (5) perform mechanical testing and analysis of simulant; analyse grain size and shape distribution, in addition to various other engineering properties (including response to shear, cohesion, compressive strength, and compaction); (6) determine how to run analogue drilling and excavating tests with maximum efficiency; and (7) use simulant to test robotic equipment.

## **PROGRESS**

Numerous reports and descriptions of Apollo samples have been studied in order to determine the desired regolith simulant properties. The required proportions and grain size distribution of regolith components have been determined for NORCAT testing purposes (see Table 1). A detailed comparison of several potential analogue components has been completed, including field investigations of several analogue rocks from the Canadian Shield. One anorthosite has been selected and sampled, based on both its physical and chemical similarities to similar lithologies on the Moon. Extensive crushing trials and grain size distribution determinations (via sieving) have been completed, and ideal methods for crushing the anorthosite component of the simulant to the proper grain shape and grain size distribution have been determined (see Tables 2 and 3). A more detailed explanation of crushing requirements to reproduce natural regolith characteristics can be found below. Crushed anorthosite will be used to represent the first three components of lunar regolith: mineral fragments, rock fragments, and breccia fragments, and therefore will account for 60-70 % of the total simulant. Processes for simulating glasses and agglutinates, which will account for the remaining 30-40 %, are currently under investigation, with preliminary results expected by October 2005.

### **Grain Size Distribution**

Target grain size distribution ranges for the rock, mineral, and breccia fragment component of the lunar regolith simulant were calculated based largely on Apollo 16 anorthositic lunar regolith data. The ranges listed in Table 1 are based largely on data from Houck (1982), and Morris et al. (1983), for Apollo 16 samples 64501 and 64500, as well as some assumptions for the 500-1000  $\mu\text{m}$ , and 0-20  $\mu\text{m}$  size ranges. Tables 2 and 3 show actual size distributions achieved during test runs. Table 2 shows an early trial, using only a jaw crusher, then roll crusher, which produced

more coarse-grained material. Table 3 shows the final trial, using a jaw crusher, roll crusher, and ring crusher in sequence, and has a size distribution close to the target ranges, as listed in Table 1.

**TABLE 1.** Size fraction target ranges for crushed rock component of simulant

<b>Size fraction:</b>	<b>0 - 75 <math>\mu\text{m}</math></b>	<b>75 - 150 <math>\mu\text{m}</math></b>	<b>150 - 250 <math>\mu\text{m}</math></b>	<b>250 <math>\mu\text{m}</math> - 1.18 mm</b>	<b>1.18 - 9.5 mm</b>	<b>&gt; 9.5 mm</b>
Percent of sample:	26 - 35 %	14 - 21 %	10 - 13 %	20 - 22 %	10 - 13 %	3 - 5 %

**TABLE 2.** Preliminary grain size distribution achieved by crushing with a jaw and roll crusher

<b>Size fraction:</b>	<b>0 - 75 <math>\mu\text{m}</math></b>	<b>75 - 150 <math>\mu\text{m}</math></b>	<b>150 - 250 <math>\mu\text{m}</math></b>	<b>250 <math>\mu\text{m}</math> - 1.18 mm</b>	<b>1.18 - 9.5 mm</b>	<b>&gt; 9.5 mm</b>
Percent of sample:	1.39 %	2.05 %	3.18 %	26.51 %	57.49 %	9.38 %

**TABLE 3.** Final grain size distribution achieved by crushing with a jaw, roll, and ring crusher

<b>Size fraction:</b>	<b>0 - 75 <math>\mu\text{m}</math></b>	<b>75 - 150 <math>\mu\text{m}</math></b>	<b>150 - 250 <math>\mu\text{m}</math></b>	<b>250 <math>\mu\text{m}</math> - 1.18 mm</b>	<b>1.18 - 9.5 mm</b>	<b>&gt; 9.5 mm</b>
Percent of sample:	29.14 %	18.00 %	17.24 %	22.08 %	9.53 %	4.01 %

## **Natural versus Artificial Crushing Processes**

Meteoroid bombardment is the largest controlling factor in the production and evolution of natural lunar regolith. It causes a general decrease in grain size through breaking down regolith particles. However it also creates regolith breccias and melt, which can then form agglutinates, thus increasing the grain size of some particles (Heiken et al., 1991). Because of the lack of wind and water on the lunar surface, however, broken particles remain angular, and do not become rounded. Therefore, in artificially replicating the crushing process to create a lunar regolith simulant, it is important to avoid rounding as much as possible. This can be achieved through minimizing the amount of time the rock spends in the crusher, and also by minimizing inter-particle interactions. Therefore, crushing machines such as jaw crushers and roll crushers, which allow crushed rock to pass through very quickly, are preferred over ball and rod mills. An ideal crushing procedure involves running rocks through a jaw crusher, roll crusher, and ring crusher, in sequence.

## **SUMMARY**

In summary, the goals of this project are to develop a “recipe” for creating a physical/mechanical lunar regolith simulant, and to generate a large quantity of simulant (on the scale of several tonnes or tens of tonnes). At this point, only the crushed rock component of the simulant (representing the crushed rock, mineral, and breccia fragments in natural lunar regolith, and accounting for 60-70 % of the total simulant) has been accurately produced. Test production of the glass and agglutinate components is underway. Producing large quantities of simulant will enable the testing of lunar drilling and excavating equipment in preparation for future lunar robotic surface missions, especially for ISRU purposes. It is our hope that ultimately this study will aid in the establishment of human colonies on the Moon, and perhaps Mars.

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