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Effect of Water Ice Content on Excavatability of Lunar Regolith

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Abstract. The amount of water ice contained within prepared samples of JSC-1 lunar regolith simulant strongly affects the excavatability of the material. As part of a NASA Phase I SBIR project, load-penetration testing of JSC-1 lunar regolith simulant was performed at water ice concentrations ranging from zero to 11% by mass (approximately saturated), after compaction and cooling to simulate probable lunar conditions. After mixing dry JSC-1 simulant with the appropriate amount of water, the samples were individually compressed into containment rings under 48 MPa of pressure. Thermocouples embedded in the samples monitored internal temperature while they were cooled in a bath of liquid nitrogen. At temperatures corresponding to the lunar polar cold traps, a 19mm-diameter hemispherical indenter was forced into the center of each sample while the required force and the resulting penetration were recorded. The results show strong sensitivity to water content. Regolith containing up to 0.3% water ice is very easy to excavate and behaves like weak coal. Regolith with 0.6 to 1.5% ice is readily excavatable and acts like weak shale or mudstone. Regolith with ~8.4% ice would be excavated with mechanical excavators, much like moderate-strength limestones, sandstones, and shales. The highest strength mix (~10.6% ice) behaves like strong limestone or sandstone, which require massive excavators. These results show that realistically compacted ice-regolith mixtures may be harder to excavate than previously believed, and that mixture variability must be well-understood to design effective excavators.

Keywords: regolith, ice, fragmentation, excavation, mining.

PACS: 91.60 Ba.

INTRODUCTION

Successful human return to the Moon requires the ability to use locally available resources. Two resources are indicated by the hydrogen signal detected by the Lunar Prospector orbiter (Feldman et al., 1998) near both lunar poles. The readings could be due either to water ice from cometary impacts, preserved within permanently shadowed regolith, or to solar wind protons implanted in regolith grains (Vondrak and Crider, 2003). Both can provide useful materials for lunar activities. Both must be excavated to extract their valuable constituent(s). Indeed, reliable excavation capability is crucial for all lunar surface activity – and much of the orbital activity – to come.

Production of geologic materials consists of several unit operations: fragmentation, loading, hauling, comminution (secondary fragmentation), and separation. The quality of the initial fragmentation is crucial to all subsequent stages, for it enables the raw material to be removed from its effectively infinite surroundings. Mechanical excavators rely on mechanical rather than explosive energy for fragmentation. This is accomplished by the cutterhead, a rotating device mounted with cutting tools that apply forces to the material in the necessary magnitude and configuration to cause it to fail. Cutting tools can be of many designs, from picks to drag bits to disc cutters. Selection of cutter type and layout depend more on the properties of the material than on anything else.

Thus the effective design of mechanical excavators relies on accurate characterization of the target material and on repeated field testing. The work reported here addresses the first requirement. The physical processes underlying

fragmentation are too complex for excavator performance prediction from basic principles, but decades of rock and soil excavation research have provided useful empirical relationships that can be used for lunar operations if the parameters are well-characterized. The goal of this project was to measure material behavior indices as the first step of excavator design. The widely used load-penetration test was chosen, to provide two basic material excavatability indices: specific penetration and specific energy.

Property data or estimates for the properties of dry lunar regolith are readily available, but very little is known about the mechanical properties of ice-regolith mixtures under conditions at the lunar poles. We inferred some properties from terrestrial experience with frozen soils and permafrost. Reports indicate that the physical properties of frozen soil are sensitive to several factors, including water content, temperature, and particle shape and size distribution. JSC-1 lunar regolith simulant was used as the most reasonable facsimile available of the source material of the hydrogen signature discovered by Lunar Prospector.

SAMPLE PREPARATION AND TESTING

Mechanically mixing water with fully dried JSC-1 lunar regolith produced samples with water concentrations ranging from less than 1% to full saturation. Multiple samples were taken from single batches of simulant after the water addition to verify that the mixtures were homogenous. Then, test samples were compressed into 10.9cm-diameter stainless steel test rings (cylinders with closed bottoms) with a force of 467 kN while bulk deformation was monitored. This was to simulate the effect of long-term regolith compaction due to meteorite impacts. After sealing to prevent contamination, the samples were immersed in a liquid nitrogen bath to cool them to approximately -196 °C (77 K), as measured by a type K thermocouple placed inside each sample.

An electro-hydraulic closed loop servo-controlled universal testing machine, operated in displacement-control mode, performed the load-penetration tests. The upper platen was displaced downward at the highest rate achievable (1.24 mm/sec), pushing a 19-mm diameter hemispherical indenter (Figure 1) vertically into center of the specimen. This simulates the action of a cutting tool on an excavator cutterhead. At the failure point the upper platen was withdrawn and a photograph was taken to show the pattern of surface chip formation. Then the specimen was sealed in a plastic bag to preserve its moisture content for later measurement. The platen displacement and the load required to achieve it were monitored at 50 Hz during the loading sequence, which also was video-recorded.

After melting of the intergranular ice, the remains of each sample were removed from its bag for careful excavation of the failed zone by hand. The sample material was divided into three groups (chips, fines, and the undamaged portion of the sample). The loose material was weighed to calculate the size of the failed portion.

The indices of interest from load-penetration tests are the specific penetration and the specific energy. Specific penetration is the slope of the load portion of the first major failure, shown in test curves (Figure 2) as the first large sawtooth waveform. It is the unit load required to reach the penetration at which the first failure occurs. Specific energy is the energy required to fragment a unit volume of material, calculated from the area beneath the loading curve (the work done by the indenter) divided by the excavated volume. Both indices are normalized values.

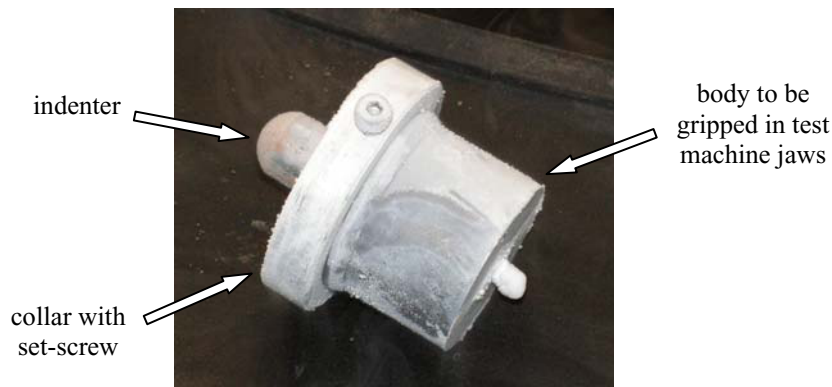


FIGURE 1. The 19-mm Diameter Hemispherical Indenter in the Holder Used during the Tests.

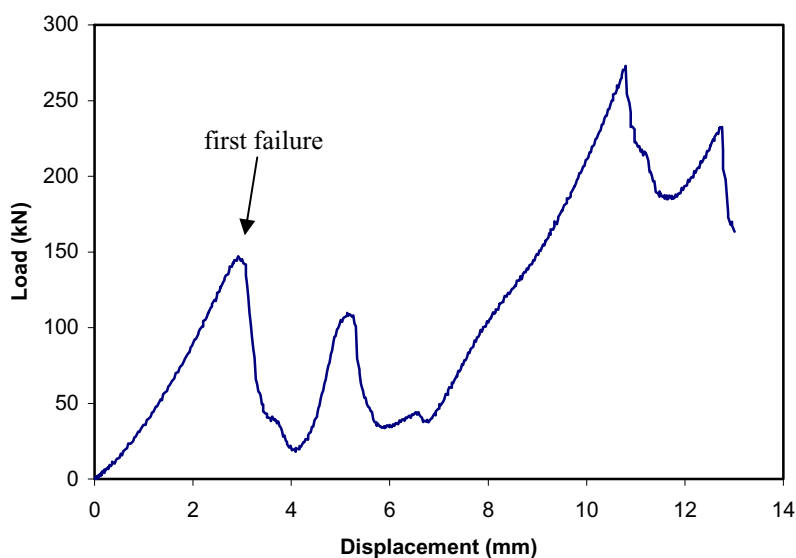


FIGURE 2. A Typical Load-Penetration Test Curve. Sample Consisted of 1.48% Water in JSC-1 Lunar Regolith Simulant, Compacted to 467 kN, Indented at a Temperature of 77K and a Speed of 1.24 mm/sec.

LOAD-PENETRATION TEST RESULTS

Table 1 lists the test results. The data are segregated into four groups according to ice content and sample behavior during indentation.

TABLE 1. Load-Penetration Results for Compacted JSC-1 Lunar Regolith Simulant with Various Water Concentrations at 77 K, Indented at 1.24 mm/sec.

Sample	Water Content (wt%)	Bulk Density (g/cm ³)	Dry Density (g/cm ³)	Failed Mass (g)	Failed Volume (cm ³)	Total Energy (J)	Volume to Energy Ratio (cm ³ /J)	Specific Energy (J/cm ³)	Average Specific Penetration (kN/mm)	First Failure Specific Penetration (kN/mm)
5	0.00	1.90	1.90			0.33			1.2	0.16
12	0.00	1.89	1.89	187	98.8	0.35	286	0.0035	0.8	0.15
TS1	0.32	1.91	1.91			0.15			2	0.22
TS2	0.25	1.88	1.88	173	91.9	0.19	477	0.0021	0.7	0.08
3	1.48	1.98	1.95			9.13			9	4.7
4	1.30	1.89	1.86			3.34			5	4.2
10	1.03	1.88	1.85	70	37.3	7.26	5.13	0.20	5	0.93
11	0.57	1.92	1.89	65	33.9	2.49	13.6	0.073	4	0.61
1	8.80	2.15	1.93			53.7			20	23
2	8.56	2.26	2.03			47.7			28	32
8	8.38	2.18	1.96	55	25.3	49.6	0.509	2.0	24	30
9	7.88	2.13	1.91	65	30.6	51.2	0.597	1.7	27	25
6	10.97	2.18	1.74	35	16.1	53.0	0.304	3.3	46	30
7	10.17	2.22	1.77			30.9			47	32
7reload	10.17	2.22	1.77	26	11.7	70.3			64	49

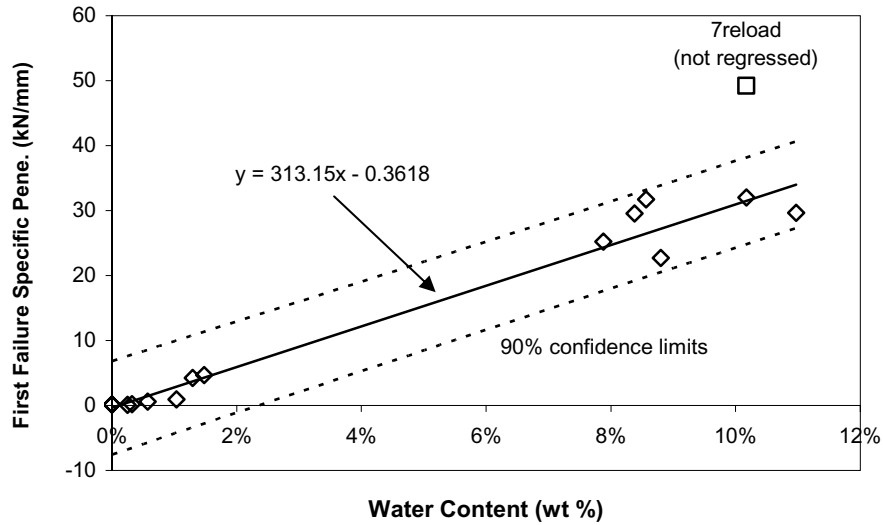


FIGURE 3. Effect of Water Content of JSC-1 Lunar Regolith Simulant on First Failure Specific Penetration.

Overall, Figure 3 shows that the specific penetration of JSC-1 lunar regolith simulant increases with increasing moisture content, at least up to saturation levels. This trend is apparent also in Figure 4, which shows specific energy as a function of water content, and in Figure 5, which shows excavated volume as a function of water content. All are affected significantly by water ice content.

Figure 3 shows an apparent change in failure mechanism between 1.0% and 1.3% water content that may be a switch from ductile (soil-like) to brittle (rock-like) behavior. This observation is supported by subtle changes in failure morphologies and in the shapes of the load-penetration curves (not shown). The greater scatter of the data near saturation, however, indicates that the apparent step pattern of the drier samples may be coincidental. Resolving this question is important. Since the apparent threshold is within the ice contents estimated for lunar polar deposits, excavators working there may have to operate in two different failure regimes, with different accompanying cutterhead requirements.

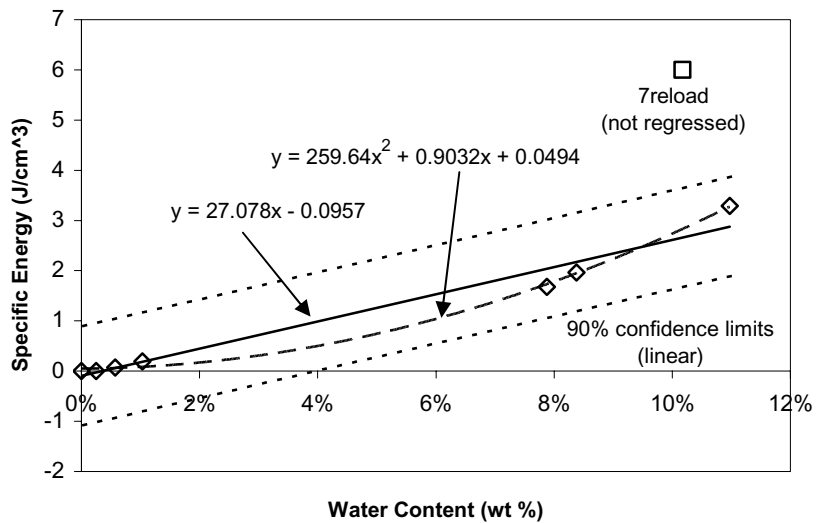


FIGURE 4. Effect of Water Content of JSC-1 Lunar Regolith Simulant on Specific Energy.

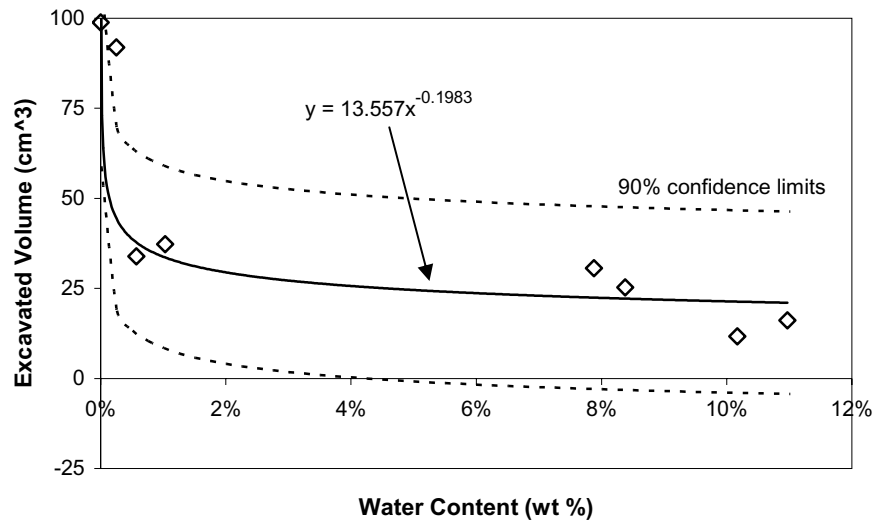


FIGURE 5. Effect of Water Content of JSC-1 Lunar Regolith Simulant on Excavated Volume.

Meanwhile, Figure 4 shows that the specific energy of the drier samples is related linearly to water content, while samples nearer saturation appear to follow a quadratic relationship. Specific energy combines two full-test measures: Total energy expended and total volume excavated. Here the potential step function is not apparent, indicating that if it is repeatable, it is more likely to be a function of the initial penetration behavior. Specific penetration has been shown to be indicative of the general excavatability and toughness of rock (Gertsch, 2000).

The points in Figure 5 are as consistent with a bilinear function (with the knee between 1% and 3% water content) as with the power law shown, indicating again some ambiguity in the relationship type. The specific penetrations plotted in Figure 3 reflect regolith behavior only during actual loading to the first failure, whereas the excavated volumes plotted in Figure 5 reflect behavior over entire tests, with multiple chip failures. Thus they represent somewhat different time-scales of behavior. Figure 5, however, does show that small increases in water content in nearly dry regolith strongly reduce the volume excavated by a single indentation. Aside from the question of changes in regolith failure mechanisms, higher moisture content thus would lead directly to lower production rates, for a given set of machine specifications of power, thrust, and torque. When the excavated volume goes down and cutting force does not change significantly, the cut spacing required for minimum energy expenditure is reduced as well. If it were not, the material would not fragment between cuts, but would remain as difficult-to-remove ridges that abrade and wear the cutterhead. When such ridges do finally break apart, they form large chunks that are difficult for the material transfer system to handle.

Note that in Figures 3 through 5, the data are mostly contained within the 90% confidence limits. Their width indicates that the small number of samples must be augmented to show whether these potential phenomena – step functions, linear vs. quadratic vs. other relationships – are real or artifacts. The sample that was reloaded after initial failure is included to show the effect of initial disturbance on material response to cutter indentation.

Examination of the individual load-penetration test plots (not shown) revealed additional features of indenter behavior that affect excavator performance. At very low water contents, significant penetration occurs before the indenter experiences meaningful resistance. As water content increases, the material begins resisting earlier in the penetration, and continues resisting to relatively high failure load; in other words, brittleness increases with water content. At 77 K, ice behaves more like a strong brittle material than like a collection of noncohesive dry regolith particles. Material with the highest water contents – approximately saturated – loads rapidly, fails at shallow penetration, then rapidly reloads and fails again several times in succession. It doesn't "give up" as readily as drier mixtures; it continues to resist as indentation increases.

To illustrate this trend, consider Table 1, which traces typical behavior from baked-dry to saturated simulant in the four groupings just discussed. Table 2 summarizes the qualitative observations of indenter behavior related to ice content.

TABLE 2. Qualitative Assessment of the Effect of Water Content in Compacted JSC-1 Lunar Regolith Simulant on Load-Penetration Test Results.

Ice Content	Penetration at First Failure	Excavated Volume	Load at Failure
Dry	Deep	Large	Low
Low	Deep	Large	Low to Moderate
Moderate	Deep	Moderate to Large	Moderate
High	Deep	Moderate	High
Saturated	Shallow	Small	Very High

These results agree qualitatively with similar tests being conducted for the Regolith & Environment Science and Oxygen & Lunar Volatile Extraction (RESOLVE) project presently underway (one of the authors [Gustafson] is a member of the RESOLVE team). They found that as water content increases from approximately 2% to 10%, ice-regolith simulant mixture behavior changes from very friable to “rock-like”. Further tests are planned.

TEST CONDITIONS VERSUS EXPECTED FIELD CONDITIONS

The ice-regolith samples fabricated and tested in this study provide an initial estimate of the mechanical properties of the material within the lunar polar cold traps that may be encountered during excavation and mining. However, the samples were formed and tested under conditions quite different than the expected lunar conditions (Table 3).

TABLE 3. Comparison of Test Sample Characteristics with the Expected Lunar Ice-Regolith Deposits.

Characteristic	Test Samples	Expected Lunar Conditions
Temperature	~77 K	30-50 K
Pressure	~1 atmosphere, air	hard vacuum
Anisotropy and Heterogeneity	uniform water content throughout	unknown
Form of Ice	crystalline (hexagonal)	amorphous or crystalline
Ice Content	0-11 wt%	average 1.5 +/- 0.8 wt% maximum 10%
Bulk Density	1.8-1.9 g/cm ³	1.3-1.9 g/cm ³
Aggregate Mechanical Behavior	JSC-1 lunar simulant	lunar polar ice-regolith mixture

The expected temperatures in the permanently-shadowed craters on the Moon (30-50 K) are lower than the temperature of the test samples (77 K). However, this difference is not expected to affect the mechanical properties of ice-regolith mixtures significantly. Ice is characterized by very weak hydrogen bonds between the atoms, bonds whose mobility decreases sharply as temperature decreases. Reduced mobility increases the strength of the ice structure. Ice strength increases approximately 5 to 10 times when temperature goes from 273 K to 150 K. Ice strength below 150 K remains approximately constant (Ivanov, 2001). Therefore, reducing the temperature from 77 K to 30 K should have little effect on the mechanical properties of ice-regolith mixtures.

The samples were tested under ambient laboratory atmospheric composition and pressure. It is not known what effect, if any, the presence of the air has on the behavior of the test samples, but this would be easy to determine by

comparing the behavior of identical samples prepared and tested under vacuum and ambient conditions. The effect of vacuum on the penetration behavior of ice-regolith mixtures is expected to be quite small.

Both the anisotropy and the heterogeneity of ice-regolith mixtures affect their fragmentation and excavation mechanics. For example, a broad size distribution of lunar soil particles with thin ice coatings will behave differently than interspersed layers of ice and soil. The most likely configurations of lunar cold trap deposits are thought to be (Rice, Gustafson, and Teeter, 2000):

- Finely granular – formed by gardening of soil with introduction of ice grains.
- Ice chunks mixed with the regolith – formed by gardening of comet ice layers.
- Solid ice/regolith layers – formed by continuous accumulation of ice and diffusion of water.
- Trapped H₂ gas from the solar wind – expected to behave similarly to dry regolith.

In general, frozen soils with larger particles are stronger than those with smaller particles, and those with a wide range of particle sizes are stronger than those with a narrow range. In addition, the angularity of the particles increases the soil strength, and the particles of the Apollo soil samples tend to be very angular.

Ice acts as a cementing agent in unconsolidated materials, increasing cohesion and thus increasing resistance to cutter penetration. However, ice solidification within already well-consolidated material decreases its strength by inducing local failure. Due to uncertainties in the field distribution of water ice, only homogenous mixtures of water and simulant were compacted and frozen for testing in this study. These samples may represent some of the stronger ice-regolith mixtures that may be encountered on the Moon, but only field measurements can confirm this.

It is not known whether water ice – if present in lunar regolith – is amorphous or crystalline. Temperatures within permanently-shadowed regions may be as low as 30-50 K, at which water vapor forms low-density amorphous ice under vacuum. However, amorphous ice is relatively unstable. If the temperature rises above 120 K, it rapidly crystallizes. And even if lunar ice is amorphous, it may crystallize under the pressure of the cutters during excavation. The effects on excavator performance are not understood. Indeed, lunar ice may already be crystalline, judging from recent infrared spectra of Charon (where temperature never exceeds 80 K and is generally 35-50 K) that show that water ice there is in fact mostly crystalline (Brown and Calvin, 2000; Young, 2000).

Variation of the uniaxial compressive strength of frozen soils with water content is consistent for all types of terrestrial soil in which the grains are equidimensional (Tsytoich, 1975). Such soil, when frozen, is weakest where it is completely dry; in that state it is weaker than pure water ice. Its strength increases rapidly with ice content to a maximum value where the soil is saturated, after which the mixture strength decreases more slowly (as ice content continues to increase) until it is between the strengths of pure water ice and dry regolith. Once most regolith grains lose contact with each other, the relative solids content has little effect, and the mixture strength remains below that of ice. It rises again to converge with the strength of pure ice as the relative solids content goes to zero. The relationship between water ice content and mixture strength becomes more complex where the grains are not equidimensional (Coble and Kingery, 1963), especially where they are aligned in a preferred orientation. Lunar regolith is not expected to be anisotropic on the scale of the grains.

Granular material is saturated when all void space is filled with water. Therefore, the volumetric water content at saturation is equal to the porosity of the dry regolith. The average porosity of lunar regolith from 0-60 cm depth is 46% by volume. The average density of solid lunar regolith grains is estimated at 3.1 g/cm³. The average density of water ice is 0.92 g/cm³. Therefore, saturated lunar regolith within 0.6 m of the surface would contain about 19% water ice by mass, on average. (The JSC-1 simulant, when compacted for this study, was able to accommodate about 11% water, indicating that the porosity of the tested material was less than the theoretical porosity of actual regolith, even when the volume change induced by freezing is taken into account.) The density and cohesion of the lunar soil increase rapidly in the first 60 cm from the surface, as the void space available for ice “cement” diminishes. Thus the probability of high-grade ice deposits, and stronger ice-cemented regolith, is greater at shallow depths. The strength of undisturbed regolith would be a simpler function of depth if the hydrogen exists instead as protons implanted in the solid grains.

If the hydrogen concentrations measured by Lunar Prospector are water ice, the ice content averages 1.5 +/- 0.8% by mass. It is likely that the ice-rich regolith is covered by a layer of relatively dry regolith. However, the resolution of the data is tens of kilometers per pixel, far too coarse to show local concentration variations. Recent re-analysis of

Lunar Prospector data indicates that local ice concentrations may exist in excess of 10% by mass, near or above the maximum strength limit. The ice may contain other volatile compounds that could affect the behavior of the material. Mapping is needed at much higher vertical and especially horizontal resolutions to determine the appropriate emphasis for further excavability tests.

The JSC-1 lunar simulant was designed to be chemically, mineralogically, and texturally similar to a mature lunar mare regolith. The glass-rich character of JSC-1 (~50%) imparts quite different properties to other lunar simulants, properties that are similar to lunar mare near-surface regolith, which is fundamentally different from lunar highland regolith. The composition of the soil in the polar regions is not known, but is believed to be closer to a highlands regolith. Therefore, it is not clear how well JSC-1 simulates the mechanical behavior of lunar soil near the poles.

CONCLUSION

Load-penetration tests of lunar regolith simulant indicate that water ice content significantly affects lunar regolith excavability. Specific penetration predicts material excavability and uniaxial compressive strength. Specific energy predicts excavator power requirements and production rate. Based on measured values of specific penetration and specific energy, the ice-regolith mixtures tested match the following terrestrial analogs: The low-strength mixture (0 to 0.3% ice) is easy to excavate and behaves similarly to very weak coal. The moderate-strength mixture (0.6 to 1.5% ice) is readily excavatable and behaves similarly to weak shales or mudstones. The high-strength mixture (~8.4% ice) would be excavated with mechanical excavators, much like moderate-strength limestones, sandstones, and shales, while the highest strength mixture (~10.6% ice) would be mined on Earth with relatively massive excavators. It behaves similarly to relatively strong limestones and cemented sandstones. Material with such a wide range of properties is difficult to excavate with a single cutterhead layout, especially where the ice concentrations vary over short distances (on the order of a few multiples of the excavator dimensions).

These experimental results show how important it is to obtain high-resolution data to characterize lunar regolith that may contain even low levels of water ice, and to design and continuously test flexible yet robust excavators that are able to deal with it. A dual-focused program of material characterization and excavator design and testing is required to maximize the chances of success in our return to the Moon and continuation to Mars and beyond.

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