

Conclusions: It is the author's opinion that there has been too much dependence upon terrestrial heuristics in suggesting digging methods for the Moon and not enough attention to basic forces, required mass, required power, and expected production rates. Progress toward more basic research is being made, however. Results of work at the University of Colorado and Texas A&M University will prove important for the selection of efficient methods. Short-term results at Texas A&M University are expected to reveal quantitative and verifiable evidence as to which methods are more promising. Long-term results are expected to include candidate methods for prototype development and testing.

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SHOCK-TREATED LUNAR SOIL SIMULANT: PRELIMINARY ASSESSMENT AS A CONSTRUCTION MATERIAL. Mark B. Boslough¹, Leonhard E. Bernold², and Yasuyuki Horie², ¹Sandia National Laboratories, Albuquerque NM 87185, USA, ²North Carolina State University, Raleigh NC 27695, USA.

In an effort to examine the feasibility of applying dynamic compaction techniques to fabricate construction materials from lunar regolith, we have carried out preliminary explosive shock-loading experiments on lunar soil simulants. Analysis of our shock-treated samples suggests that binding additives, such as metallic aluminum powder, may provide the necessary characteristics to fabricate a strong and durable building material ("lunar adobe") that takes advantage of a cheap base material available in abundance: lunar regolith.

Introduction: Because of transport cost considerations, it is clear that the vast majority of construction material for lunar structures must be indigenous. The most readily attainable material on the Moon is regolith, so an obvious question is: What is the easiest method of converting lunar regolith to a construction material?

One technology that has been used to modify materials involves the use of shock treatment [1,2]. The principal concept relies on exerting an extremely high dynamic force on a certain base material that is mixed with an agent and thus changes its properties. If such a process could be emulated on the Moon, new soil-based "lunar adobe" construction materials could be created. Although this technology has been proven on Earth, research is needed to study the feasibility of such an approach under lunar conditions and to evaluate the consequences on the design, engineering, and construction of lunar bases.

Experimental: We have performed two shock recovery experiments on samples of a lunar soil simulant. These experiments made use of the Sandia "Momma Bear" explosive loading fixtures to achieve well-characterized shock states. These recovery fixtures allow samples to be shocked in a controlled, reproducible manner. A planar shock wave is generated by detonating a high-explosive lens next to an explosive pad. The shock wave passes through an iron pulse-forming plate and into the copper fixture, which contains the 5 cm³ powder sample. The entire assembly has cylindrical symmetry. Because of the large impedance difference between the sample and copper, and the finite lateral extent of the sample, the shock loading is not a simple, one-step uniaxial process. On the contrary, the initial loading is due to a radially converging shock wave, and the final shock state at a given position is reached by a series of shocks.

Shock pressure and temperature histories were determined numerically by two-dimensional computer simulations [3,4]. These calculations are based on the geometry of the sample holder, the type of explosive, and the initial packing density of the powder (in general, the lower the packing density, the higher the shock temperature as long as nothing else is changed). The two experiments for the present study made use of the explosive Baratol, and the peak shock pressure range was 510 GPa, with the peak pressure a function of position within the sample.

For the first experiment (13B917) the sample was "Minnesota Simulant" Lot 2, with particle size between 50 and 100 mesh, and a mean initial powder density of 1.896 g/cm³. The second experiment (14B917) made use of the same simulant, with an admixture of aluminum metal; CERAC A-1189, 99.99% pure with a particle size less than 325 mesh. The mean initial powder density of the mixture was 2.051 g/cm³. The material used in these experiments was intended to simulate the crystalline fraction of basaltic lunar regolith. The simulant was taken from the fine-grained basalt of the Duluth Complex, Minnesota, and was provided by P. W. Weiblen [5].

Results: Macrocracking was only observed in the sample with aluminum binder. It is possible that the cracking was created during the postshock handling of the compacts. The samples appear to have been compacted to densities in the range from 70 to 85%, but they had very little mechanical strength. However, strong metallurgical bonding of nonmetallic powders by weak shock in the peak pressure range of 5-10 GPa cannot be expected. A rough estimate of the threshold pressure required for shock consolidation is twice the Vickers microhardness of the solid materials. Thus, without the use of binding additives, several tens of GPa are required to consolidate lunar simulants.

TABLE I. Impression tests of lunar material.

Sample	$E_c \left(= \frac{d\sigma_c}{d\epsilon_c} \right)$ [MPa]	σ_c^i [MPa]				σ_c^{max} [MPa]	ϵ_c^{max}	K'	n'
		0.2%	0.5%	UYP	LYP				
Lunar #2-1	1057	37.5	36.5	38	36.7	54.9	0.077	494	0.945
Lunar #2-2	1078	58.2	60.3	58.2	58.2	73.8	0.093	396	0.904
Lunar #2-3	1329	54.3	52.5	56.4	52.4	67.2	0.064	388	0.810
#2/Al Binder	8957	175	207	—	—	210.6	0.032	5021	0.971

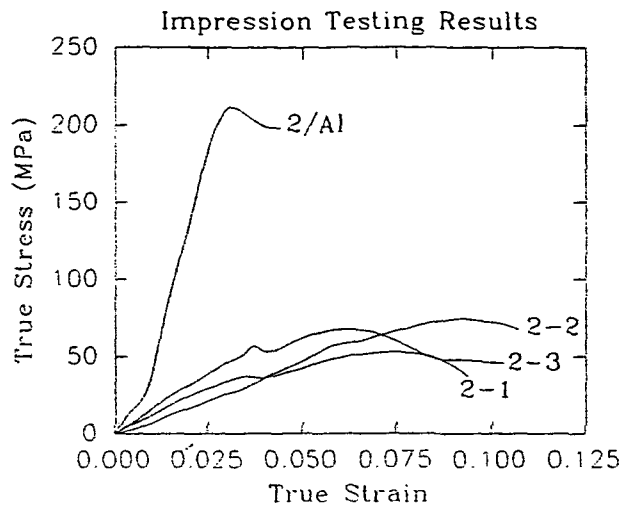


Fig. 1. Results of impression tests. 2-1, 2-2, and 2-3 are samples from experiment 13B917 without binder. 2/A1 is from experiment 14B917 with aluminum binder.

There are two noteworthy features that are evident from optical microscopy:

1. Compact densities are strongly influenced by the addition of aluminum particles. The metal appears to have acted as a lubricant to enhance densification through interparticle sliding and rotation.
2. Aluminum particles are well dispersed as thin boundary layers between simulant particles. This type of mixing cannot be easily achieved by conventional mixing methods. Also, thinly dispersed layers may be exploited to enhance postshock processing of shock-compacted materials by acting as an agent for dynamic reaction sintering of lunar materials.

Impression Testing: Stress vs. strain curves were determined with a WC indenter (diameter = 1 mm, cross-head speed = 0.002 in/min). Material recovered from experiment 13B917 (no binder) was sampled from three different locations (2-1, 2-2, and 2-3). One sample (2/A1) was taken from experiment 14B917 (Al binder). Stress-strain data for these four samples are summarized in Table 1, and plotted in Fig. 1. The following is a brief summary of impression testing results for the two recovery experiments.

13B917 (no binder): Samples 2-2 and 2-3 yielded nearly identical values for strengths, but the strains were not consistent. When the samples were crushed, there was not enough strain energy to cause them to fly.

14B917 (Al binder): Sample 2/A1 was much stronger (see Fig. 1). Moreover, the failure mode was quite different from the other samples. The resistance to impression was very large, higher by a factor of about 3. The elastic modulus was higher by a factor of about 6. Strain energy caused the sample to shatter under maximum load, launching fragments at high velocity.

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A LUNAR PENETRATOR TO DETERMINE SOLAR-WIND-IMPLANTED RESOURCES AT DEPTH IN THE LUNAR REGOLITH. W. Boynton¹, W. Feldman², and T. Swindle¹, ¹University of Arizona, Tucson AZ 85718, USA, ²Los Alamos National Laboratory, Los Alamos NM 87454, USA.

Introduction: Several volatiles implanted into the lunar regolith by the solar wind are potentially important lunar resources. ³He might be mined as a fuel for lunar nuclear fusion reactors [1]. Even if the mining of ³He turns out not to be feasible, several other elements commonly implanted by the solar wind (H, C, and N) could be important for life support and for propellant or fuel production for lunar bases [2]. We propose a simple penetrator-borne instrument package to measure the abundance of H at depth. Since solar-wind-implanted volatiles tend to correlate with one another, this can be used to estimate global inventories and to design extraction strategies for all of these species.

Current Knowledge: A considerable amount is known about the distribution of solar-wind-implanted volatiles from analyses of Apollo and Luna samples. Since the energy of the solar wind is only sufficient to implant ions to depths of less than a micrometer into grains, these volatiles are only found on grain surfaces that were once exposed to the solar wind. However, the regolith is constantly gardened by impacts, so volatiles are mixed to depths of order several meters. Models predict that the hydrogen abundance of formerly exposed grains will fall off with depth in the lunar regolith (e.g., the model of [3] predicts an exponential fall-off with an e-folding distance of about 3 m). The Apollo drill cores are not much help in testing this because their lengths are short compared to the scales of interest (only one is longer than 2 m, and that one is only 3 m). In fact, the Apollo cores do not clearly show that there is any systematic decrease in volatile abundance with depth for the first 2-3 m [4]. This uncertainty could have a large impact on resource evaluation [4]: assuming that volatiles are uniformly distributed throughout the regolith (8-15 m deep) leads to a factor of 10 higher estimated global inventory than does assuming the distribution derived from the model of [3]. Furthermore, mining strategies for a resource found throughout the top 10 m or so of the regolith might be substantially different from ones for a resource found only in the top 2 or 3 m.

In the Apollo samples, most of the solar-wind-implanted volatiles correlate with one another and with other measures of soil "maturity" (extent of exposure to the solar wind) [5]. The exceptions are He and Ne, whose abundances show a strong dependence on the amount of the mineral ilmenite (and hence the Ti content). However, He and Ne also correlate with maturity if the Ti abundance is factored out [6]. Although the correlation of H content with maturity is not as strong as for some other elements in the Apollo samples (perhaps reflecting the difficulty in eliminating H contamination of the dry lunar soils), measurements of H with depth in the regolith should be indicative of all solar-wind-implanted species.

Basis of the Technique: Simple neutron counters have been shown to provide high sensitivity for the detection of low H