MECHANICAL STRENGTH OF MARTIAN ANALOG SOILS. J. Hanley[1], M. T. Mellon[1], and R. E. Arvidson[2]. [1]Department of Space Studies, Southwest Research Institute, Boulder, CO; [2]Department of Earth and Planetary Science, Washington University, St Louis, MO; jhanley@boulder.swri.edu.

Introduction: Mechanical properties of soils on Mars are important to understand since they affect various geophysical processes such as slope stability and wind erosion. The nature of cohesive bonds is also affected by the hydrologic cycle and aqueous geochemistry. Thus, mechanical properties serve as a window to modern martian climate processes.

Physical properties of the soil have been measured at every landing site [1-5]. High soil cohesion was encountered at the Phoenix landing site making sample analysis challenging; these soils were also reported to contain perchlorates [6]. Additionally, these soils had the characteristic of changing cohesion with time. Collected samples would clump and stick to spacecraft hardware (scoop and sample inlets) and release at a later time. Such cohesion may result from hydrated salts and eutectic brines bonding grains together at their contacts by wetting, or from salts crystallizing at grain contacts. Changes in hydration state with time (e.g., diurnally or seasonally) may then result in correlated changes in cohesive properties.

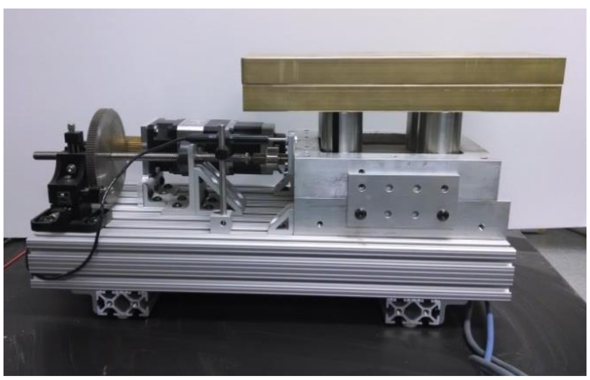

Figure 1. *Direct shear box apparatus, showing sample chamber and direct normal load (brass weights) on right and drive motor with shear stress and strain measurement on left.*

Determining Shear Strength: Soil strength is typically expressed as the Mohr-Coulomb failure criteria or failure envelope:

$$\boldsymbol{\tau = \sigma \tan(\varphi) + c}\,, \qquad (1)$$

where τ is shear stress at failure (Pa), σ is stress normal to the shear plane (Pa), φ is angle of internal friction (deg), and c is cohesion (Pa). By plotting shear stress versus normal stress and fitting a regression equation to the data, we are able to determine c and φ. Cohesion and angle of internal friction are not necessarily independent, as they both relate to physical interactions between grains. The cohesion is a strong measure of the adhesion of individual grains through forces associated with soil water, mineral cementation, and electrostatic attractions between charged grains. The angle of internal friction is influenced by the shape and roughness of grains and their ability to slide, including such factors as porosity and particle size distribution. The angle of internal friction is conceptually related to the angle of repose, though they are only equal in a dry, cohesionless soil.

Liquid water plays an important role in soil strength. In large quantities it can lubricate grains and reduce friction, but in small quantities it can result in increased cohesion due to capillary tension. Even thin films of adsorbed water can result in adhesion at grain contacts. At subfreezing temperatures, liquid-like films of adsorbed water remain stable in a liquid like state with a decreasing concentration with temperature or vapor pressure [7, 8], as well as ice. Both may act as a cementing agent.

We constructed a direct apparatus "shear box" (Figure 1) to test the mechanical strength of simulated martian regolith [9]. The top half of the box is moved with constant shear rate while the bottom half remains fixed. As stress on the soil is increased, failure will occur along the shear plane between the two halves. Normal loads are varied between 2 and 42 kg. Shear stress is measured with a load cell. An example of the results from a shear test is shown in Figure 2.

We conducted shear tests on two soil stimulants: (1) bulk Mojave Mars Simulant (MMS) [10], and (2) Glass Spheres of 150-180 μm (hereafter referred to as GS). The MMS was prepared in two sets: (i) dried at 100°C, and (ii) equilibrated with 100% humidity at ~23ºC. By measuring mass change, these resulted in: 0 wt% = dry and ~ 5 wt% = wet, respectively.

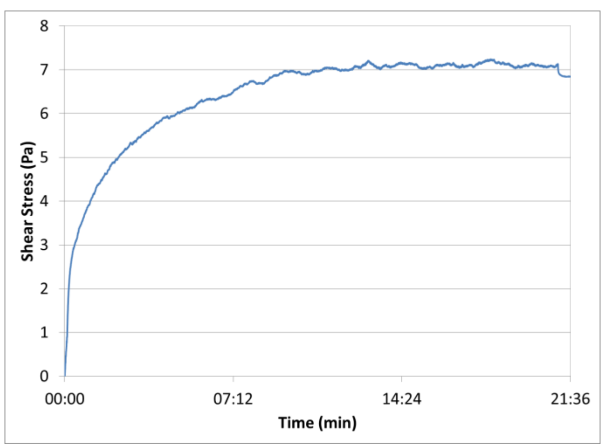

Figure 2. *Shear Stress (Pa) versus Time (hr) for dried MMS with 30 kg normal load. Shear stress increases quickly at first during elastic deformation before transitioning to plastic deformation [11]. Failure occurs at peak strength.*

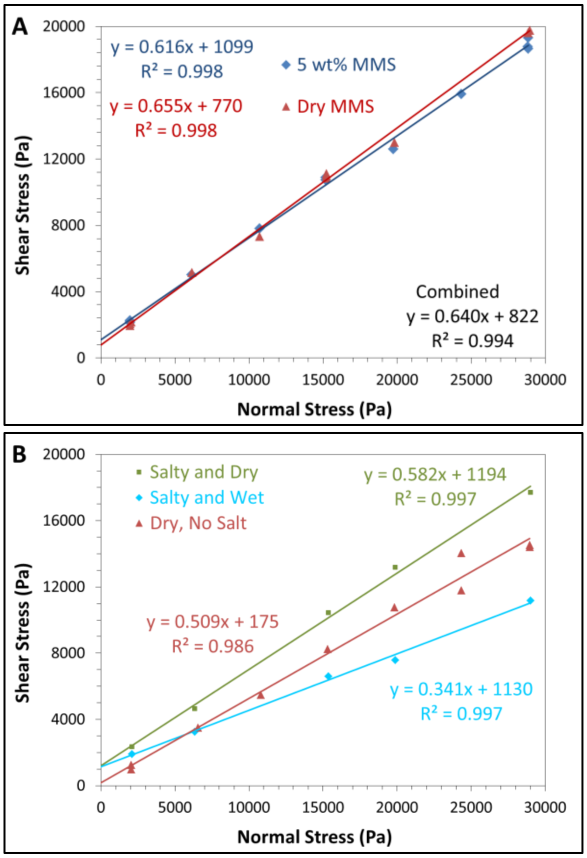

Figure 3. *Shear Stress vs Normal Stress for (A) MMS at various water contents and (B) Glass Spheres (GS) 150-180 μm at various salt and water concentrations. The regression equation gives the cohesion and angle of internal friction from Equation 1.*

Three sets were prepared of GS: Dry, no salt; salty and dry; and salty and wet. "Dry, no salt" was dried at 120°C overnight to remove all ambient water. For "salty and dry," $MgCl_2$ was dissolved in DI water and mixed with the GS, then dried at 50°C for two hours, with final drying occurring over two days in a dehumidifier, resulting in ~1.4 wt% $MgCl_2$. "Salty and wet" had 5.5 wt% water added to the salty and dry sample. All shear tests were done at room temperature.

Results and Discussion: MMS did not show significant differences between the two water contents (Figure 3A). The quantity of adsorbed water and its influence on the cohesion may be limited by the grain size and available surface area for the samples tested. Large grains relative to the wetted contact area may limit the total capillary tension. Natural soluble salts could also play a role, however MSS contains only on the order of 1 ppm of natural soluble salt.

Taken together, the cohesion for MMS <5 wt% is 822 Pa and the angle of internal friction is 32.6°. This cohesion falls between the previous measurements for the MMS sand component (810-1960 Pa and 38-39°) and that of the MMS "dust" component (380-530 Pa and 30-31°) [10].

Compared to measurements of soil strength taken on Mars, MMS falls on the low range of cohesion and in the middle of reported internal friction angle values (Table 1). In contrast, JSC Mars-1 has a reported cohesion of only 210 Pa and high angle of internal friction at 47° compared to Mars. This is unsurprising since JSC Mars-1 was manufactured for its spectral similarities to Mars, rather than its physical characteristics.

For GS, there are two effects (Figure 3B). First, by adding salt, the cohesion increases from 175 to 1194 Pa, but the angle of internal friction does not change much (27.0 vs 30.2°, respectively). However, once some water (5.5 wt%) is added to the salty GS, the angle of internal friction decreases from 30.2 to 18.8°, while the cohesion remains almost the same. This suggests that the salt is increasing cohesion, while water + salt will decrease angle of internal friction.

Conclusions: By studying different martian soil analogs (such as various arctic soils) and varying the water and salt content, as well as temperature, we can begin to understand the various factors that affect soil strength. Analysis of data from past, present and future missions will be enhanced by understanding the causes of slope failures, which contribute to mass wasting, dune migration and avalanche formation.

Table 1. Physical Properties of Mars Soils and Analogs.

	φ	*Cohesion (Pa)*
Phoenix [5]	29 – 47°	200-1200
MER Rovers [12]	30 – 37°	0-2000
Pathfinder [1, 13]	15 – 41°	10-600
Viking Landers [2]	18 – 35°	1100-5100
JSC Mars-1 [14]	47°	210
Our results		
Quartz sand	41.4±1.4°	24±103
MMS 5 wt% H_2O	31.6±0.7°	1099±168
MMS Dry	33.2±0.8°	770±184
GS Dry	27.0±1.8°	175±405
GS 5.5wt% H_2O, 1.4wt% $MgCl_2$	18.8±1.3°	1130±203
GS Dry, 1.4wt% $MgCl_2$	30.2±1.7°	1194±318

References: [1] Moore, H.J., et al. (1999) *JGR*, *104*, 8729-8746. [2] Moore, H.J. and B.M. Jakosky (1989) *Icarus*, *81*, 164-184. [3] Arvidson, R.E., et al. (2004) *Science*, *305*, 821-824. [4] Arvidson, R.E., et al. (2004) *Science*, *306*, 1730-1733. [5] Shaw, A., et al. (2009) *JGR*, *114*, E00E05. [6] Hecht, M.H., et al. (2009) *Science*, *325*, 64-67. [7] Anderson, D.M. and A.R. Tice (1972) *Highway research record*, 12-18. [8] Zent, A. and R. Quinn (1997) *JGR*, *102*, 9085-9095. [9] D-07, A., *Standard Test Method for Consolidated Undrained Direct Simple Shear Testing of Cohesive Soils*. ASTM Int'L. [10] Peters, G.H., et al. (2008) *Icarus*, *197*, 470-479. [11] Panien, M., et al. (2006) *J. Struc. Geol.*, *28*, 1710-1724. [12] Sullivan, R., et al. (2011) *JGR*, *116*, E02006. [13] Team, R. (1997) *Science*, *278*, 1765-1768. [14] Perko, H., et al. (2006) *J. Aerospace Eng.*, *19*, 169-176.