EXPERIMENTAL CONSTRAINTS ON THE MECHANICAL STRENGTH OF THE MARTIAN SOIL. J. Hanley[1], M. T. Mellon[1], and R. E. Arvidson[2]. [1]Southwest Research Institute, Boulder, CO; [2]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 chlorides, sulfates and perchlorates [6]. Trench walls were often very steep with some soils featuring "clods" that did not fall apart when disturbed (Fig. 1). Some of 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. In one instance, even after pressure with the robotic arm, the sample still did not fall through the inlet sieve into the WCL-3 cell. 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.

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

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

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

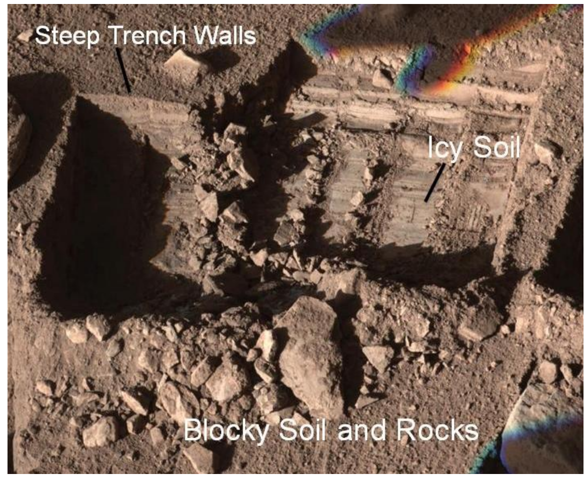

Figure 1. *SSI image of "La Mancha" trench excavated by Phoenix. Textures of the soil where the arm has disturbed it are indicators of the cloddiness of the soil. Image credit: NASA/JPL/University of Arizona/Texas A&M University.*

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 2) to test the mechanical strength of simulated Martian regolith [9, 10]. 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.

We conducted shear tests on two soil simulants: (1) bulk Mojave Mars Simulant (MMS) [11], and (2) Glass Spheres (GS). Two grain sizes were used: 150-180 μm and 38-45 μm. The MMS was prepared in two

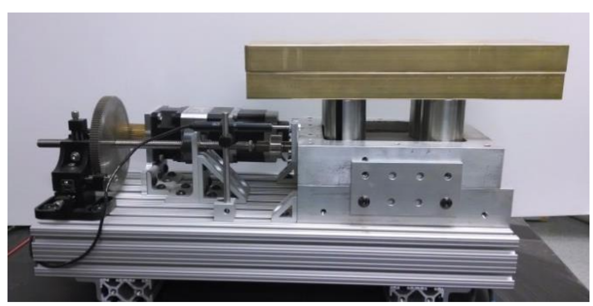

Figure 2. *Direct shear box apparatus, showing sample chamber and direct normal load (brass weights) on right and drive motor with shear stress and strain measurement on left.*

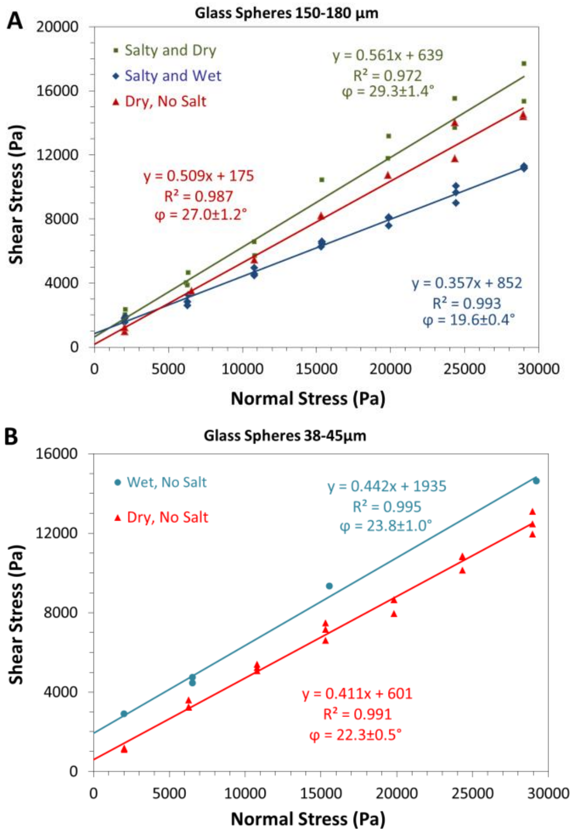

Figure 3. *Shear Stress vs Normal Stress for Glass Spheres (GS) (A) 150-180 µm and (B) 38-45 µm at various salt and water concentrations. The regression equation gives the cohesion and angle of internal friction from Equation 1.*

sets: (i) dried at 100°C (Dry), and (ii) equilibrated with 100% humidity at ~23ºC. Four sets were prepared for each GS: Dry, no salt; wet, no salt; salty and dry; and salty and wet. “Dry” samples were heated at 120°C overnight. “Wet” samples had 5 wt% water mixed in. For “Salty” samples, ~1.4 wt% $MgCl_2$ was mixed with the GS. All shear tests were done at room temperature.

Results and Discussion: For GS, there are multiple effects (Figure 3) due to salt, or water, or a combination of the two. First, for 150-180 µm (Figure 3A), by adding salt the cohesion increases, but the angle of internal friction does not change much. In the smaller grain size, 38-45 µm (Figure 3B), the effect of water alone is seen very clearly: by adding 5 wt% the cohesion is increased while the internal friction angle is unchanged. However, when salt and water are combined, the angle of internal friction decreases, while the cohesion remains almost the same as with salt or water alone.

MMS did not show significant differences between the two water contents. 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. 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.

Implications for Mars: Adding either salt or trace water will increase the cohesion by a factor of 3-5. Although the salt and water concentrations may differ, this is similar to what was observed at the Phoenix landing site, where a factor of 6 difference was seen between various measurements (200-1200 Pa) [5]. The cloddy soil texture seen in Figure 1 is also observed in the laboratory with small amounts of salt present.

By studying different Martian soil analogs (such as various arctic soils) and varying the water and salt content, as well as temperature, we can 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. *Mechanical 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	φ	*Cohesion (Pa)*
MMS	31.6±0.7°	1099±168
MMS Dry	33.2±0.8°	770±184
GS150-180 Dry, no salt	27.0±1.2°	175±405
GS150-180 Salty and Wet	19.6±0.4°	852±116
GS150-180 Salty and Dry	29.3±1.4°	639±401
GS38-45 Dry, no salt	22.3±0.5°	601±164
GS38-45 Wet, no salt	23.8±1.0°	1935±276

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] Hanley, J., et al., (2014) *LPSC*, #2879. [11] Peters, G.H., et al. (2008) *Icarus*, *197*, 470-479. [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.