MARTIAN REGOLITH COHESIONS AND ANGLES OF INTERNAL FRICTION FROM ANALYSIS OF MER WHEEL TRENCHES.

R. Sullivan[1], R. Anderson[2], J. Biesiadecki[2], T. Bond[1], and H. Stewart[1], [1]Cornell University, Ithaca, NY 14853, [2]Jet Propulsion Laboratory, Pasadena, CA 91109.

Introduction: Wheel trenching was carried out by the MER vehicles primarily to expose subsurface regolith for investigation by the science payload. In addition, opening a trench involves wheel/regolith interactions from which information about regolith strength can be obtained. Cohesion and angle of internal friction are paired parameters frequently used to describe soil strength characteristics in numerous terrestrial settings, as well as in previous missions to the Moon and Mars (e.g., [1-4]). These parameters help constrain designs of future mechanisms intended to interact with regolith (e.g., wheels, landing systems, structural supports). Here we report cohesions and angles of internal friction for regoliths trenched at several locations along the traverses of *Spirit* and *Opportunity*.

Background: Soils derive their strengths through grain-to-grain friction, and grain-to-grain cohesion due to cementation, chemical bonding, electrostatic attraction, or other influences. In terrestrial practice, values of friction angle, ϕ, and cohesion, c, can be determined by performing several controlled shearing failure experiments under different normal stresses. With normal stress and shear stress failure values plotted as (x,y) pairs, the experiment results scatter along a straight line, with the slope and y-intercept identified as $\tan\phi$ and c, respectively. Several factors influence ϕ, including void ratio, grain angularity, sorting, particle size, mineralogy, and strain rate.

The MER trenching sequence was developed to (1) provide as deep a hole as possible consistent with vehicle safety; (2) provide a hole wide enough to allow instruments on the end of the Instrument Deployment Device (IDD or the “arm”) access to the trench floor and walls; (3) minimize contamination of the trench interior by surface materials; (4) place the finished hole within the work volume of the IDD without need for further driving; and (5) preserve in situ stratigraphy of the soil in at least one place within the trench viewable by the Microscopic Imager (MI). This was accomplished by a sequence with ~195 commands (including embedded imaging) that required about an hour on the martian surface to run. The rover turns in place back-and-forth many times, pausing frequently for one of its front wheels to either dig into fresh soil, or dig into tailings to move them out of the way. This finally results in a linear trench 6-10 cm deep spanning most of the distance between the front wheels, with trench interior (as well as undisturbed surface terrain) reachable by IDD-mounted instruments (MI, APXS, and Mössbauer).

Data: Primary data were the engineering telemetry describing motions and reactions of the rover to the regolith, including motions of the rover rocker-bogie suspension system, wheel rotations, motor voltages and currents, and vehicle accelerometer data yielding orientation relative to gravity. These data were supplemented with images obtained during the trenching process and more detailed views obtained after each trench was completed.

Three trenches were dug by *Spirit*, all before reaching the Columbia Hills. Suspension telemetry was not recovered from *Spirit* for the Asol047 trench, although wheel current and other telemetry was. The Asol113 trench began with the dig wheel perched on a sizable stone, affecting calculations of cohesion from wheel plunge during the initial dig cycle. Four trenches were dug by *Opportunity*: two trenches in different units within Eagle crater, and two more at widely-spaced locations on the plains (one between Eagle and Endurance craters, and the other south of Endurance crater near a transition between two types of rippled plains).

Methods: Fundamentally, we seek the effects of soil strength in the electromechanical work expended by the rover’s attempted trenching motions. Motor currents during wheel dig motions, combined with voltages and durations, yield electromechanical work expended. Much of this work is consumed overcoming internal friction within the motor bearing and 1502:1 reduction gearing, which must be factored out to isolate the resistance due only to the soil. Motor performance is also temperature-dependent—important because initial motor temperature is different for each trench, and motor temperature typically changes (rises) during each trenching operation. Accordingly, no-load data collected at widely different temperatures prior to launch and on the surface during rover “stand-up” (while still on the lander) were combined to create a temperature correction curve. These efforts allow isolation of the wheel motion resistance due only to the martian regolith, while accounting for temperature-dependency of motor efficiency. Normal stress applied to the soil depends on the changing weight distribution among the wheels; this, too, was accounted for in our calculations.

Soil strength may derive contributions from both non-zero friction angle ϕ, and non-zero cohesion, c.

Many previous analyses of soil strength, including analyses of lunar and martian soils, have sought to solve for ϕ and c simultaneously. While desirable, and often unavoidable, simultaneously solving for both parameters can lead to error or uncertainty in one parameter affecting the derived value of the other. Here, we take a different approach, exploiting the dryness of the martian regolith and features of the trenching sequence. Many of the individual commands during the trenching sequence are devoted to digging into tailings in order to move them away from the hole. Tailings represent regolith with all cohesion more-or-less destroyed; resistance is from grain-to-grain friction angle ϕ only. Initial dig commands into pristine soil represent the opposite: the wheel is digging into soil in which all original cohesion is present, and total resistance is due to $\phi + c$. For each trench we solved for ϕ values analyzing tailings digs, then analyzed initial digs into pristine soil to help determine the $(\phi + c)/\phi$ ratio at the appropriate normal stress to derive values of c. Calculation of ϕ did not require knowledge of engaged wheel/soil contact area, but this needed to be estimated to finish calculating values of c. Experiments at the George Winter Laboratory (Cornell) using a spare MER flight wheel and flight-like ground support commanding equipment guided our calculations of wheel/soil contact area. Wheel imprints, traverse tracks, and wheel digs performed under laboratory conditions were compared with single-wheel sinkages in the vicinity of each martian trench to derive starting wheel/soil contact areas required for our calculations of c.

Results: Table 1 summarizes results. Friction angles range from 30-37°, and cohesions typically are several kPa. A notable exception is the B054 basaltic ripple sand, which had cohesion too low to be measured with our technique; this result is consistent with these particular ripples being recently active, aligned with winds implied from the local wind streak azimuth[5]. Overall, the ϕ and c values in Table 1 are within the ranges reported for some regolith classes at the Viking Lander sites[3], and are higher and less variable than values reported from *Sojourner* rover experiments at the *Pathfinder* site[4]. Values of ϕ reported here are 5-17° higher than reported for the initial traverse segments of the MER vehicles (based on wheel sinkage analysis)[6,7].

References: [1]Shoemaker et al. (1969) in NASA SP-189, 19-128. [2]Carrier et al. (1991) in *Lunar Sourcebook*, 475-594. [3]Moore et al. (1987) USGS PP-1389, 222 pp. [4]Moore et al. (1999) *JGR*, *104*, 8729-8746. [5]Sullivan et al. (2005) *Nature*, *436*, 58-61. [6]Arvidson et al. (2004) Science, 306, 1730-1733. [7]Arvidson et al. (2004) Science, 305, 821-824.

Table 1. Summary of MER wheel trenching results for martian regolith ϕ and c.

Trench (Rover and sol #)	**Setting**	**Angle of Internal Friction ϕ (deg)**	**Cohesion c (Pa)**	**Notes**
Asol047	Fine-grained soil in "hollow" on plains between lander and Bonneville crater	N/A*	N/A*	*No suspension telemetry available
Asol113	Rocky soil on plains between Bonneville crater and Columbia Hills	30	>1900	Initial dig affected by dig wheel perched on surface stone, degrading cohesion value
Asol135	Rocky soil on plains between Bonneville crater and Columbia Hills	37	5200	Surface stones much smaller than Asol113 trench
Bsol023	Mixed basaltic soil with embedded hematite concretions inside Eagle crater, near outcrop	37	4700	On 9° slope, so trench sequence half as long
Bsol054	Relatively young ripples (aligned with recent wind streak) in basalt sand, on central floor of Eagle crater	33	very low	Initial dig probably affected by wheel perched across ripple crests. Reduced traction in weak regolith "smeared" initial stages of trench, reducing final depth.
Bsol073	On plains near Anatolia trough, between Eagle and Endurance craters	30	5600	Bisected plains ripple
Bsol366	On plains south of Endurance crater, just south of heat shield impact site	34	5100	Bisected plains ripple