COHESIONS AND FRICTION ANGLES OF MARTIAN REGOLITH FROM MER WHEEL TRENCHES AND WHEEL SCUFFS. 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: Characterization of physical and mechanical properties of regolith has been a fundamental part of *in situ* planetary exploration beginning with the Surveyor series of lunar landers, continuing through the Apollo program, and extending to Mars with the Viking, Pathfinder, Mars Exploration Rover, and Phoenix missions.[1-10] Regolith mechanical behavior commonly is described as paired values of cohesion, c, and friction angle, ϕ. These parameters are fundamental inputs for design of future mission hardware that must interact with regolith (e.g., landing systems, contact instrumentation, wheels, and regolith-conveying systems such as scoops that support science activities). Factors that influence friction angle, ϕ, include sorting, grain shape, and grain angularity. Cohesion, c, can be due to cementation, chemical bonding, electrostatic attraction, or other processes in the regolith. Thus knowledge of ϕ and c can provide information about regolith processes as well as other properties. Here we extend our earlier results[8] by reporting derived friction angle ϕ and cohesion c for an additional wheel trench and ten wheel scuffs distributed across both MER landing sites, and we summarize all MER trench and scuff results obtained to date (Table 1).

Methods: With few exceptions, wheel trenches and wheel scuffs are conducted primarily to expose otherwise hidden subsurface materials to the science payload; soil mechanics is secondary. Generally, wheel-trenching and wheel-scuffing use one of the MER front wheels to dig into regolith at 100% slip while the other five wheels hold the vehicle still. However, trenching and scuffing are very different activities. Trenching uses a 195-command sequence with many separate wheel-dig motions. The rover turns in place back-and-forth, pausing frequently to either dig deeper into fresh soil, or dig into tailings to push them aside and prevent them from falling back into the growing cavity. This eventually opens up a trench as much as 10 cm deep that is spacious enough for the IDD (Instrument Deployment Device or "arm") to probe down inside with MI, APXS, and Mössbauer instruments. Wheel scuffs, on the other hand, are much simpler maneuvers of only one or two wheel motions that create much smaller cavities 1-3 cm deep, generally exploited only for remote-sensing (multispectral Pancam imaging, MiniTES). For our purposes here, the important distinction between wheel trenching and scuffing is that the trenching procedure includes within it several wheel digs into tailings piles where regolith strength is due to ϕ only, as well as several other digs into pristine materials where strength is due to both ϕ and c. So trenching data sets allow the contribution of ϕ to be determined from the tailings pile digs, then this value can be applied to the pristine soil digs to solve for c. Wheel scuffs, on the other hand, are too simple to allow ϕ or c to be determined independently from one another.

Motor currents, voltages, and durations during any wheel dig motion yield electromechanical work. Most of this work, however, is expended overcoming friction from motor bearings and reduction-gearing. To isolate the work performed overcoming soil strength, we use temperature-dependent no-load corrections derived from no-load tests performed prior to launch, and briefly after landing (during the initial "stand-up" maneuvers before each rover drove off its respective lander). We also incorporate time-variable normal stress applied by the digging wheel to the soil; this depends on the rover's orientation on sloping terrain and how the weight distribution among the wheels changes as digging proceeds.

Analysis and Results: Our previous analysis included seven wheel trenches distributed around both MER sites, and reported paired ϕ and c values for each trench location (with the exception of the Asol047 trench into Laguna Hollow, which lacks a complete suspension telemetry data set). For all of these trenches, friction angles ranged from 30-37° and cohesions ranged from ~0 (for active aeolian sand ripples) to around 4-6 kPa.[8]

Only after completing this analysis (and while collecting more data during the ongoing mission), it became clear that: (1) friction angles are confined to 30-37° at both sites, consistent with non-platy, mechanically weathered, dry soil grains; and (2) at the relatively modest normal stresses applied under a rover wheel, uncertainty and/or variation in ϕ does not strongly affect the derived values of c. These realizations opened up new possibilities for analyzing 18 wheel scuffs distributed across both landing sites, for insights into cohesion at these locations. Cohesion ranges for nine of these scuffs are reported in Table 1, assuming ϕ likely is 30-37°. Analysis of the remaining wheel scuffs could not be brought to conclusion due to poor stereo image documentation, obvious encounters with rock revealed in post-scuff images, or other complicating factors. Additionally, the Bsol919 trench, a unique sequence that accommodated *Opportunity's* failed right front steering actuator, yielded ϕ and c values similar to other trenches elsewhere at both landing sites. Overall, regolith at both MER landing sites has ϕ values 30-37° (from trenching analyses), as might be expected for mechanically weathered, rigid, non-platy grains composing a hyperarid soil. Cohesions are low, around 10 kPa or less (where pediment and other bedrock is not encountered). Cohesion variations correlate to some extent with geologic setting, but also reflect real, very local variations revealed also by variable wheel sinkage expressed as locally varying track widths.

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]Arvidson et al. (2004) *Science*, *305*, 821-824. [6]Arvidson et al. (2004) *Science*, *306*, 1730-1733. [7]Richter et al. (2006) Proc. 10th ISTVS. [8]Sullivan et al. (2007) LPSC XXXVIII, #2084. [9]Arvidson et al. (2009) JGR, 114, doi:10.1029/2009JE003408. [10]Shaw et al. (2009) JGR, 114, doi:10.1029/2009JE003455.

Table 1. Friction angles and cohesions from MER trenches and scuffs (A = *Spirit* and B = *Opportunity)*.

Trench or Scuff	Geological Setting	Friction Angle ϕ (deg)	Cohesion *c* (kPa)	Notes
Asol047 trench	Fine-grained soil in "hollow" on plains between lander and Bonneville crater	N/A	N/A	No suspension telemetry available, unfortunately.
Asol113 trench	Rocky soil on plains between Bonneville crater and Columbia Hills.	30	>2	Initial dig affected by dig wheel perched on surface stone, degrading cohesion value
Asol135 trench	Rocky soil on plains between Bonneville crater and Columbia Hills	37	5	Surface stones much smaller than Asol113 trench
Asol694 scuff	Soil mixed with pediment materials	N/A	25-28	Cohesion values if ϕ = 30-37°. High cohesion probably is still a minimum value, reflecting some rock/wheel contact.
Asol1201 scuff 1	Trough immediately east of Home Plate	N/A	10-11	Cohesion values if ϕ = 30-37°
Asol1201 scuff 3	Trough immediately east of Home Plate	N/A	4-5	Cohesion values if ϕ = 30-37°
Asol1201 scuff 4	Trough immediately east of Home Plate	N/A	7-8	Cohesion values if ϕ = 30-37°
Bsol023 trench	Mixed basaltic soil with embedded hematite concretions inside Eagle crater, near outcrop	37	5	On 9° slope, so trench sequence half as long
Bsol054 trench	Relatively young, active ripples (aligned with recent wind streak) of basalt sand, on central floor of Eagle crater	33	very low	Initial dig affected by wheel perched across ripple crests. Reduced traction in weak regolith "smeared" initial stages of trench, reducing final depth.
Bsol056 bog	Regolith-covered high interior rim of Eagle crater (failed drive out of Eagle crater)	32-34	very low*	Left Front wheel 34°, Right Front wheel 32°. Caked wheels driving in place, so essentially soil-to-soil friction. *Hence *pristine* cohesion likely NON-zero.
Bsol073 trench	On plains near Anatolia trough, between Eagle and Endurance craters	30	6	Also bisected plains ripple
Bsol088 scuff	On plains near Fram crater, between Eagle and Endurance craters	31	very low*	Cohesion destroyed before scuff by 90° wheel twisting in place. *Hence *pristine* cohesion likely was NON-zero.
Bsol366 scuff	On plains south of Endurance crater, just south of heat shield impact site	N/A	9-10	Cohesion values if ϕ = 30-37°. Variation compared with Bsol366 trench in keeping with wide variation of drive sinkage at this location.
Bsol366 trench	On plains south of Endurance crater, just south of heat shield impact site	34	5	Trench also bisected a 3 cm-high coarse-grained ripple
Bsol878 scuff	West-facing lower flank of large coarse-grained ripple north of Victoria crater	N/A	1	Cohesion values if ϕ = 30-37°. Lower strength is consistent with typically deeper drive sinkage on west-facing (vs. east-facing) ripple flanks.
Bsol919 trench	Victoria crater annulus	36	3	Unique trenching sequence to accommodate failed RF steering.
Bsol1489 scuff	Sand between flat rocks within Victoria crater	N/A	2	Vibration of rover during scuff suggests occasional encounters with rock(s)