ESTIMATING ROCK STRENGTH PARAMETERS FROM ROCK ABRASION TOOL (RAT) GRINDS.

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Introduction: Each of the Mars Exploration Rovers carries a Rock Abrasion Tool (RAT), which is a miniature grinding tool designed by Honeybee Robotics to clean off the outer surface rinds of rocks and allow access to their more pristine interiors [1]. Just as a field geologist would use a rock hammer to cleave open rocks to expose fresh surfaces for examination, the rovers use the RAT to grind off the outer surface layers of rock and outcrop targets to expose fresher interior surfaces. Analyses of surfaces before and after RAT brushes and grinds reveal the near-ubiquitous presence of surface coatings and alteration rinds on exposed surfaces on Mars [e.g., 2-4], reaffirming the RAT's utility as an exploration tool.

In addition to providing access to fresher interior surfaces for other instruments to analyze, the RAT itself provides a wealth of information about the physical properties of the target being abraded. Physical properties such as strength, density, hardness, and texture reflect the formation conditions of a rock and are also sensitive to weathering and alteration processes. When analyzed in concert with other data, physical properties measurements can provide a fuller picture of the nature of surface material [e.g., 5].

Motor currents consumed during RAT grinding operations provide an indication of the amount of energy required to abrade a given volume of rock. Our goal in this project is to test a suite of terrestrial rocks with both RAT grinds and crushing experiments, and use the results to establish a direct, empirical correlation between the specific grind energy measurements recorded by the RAT and more traditional, lab-measured rock strength parameters.

Rock Abrasion Tool Description: A detailed description of the RAT is given in *Gorevan et al.* [1]. Mounted on rover's robotic arm or IDD (Instrument Deployment Device), the RAT instrument is composed of three separate motors in a cylindrical housing 8.5 cm in diameter and 12.8 cm in length. The cutting surfaces of the RAT grinding bit consist of two diamond-impregnated phenolic resin pads attached to either end of a "paddle wheel." This grinding bit is mounted off of the RAT's central axis, and rotates up to 3000 rpm on its own axis and 0-2 rpm about the central axis. Separate motors drive these two circular motions while a third motor controls the grinding depth, which is increased in small, quantized steps (0.05 mm per revolution in dense targets). A successful grind produces an abraded circular area that is 4.5 cm in diameter and nominally 0.5 cm deep. Each motor's power consumption is recorded for transmission to Earth at a nominal rate of 2 Hz (i.e., 0.5 seconds per sample interval). Other ancillary data captured include motor positions, contact switch states, temperature sensor values, bus voltage, and various software states.

Methods: We assembled a suite of terrestrial rocks for testing. This suite was selected to span a wide range of rock strengths and not necessarily to match martian rock chemistry or mineralogy. Samples included sandstone, limestone, kaolinite, and three varieties of basalt (Table 1). Crushing tests and RAT grinding tests were conducted on each sample.

Table 1. Terrestrial rocks samples used in this study.

Sample ID	*Rock type*	*Source region*
bas-01	basalt, aphanitic	Prescott, AZ
bas-02	vesicular basalt	Keeler, CA
ss-01	sandstone	St. George, UT
bas-03	basalt	Mojave Desert, CA
kal-01	kaolinite	Mammoth Mountain, CA
ls-01	limestone	Santa Barbara, CA

Compressive strength test procedure. The most widely quoted index property of rock is the uniaxial strength of an unconfined cylindrical test specimen [e.g., 6]. We performed compressive strength tests on the samples listed in Table 1 using an Instron 8502 mechanical load frame (with 8800R control electronics) at JHU/APL equipped with a 250 kN load cell. A constant strain rate of 10^{-4} s^{-1} was maintained for all samples. Samples were prepared by extracting cylindrical cores using a diamond-tipped rotary drill bit on a Bridgeport drill press. These cores were 24 mm in diameter and ideally 48 mm in length, although lengths varied. The core ends were trimmed and precision ground to create two parallel surfaces. Each test was run by loading the rock core in the Instron until brittle failure occurred. The peak force withstood by the sample divided by its cross-sectional area yields the Unconfined Compressive Strength (UCS).

RAT grinding test procedure. An engineering flight spare of the RAT is kept at Honeybee's facility in New York. The RAT is mounted in a vertical position along a helical axis and can be raised or lowered down onto a planar facet of a rock sample. Natural rock surfaces were ground in order to better replicate

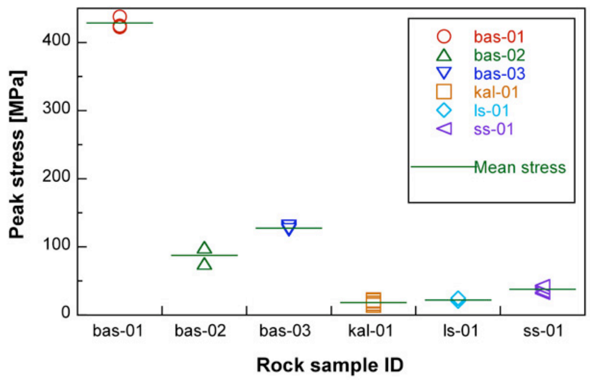

Figure 1. Compilation of uniaxial compressive strength (UCS) tests of rock samples. Green horizontal lines are mean values; individual measurements are indicated by multiple symbols per sample type.

field conditions for the RAT. Each grind began with a standard "seek-scan" pre-programmed routine that was designed for autonomous operation on Mars. This routine locates the highest point of the rock surface within the grind area and ensures that the grind starts just above this point. The target grind depth was 5 mm. Due to the irregular texture of natural samples, the surface area ground tended to increase with depth into the rock as the paddle wheel attained full contact with the rock surface. Therefore, motor currents were averaged over the last 0.25 mm depth of the RAT grind to determine the specific grind energy (SGE, units J/mm^3), with is which is a measure of the work done per unit volume of abraded material.

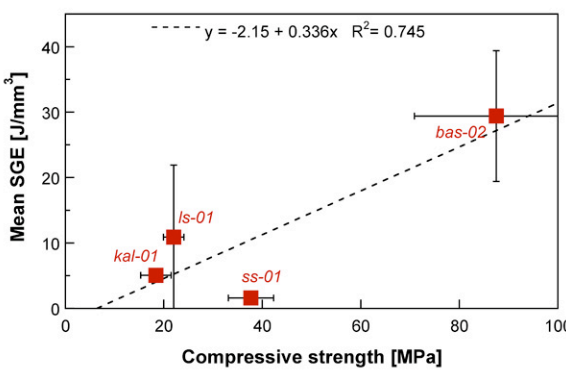

Figure 2. Uniaxial compressive strength (UCS) values plotted again specific grind energies (SGE) as determined from RAT grinds. Dashed line is a linear fit to the data.

Results: Compressive strength test results are given in Fig. 1. Despite the variability inherent in natural rock samples, the results show a high degree of self-consistency. With the exception of the vesicular basalt (sample *bas-02*), the standard deviation of the mean was less than a few MPa. Void spaces in the vesicular basalt sample have a heterogeneous distribution and the measured strength values are sensitive to their specific distribution and orientation within a given sample.

RAT grind tests are ongoing, but as of this writing we have completed preliminary tests on four of the six samples. An initial comparison of UCS versus SJE is given in Fig. 2. As expected, of the four samples for which both tests have been conducted, the highest specific grind energy required was for the basalt sample (bas-02) that also withstood the greatest compressive force. Although these data generally follow a simple linear trend (R^2 value = 0.75) with a roughly 1:3 slope, the sandstone sample falls well below this line.

Discussion: Preliminary results of our study indicate that an approximate correlation can be determined between specific grind energy as recorded by the RAT and lab-measured compressive strength values. More competent samples tend to require more energy to grind. However, complications are evident even in this limited sample set. The sandstone sample is composed of medium-sized, rounded quartz grains with a diagenetic cement. Although resistive to compression (as compared to the kaolinte sample, for example), it may be that the grinding action of the RAT dislodges or plucks individual quartz grains more efficiently than for a non-granular target, thus lowering the amount of energy necessary to grind such a sample. Further testing will expand upon these results with the ultimate objective of better establishing the relationship between the parameters plotted in Fig. 2.

References: [1] Gorevan S.P. et al. (2003) *JGR*, *108(E12),* doi:10.1029/2003JE002061. [2] Herkenhoff K.E. et al. (2004) *Science*, *305*, 824-827. [3] Arvidson R.E. et al. (2006) *JGR*, *111(E2)*, doi:10.1029/2005JE002499. [4] Hurowitz J.A. et al. (2006) *JGR*, *111(E2)*, doi:10.1029/2005JE002515. [5] Arvidson R.E. et al. (2004) *Science*, *305*, 821-824. [6] Attewell P.B. & Farmer I.W. (1976) *Principals of Engineering Geology*, 1045 pp.