MEASUREMENTS OF THE COEFFICIENT OF RESTITUTION OF QUARTZ SAND ON BASALT: IMPLICATIONS FOR ABRASION RATES ON EARTH AND MARS

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Introduction: Knowledge of the rates at which rocks abrade from the impact of saltating sand provides important input into estimating the age and degree of modification of arid surfaces on Earth and Mars. Previous work has relied on measuring mass loss rates in the field [1-3] and the laboratory [4,5]. The susceptibility of rocks and other natural materials has been quantified on a relative scale from laboratory studies [4,5].

These previous investigations did not include observations of the physical interaction between the impacting sand grains and actual rock surfaces. A potentially effective method to do this is using high speed video (HSV). Previous investigations have used HSV to determine spin (Magnus) effects on particle lift [6], accurate particle speeds as a function of height [7], saltation threshold [8], and dust storm triggering mechanisms [8]. Using high speed video to assess grain-rock interactions has, until this study, not been done. Herein we report on analysis of saltating quartz grains hitting basalt targets under terrestrial conditions. We find that the coefficient of restitution indicates that the kinetic energy lost on impact is generally proportional to incoming velocity and impact angle, but that only a small fraction of this energy goes into direct abrasion of the rock surface.

Methods: All of the experiments were performed using the Mars Surface Wind Tunnel (MARSWIT) at the ASU Planetary Aeolian Facility at NASA Ames Research Center, Moffett Field, California. A basaltic rock was placed approximately 5 meters downwind from where sand was being dropped into the wind by a hopper located on the top of the tunnel. A high speed video was filmed at 500 frames per second (exposure time of 1/500th second) showing quartz sand grains impacting the basaltic rock. This was done at terrestrial pressure using 500 µm sand grains and wind speeds of 5.5 and 11 m/s. For each wind speed, the face of the basalt rock target was angled at 90, 60, 45, 30, 15, and 0° to the wind. The chamber was also pumped down to a pressure of ~10 mb to simulate Martian atmospheric conditions and the experiments were repeated using wind speeds of 30 and 60 m/s.

The video was analyzed by tracking the trajectories of individual sand grains on a frame-by-frame basis. The velocity, *v*, of grains was determined from the change in horizontal (d*x*) and vertical (d*y*) distances as a function of time (d*t*): $v = ([dx/dt]^2 + [dy/dt]^2)^{0.5}$. Knowing the particle size (~500 µm), quartz density (2650 kg m^{-3}), and the difference between the incoming and outgoing velocities, the kinetic energy loss can be computed: $V = 4/3\square r^3$, $m = \square V$, and $KE = 1/2(mv^2)$. The coefficient of restitution (*e*), or the ratio of the differences in kinetic energy before and after impact, was then calculated such that *e* = (*v* before impact) / (*v* after impact) or $e = ([dx/dt]^2 + [dy/dt]^2)^{0.5}$ incoming / $([dx/dt]^2 + [dy/dt]^2)^{0.5}$ outgoing.

Results: As of this writing, data have been reduced for experiments run at 11 m s^{-1} freestream at Earth pressure onto 60°-angled basalt (additional data reduction is expected by LPSC). From this data set, 25 particles were tracked. Of these, 3 particles rebounded off the basalt and hit one more time and 2 particles hit two more times. This provided 32 measurements of the coefficient of restitution for a range of incoming velocities and impact angles (defined as the angle relative to the 60° slope) (Fig. 1-2).

The data are effectively represented by plotting impact angle vs. the coefficient of restitution (*e*). There is some scatter and, for particles with low velocities, values of *e* that are greater than 1 and cannot be valid. Although the magnitude of various sources for the scatter and invalid values of *e* are still being assessed, contributors are: 1) The spatial and time resolution of the HSV, leading to compounded errors in determining velocity, 2) The effects of wind on the rebounded trajectory, 3) The effect of spin (Magnus forces) on the velocity and angle of rebound. Despite these and possibly other sources of uncertainty causing the scatter, there are several trends in Figure 2 that have physical significance:

1) In a given velocity class above 3 m s^{-1}, *e* is roughly inversely proportional to impact angle.
2) For a given impact angle range, higher velocity incoming trajectories generally result in a lower *e*.

Interpretation: Figure 3 illustrates the kinetic energy loss into basalt from quartz sand impacting at various angles and velocities. Considering order of magnitude ranges in Joule units:

- Energy losses > 10^{-6} J/particle are generally for particles moving > 6 m/s at impact angles of 60-75°.
- Energy losses of 10^{-7}-10^{-6} J/particle are attributable to particles moving 3-9 m s^{-1} with impact angles of 40-80°, most commonly 55-80°.
- Energy losses <10^{-7} J are generally for particles <6 m s^{-1} for impact angles of ~55-85°.

Overall, it seems that incoming velocity exerts a greater effect on kinetic energy loss than impact angle. However, within a given velocity range, kinetic energy loss exhibits a somewhat scattered trend proportional to impact angle.

Discussion: We now assess whether the amount of energy transferred onto rock surfaces (ΔE) can be used to estimate abrasion rate. The compressive, tensile, and shear strengths of basalt and other rocks are well known (generally on the order of 10^7-10^8 N m^{-2} [9]) and studies so far indicate that the former two are important factors in near perpendicular collisions [4] whereas the latter is probably relevant for shallower impact angles in which rocks abrade by cutting or gauging. Ideally, the energy transferred onto the rock surface for a given grain impact will propagate inward a distance r as hemispheric waves of surface area $2\pi r^2$. When the energy per unit volume of the half hemisphere ($E/[2/3\pi r^3]$) exceeds the strength (S, with the appropriate strength used depending on the impact angle) of the rock, the rock will fail. The depth of abrasion will be, under this ideal scenario, equal to $(3\pi\Delta E/2S)^{1/3}$. Considering a generic strength of 5×10^7 N m^{-2} and maximum kinetic energy loss from our experiments of 5×10^{-6} J, implies that the depth of abrasion from a single high energy impact is 80 µm. This value is within the ~30-500 µm yr^{-1} for annual abrasion rates in natural aeolian settings on Earth [1-3]. As such, it is clearly too high for a single particle impact. In reality, the energy of impacting sand grains must also be converted into fracturing and indentation of the rock surface, as indicated in previous work using SEM images [10-13], and probably minor heating as well, such that this depth of abrasion is a maximum idealistic value.

On Mars, abrasion rates should be much higher given the high threshold friction speeds necessary to induce saltation (14,15). Because trajectory angles are flat through most of a high energy saltation path, facets more steeply angled than 60° should generally have steeper impact angles and lower restitution coefficients. We expect greater kinetic energy transferred into such rock surfaces, particularly under high energy Martian conditions, than those reported here and a concomitant increase in abrasion rate. Future work will focus on these other conditions, such that energy transfer into rock for the range of abrasion expected conditions on Earth and Mars can be quantified.

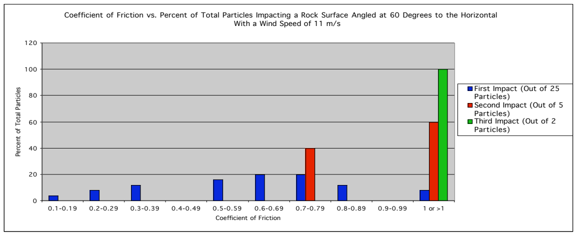

Figure 1: Histogram showing percentage of particles as a function of the coefficient of restitution.

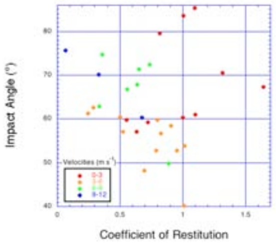

Figure 2: Impact angle vs. the coefficient of restitution as a function of incoming velocity.

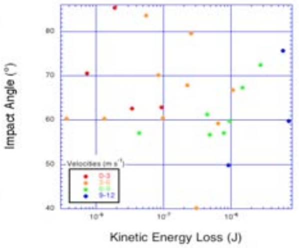

Figure 3: Kinetic energy loss into basalt from impacting quartz sand as a function of incoming velocity.

Acknowledgements: Use of the Mars Surface Wind Tunnel, managed by R. Greeley of Arizona State University, is gratefully acknowledged. E.E. Eddlemon helped with experimental setup. Guidance by B.R. White was critical to setting up and interpreting the HSV.

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