Thermal Conductivity of Planetary Regoliths: The Effects of Pebbles and Cobbles in a Fine Grained Matrix.

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Introduction. The thermal conductivity of a planetary regolith is an important property. Volatile transport and stability (such as within icy permafrost) depends strongly on subsurface heat flow in response to insolation. Also, the physical structure of a planet's regolith is a window to its geologic history, interpretation of which often comes from thermal inertia, which in turn is dominated by the thermal conductivity.

Thermophysical properties are typically determined through remote sensing of the bulk surface layer. Previous studies investigating the major factors that control thermal conductivity have largely focused on homogeneous geologic materials. Heterogeneity has received only limited attention.

We present a combined theoretical, laboratory and field examination of the effects of embedded pebble and cobble heterogeneities on the thermal conductivity in an otherwise fine grained regolith. We find that the effect of these rock inclusions can be to increase the bulk conductivity up to factor of several. Implications for interpretation of planetary regoliths are discussed.

Background: Thermal Conductivity of a Regolith. Many factors influence the thermal conductivity of a planetary regolith: particle geometry (size, shape, and density), interstitial gas, cementation, and composition. These factors are often expressed in terms of combinations of conduction in series or parallel, analogous to electrical conductors (*Wecshler et al.,* 1972; see *Mellon et al.,* 2008 for a thorough discussion). Within a homogeneous bulk soil thermal conduction (k_b) can be expressed as series conduction between particle grain "*p*" and interstitial void space "*v*" for a porosity *α*:

$$k_\mathrm{b} = \frac{k_\mathrm{p} k_\mathrm{v}}{\alpha k_\mathrm{p} + (1-\alpha) k_\mathrm{v}}. \quad (1)$$

In the case $k_p >> k_v$, then $k_b \approx k_v/\alpha$. Similarly, conduction through the void space can be expressed as a sum of parallel paths via contacts "*c*", gas conduction "*g*", and thermal radiation "*r*" between grains:

$$k_\mathrm{v} = k_\mathrm{c} + k_\mathrm{g} + k_\mathrm{r}. \quad (2)$$

The influence of heat conduction through the interstitial gas can be substantial and highly dependent on the pressure. Figure 1 shows the relationship between gas pressure and thermal conductivity (*Fountain and West,* 1970; *Mellon et al*., 2008). Particle size can be a key component depending on the mean free path of gas molecules relative to the pores size between grains.

Mars atmospheric pressures fall within a range <1 to >10 mb, noted by vertical dashed lines in Figure 1. At Earth atmospheric pressures (far right) grain size has little influence and conductivity maintains a high value. Within the relative vacuum of Lunar and asteroid regoliths (far left) thermal conductivity maintains low values also independent of grain size. For this reason, in martian studies thermal conductivity (and its cousin thermal inertia) are often equated to an effective particle size, assuming a homogeneous regolith (*Kieffer et al.,* 1973; *Presley and Christensen,* 1997).

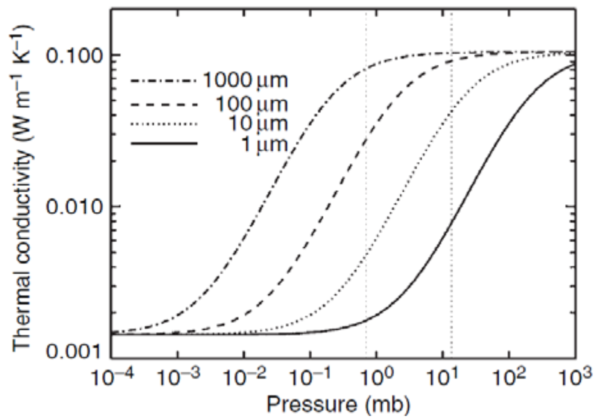

Figure 1. Thermal conductivity of a homogeneous particulate regolith as a function of grain size and interstitial gas pressure (from Mellon et al., 2008).

Irrespective of this pressure/particle-size dependence, variations in thermal conductivity between soils may also result from cementing or a fractional coverage of surface boulders and bedrock. On the Earth and airless bodies (Moons, asteroids, etc.) these factors become more important.

In this work we examine the case of an intimate mixture of embedded cobbles and pebbles within an otherwise homogeneous matrix of fine regolith grains.

Real planetary regoliths are rarely characterized by a single grain size except in the case of sorting by wind or water. In practice, competition occurs between the various regolith production and evolution processes: physical and chemical weathering of rock; volcanism; impact gardening; glaciation; aeolian and fluvial transport. These competitions result in complex and typically multi-modal distributions of particles.

Previous Studies. Previously, *Kieffer et al.* (1973) and *Presley and Christensen* (1997) showed that at Mars atmospheric pressures a strong relationship exists between thermal conductivity and particle size (when a uniform size is assumed). *Presley and Craddock* (2006) later examined the thermal conductivity of several natural terrestrial regoliths under Mars-like atmospheric pressures, regoliths that exhibit broad (but pheric pressures, regoliths that exhibit broad (but unimodal) particle-size distributions. They found that the bulk thermal conductivity corresponded to an effective particle size skewed toward that of the large grains rather than median grains. While bimodal distributions of grains or rock inclusions were not considered, their results suggest such inclusions and mixtures would also exhibit higher thermal conductivities.

Farouki (1981) discussed various models of the thermal conductivity of regolith with different volumetric constituents. A simple model either of series or parallel conduction (analogous to eqns 1 and 2) was presented with real regoliths expected to fall between these end members.

Terrestrial Field Observations. A valuable terrestrial analog to planetary regoliths occurs in the Antarctic Dry Valleys, where liquid water is absent in the dry subfreezing climate. *McKay et al.* (1998) measured surface and subsurface temperatures in the ice-free unconsolidated regolith of Linneaus Terrace in upper Wright Valley. Fitting a simple model of heat conduction to the seasonal data, they found the bulk thermal conductivity was 0.6 W m^{-1} K^{-1}. Recently, we measured the thermal conductivity of collected regolith from this site using a heated needle probe and found a substantially lower value of 0.2 W m^{-1} K^{-1}.

Putkonen et al. (2003) conducted a similar study of heat conduction from measured subsurface temperatures from a site in Central Beacon Valley and found a bulk thermal conductivity of 0.4 W m^{-1} K^{-1}, while field measurements of this regolith via a heated needle probe also resulted in a lower 0.2 W m^{-1} K^{-1}.

The discrepancy between bulk values derived from ground temperatures and those from a heated-needle probe presents us with something of a puzzle. We hypothesize that small pebbles and cobbles within the regolith (typically avoided when sampling for laboratory analysis or within the needle-probe's sensing volume) results in a higher thermal conductivity. Furthermore, substantial thermal conductivity variations would result from different intimate mixtures of subsurface pebbles and cobbles within planetary regoliths.

Analysis. To investigate and quantify this effect we examined field samples of Antarctic soils and subsurface temperature data (discussed above), model the heat flow through heterogeneous mixtures of materials, and conduct laboratory measurements of simulated bimodal heterogeneous regoliths.

Modeling. Modeling heat flow and bulk thermal conductivity of heterogeneous mixtures is accomplished in two ways. (i) First is finding analytic solutions to simplified geometries. An example of this approach is the parallel and series end members discussed by *Farouki* (1981), as shown in eqns 1 and 2. This approach provides valuable end-member constraints, but fails to properly represent the complex and infinitely variable geometry of a real regolith. (ii) A second approach is to use a finite-element model of heat conduction in a complex 3-dimensional array of material elements, representing the heterogeneous regolith. The approach allows for complex pebble-inclusion geometries, but can be inaccurate due to discretization errors.

Laboratory Simulations. Bulk thermal conductivity of simulated heterogeneous regoliths can be measured directly in a laboratory. Simulated planetary regoliths may be natural terrestrial regolith or admixtures of natural or artificial grains. To compare with modeled end members, we created an artificially bimodal distribution by mixing borosilicate glass beads (2.2 mm diameter "pebbles") with borosilicate glass powder (53-63 µm diameter "fines"). We used a Decagon Devices KD2-Pro heated-needle probe to determine the bulk thermal conductivity. At Earth atmospheric pressure, both materials alone exhibited thermal conductivities between 0.1 and 0.13 W m^{-1} K^{-1} as expected (Figure 1). When mixed the bulk thermal conductivity increases with the volume fraction of beads (Figure 2).

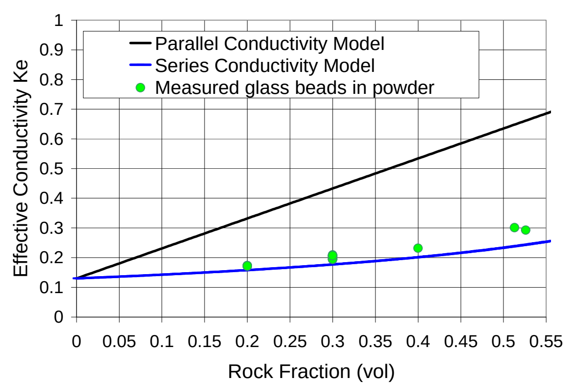

Figure 2. Parallel and series end member models compared with laboratory measurements using borosilicate glass beads (rocks) in fine glass powder.

Conclusions: The bulk thermal conductivity of a heterogeneous bimodal mixture of coarse pebbles or cobbles within a fine grained regolith generally increases with the volume fraction of the coarse component. The functional dependence is similar to, but greater than, that of a series model of thermal conductors of the two components. In this study, the bulk thermal conductivity increases by up to ~2.5x for densely packed beads with interstitial powder relative to the powder alone (0.13 W m^{-1} K^{-1} at zero rock fraction). This result is comparable to the 2-3x increase in thermal conductivity observed in Antarctic field data.