COHESION AND HEAT TRANSFER IN ASTEROID REGOLITH COMPOSED OF IRREGULAR, ROUGH, POROUS PARTICLES.

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Introduction: We reviewed the conventional, notionally physics-based models of dry/humid adhesion and effective thermal conductivity of granular media and found them not applicable to rough, irregular, polydisperse particles that make up real regolith on planetary bodies, moons and asteroids.

We present new theories of the co-/adhesion and effective thermal conductivity of granular media consisting of rough, irregular grains, the grains being mechanical polycrystalline or amorphous aggregates of constituent pure silicate minerals.

Thermal inertia of the surface material is defined as $\Gamma = \sqrt{\rho k(T) c_p(T)}$, where T is absolute temperature in K, k is thermal conductivity in W m^{-1} K^{-1}, ρ is bulk density in kg m^{-3}, and c_P is specific heat [1] at constant pressure in units of J^{-1}.

Fractal roughness of fractured rock surfaces. All surfaces of solids have surface roughness, and surfaces produced by fracture, as may be the case for asteroid particles (or fragments) due to collisions between asteroids or due to the impact of meteorites, have usually large roughness which exhibits self-affine fractal behavior. We measured the roughness of over 20 freshly shattered mineral and rock surfaces stone and mineral samples (Figure 1) and find that the 2D radially averaged power spectral density always follows a power law (no roll-off) with a slope close to -4 (Hurst exponent 0.9±0.1) in all cases.

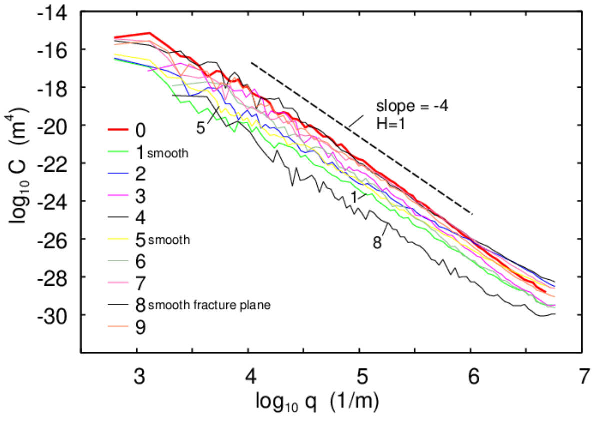

Figure 1 Examples of measured power spectral density: 1 albite, 2 antigorite, 3 augite, 4 dunite (Norway), 5 feldspar, 6 magnetite (Italy), 7 dunite (Albany), 8 olivine (USA), 9 talcum. The stones were cracked by hammer and the topography of the cracked surfaces measured by a stylus instrument [A.E. Yakini, B.N.J. Persson and J. Biele, manuscript in preparation, see also [3]]

The absolute power varying by at most 1 order (smaller or larger) of magnitude (mean PSD (at reference wavenumber q=10^4 m^{-1} of the order of 10^{-18} m²). We assume that the power-law can be extrapolated to atomic dimensions (cut-off wavenumber 1.4·10^{10} m^{-1}). For details, see [2].

Results: For adhesion, we find [2,3] almost no size dependence (as opposed to the ~R dependence in classical models) and a generally very small adhesive force F_{adh} of the order of 1 nN*, strongly dependent on the magnitude of fractal roughness.

The VdW forces as well described in the Lifshitz-theory [e.g., 6] have to be integrated over the randomly rough contact proximity zone, which entails numerical simulation and taking ensemble averages [2]. This can be extended [3,5] to contacts with capillary bridges, forming, e.g., if the (hydrophilic silicate) surfaces are not completely dry – a few layers of water molecules suffice for this mechanism, a fact mostly overlooked in experiments. The approximate numerical result is

Fdry = n*0.45*$s^{-1.84}$ [nN]

Fcap = n*21*s^{-2} [nN] RH=40%

where s is a relative (to our granite sample) roughness PSD magnitude, s=C(actual at q=10^4 m^{-1})/10^{-18} m^{-1} and n is the number of micro-contacts per macrocontact (typically n=1..3, compare [7]).

We measured adhesion force as a function of relative humidity with a very simple but effective experiment [3] and find very close agreement to theory.

As for the effective thermal conductivity of granular media, we present a self-consistent new contact conductivity model. applicable to regolith in vacuum or in a gaseous medium, with or without capillary bridges caused by humidity. It describes weak phononic, capillary bridge, gas and, significantly, near-field evanescent wave "contact" conductivity 4,5]. There are no free parameters, provided the average roughness power spectra and some bulk material properties of the particles and the porosity of the mixture is known. We find that heat transfer by near-field evanescent waves contributes significantly to contact conductivity, and the weak-contact phononic heat transfer is important, especially due to contact stiffening by adhesion forces, but cannot be described by conventional contact mechanics theories (JKR contact radius → constriction resistance). Constriction resistances are usually negligible!

Ongoing: Porous, cracked rocks. The effective k of a competent, but very porous "rock" cannot yet be satisfactorily modeled. Only empirical relations based mainly on porous meteorites exist for now, e.g., 8,9] – yet porosity cannot be the only parameter. The nature of contacts (by sintering / cold or hot pressing) is likely fundamental, i.e., the formation history of the rock. A credible physics-based thermal conductivity and strength model for porous "rocks" (or complex grains of a granular medium), being a mixture of mineral grains, cracks and pores is not yet available and subject of a current project at DLR. Cracks deserve special attention, since they could make apparent thermal conductivity size- (relative to the diurnal skin depth) and orientation-dependent. [10]. However, it is not clear what a realistic magnitude of heat transfer across the crack is: classical Stefan-Boltzmann radiative transfer certainly, but for crack widths < 1µm the evanescent wave heat transfer dominates. Also, cracks may have actually many points of (atomic-sized) contacts across their walls.

Experimental verification. Cohesion forces will be measured by AFM on Bennu particles paying close attention to avoiding any physisorbed terrestrial water and to determine the roughness PSD, also with AFM. (see talks by C. Hoover and K. Jardine, this conference).

Conclusions: Both new theories are computationally intensive for handling the roughness, but correlation equations depending on (1 or 2) fractal roughness parameters and composition (mainly complex refractive index in IR) may be derived from once-only numerical calculations - then the application is extremely fast and easy. Cohesion is nearly particle-size independent. We show that the effect of heat transfer via evanescent electromagnetic waves is of the same magnitude as the weak phononic heat transfer at low temperatures. At very high temperatures our theory converges to conventional ones since conventional radiative heat transfer dominates.

Experimental validation is sought and requirements for such experiments are given. We note that it is extremely important to control humidity (water molecules adhering to the surfaces of usually hydrophilic silicate grains), since even a humidity of the order of 1 % can lead to the formation of liquid (or ice-like) capillary bridges at the contact points between grains, increasing the contact thermal conductivity by orders of magnitude.

References:

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