HOW HARD IS THE SURFACE OF COMET NUCLEUS? A CASE STUDY FOR COMET 67P/CHURYUMOV-GERASIMENKO.

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Introduction: Landing on cometary bodies offers a unique opportunity to closely study their physical and compositional properties with a unique set of experiments that complement both orbital and ground-based observations. On the 12th of November 2014, the Rosetta spacecraft delivered its lander Philae to the surface of comet 67P/Churyumov–Gerasimenko (C67). A quantitative understanding of the compressive strength of the upper icy regolith layer of the comet nucleus is crucial for a safe landing, proper anchoring, and for assessing the Philae lander´s foot penetration into the upper layer of the cometary regolith. The benefits of such characterization extend also to future proposed landing mission on icy moons. For instance, high compressive strength values of the surface may result in the lander rebounding back from the surface while lower ones may result in sinking the Philae landing feet into the upper regolith of the comet nucleus, compromising the anchoring and subsurface sampling experiments' data acquisition.

In our analysis herein, we first provide an algorithm based on previous characterization of dry-snow as cometary analog to retrieve the surface compressive strength for C67. We also propose a model that correlates the surface compressive strength to the dielectric properties for future validation using the Comet Nucleus Sounding Experiment by Radiowave Transmission (CONSERT) and Bi-Static Radar (BSR) observations onboard the Rosetta mission. We then estimate the penetration depth of the lander feet as a function of different ranges of the assessed compressive strengths of the comet's surface for the different speeds of impact. Additionally, we use the observed surface temperature of -70° C measured by Visible and Infrared Thermal Imaging Spectrometer (VIRTIS) and the occurrence of three bouncing impacts at different speeds for the Philae lander until reaching total stability, to constrain the surface compressive strength and deduce an estimate of the surface density and the associated surface dielectric constant. Finally, we explore potential sinking of the lander under its own mass after reaching full surface stability arising from the change in surface compressive strength driven by the diurnal temperature variations and the approach of the comet to the perihelion.

Methodology: For compressive strength measurements, we used the compressive strength laboratory measurement data conducted by [1] as they measured the compressive strength of dry-snow at different temperatures under variable densities. The lowest reported temperature in their measurements is ~ −50° C, therefore, we linearly extrapolated the results to −70° C to approach the comet's surface temperature at 3 Astronomical Unit (AU) [2]. Figure 1 shows the compressive strength of dry-snow as a function of temperature for different bulk densities. The compressive strength is observed to increase as a function of density and temperature. At densities of 0.4 and 0.55 g cm^{-3}, the compressive strength increase linearly from 0.10 and 1.3 MPa at −23° C, and to 0.3 and 2.3 MPa at temperature of −70° C.

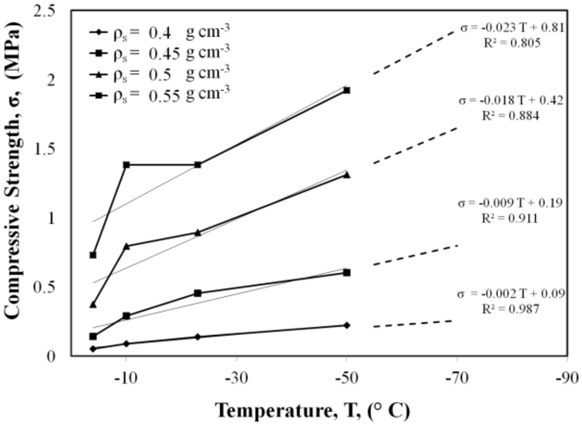

Figure 1. Compressive strength of dry-snow as function of temperature [1].

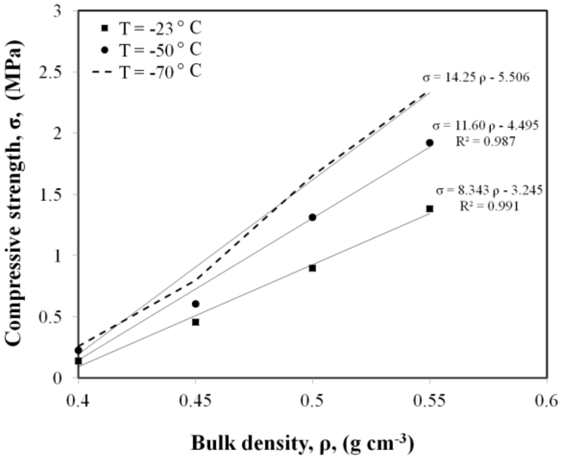

Figure 2. Compressive strength of dry-snow as a function of bulk density at different temperatures.

Figure 2 shows the compressive strength of dry-snow as a function of density at different temperatures along with the linear data extrapolation from Figure 1 to temperatures of −70 °C. The compressive strength is observed to increase along with the decrease in temperatures. For density of 0.55 g cm^{-3}, the compressive strength substantially increases from 1.3 MPa, at a temperature of −23° C, to ~2.4 MPa, at -70° C. From the above results in Figure 1 and 2, we derive an empirical model (equation 1) that calculates the compressive strength for ice-rich regolith as a function of surface temperature and bulk density.

$$\sigma = -0.003\,T + 12.5\,\rho - 4.326 \qquad (1)$$

Where σ is the compressive strength in MPa, T is the temperature in degree C, and ρ is the bulk density in g cm^{-3}.

Dry-snow dielectric measurements used in our analysis are obtained from the laboratory characterization conducted by [3], as their experiments covered low dry-snow densities from 0.22 to 0.93 g cm^{-3} at a low temperature of respectively −18° C. By using the temperature as a common variable in both laboratory measurements on dry-snow compressive strength and dry-snow dielectric constant at different temperatures, it is possible to correlate the two parameters in an empiric model as follow in equation 2 for the case of surface temperature of −70° C:

$$\sigma\,(T) = 5.93\,\varepsilon(T) - 12.37 \qquad (2)$$

Where σ is the compressive strength in MPa and ε is the real part of the dielectric constant, both for dry-snow at a given temperature T.

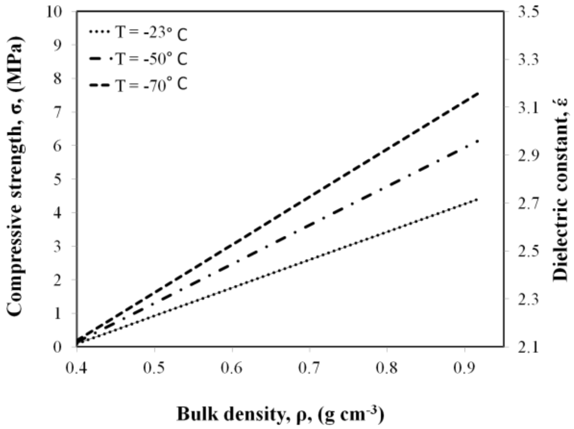

Figure 3. Compressive strength as a function of the dielectric constant of dry-snow, and its bulk density for three surface temperatures.

Figure 3 shows the correlation between the surface compressive strength, bulk density and the surface dielectric property for three temperatures -23, -50 and -70° C. It is observed that the compressive strength increase linearly with the dielectric constant for the case of dry-snow surface analog. The presence of substantial dust impurities in the snow can change the slope of the dependency of the compressive strength and the associated dielectric properties. This effect is not discussed in our current first order study.

Implications: Herein, we calculate the lander feet penetration depth using the model developed by [4] and apply it to different impact velocities and using ice rich surface compressive strengths, derived from dry-snow materials.

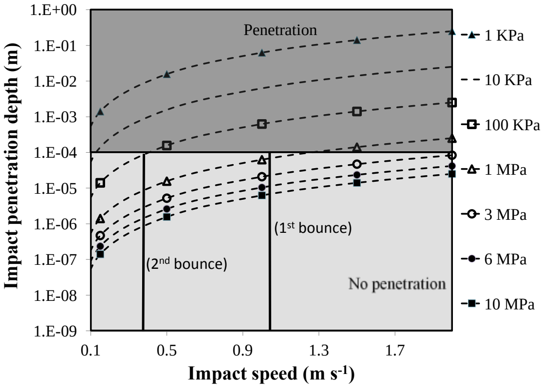

Figure 4. Lander penetration depth as a function of different impact speeds for different surface compressive strengths.

Figure 4 shows the lander feet penetration depth at different impact speed for different compressive strengths. An increase in the impact speed corresponds to a power increase in the penetration depth. Knowing that the Philae lander landed initially with an impact speed of ~ 1 m s^{-1} for its first bounce, then ~ 0.38 and 0.03 m s^{-1} for its second and third bounces; we consider a wider range of impact speeds from 0.02 to 2.1 m s^{-1}, which can be useful for future cometary landing experiments in low gravity environments as well as for icy moons.

Conclusions: We suggest the minimum surface compressive strength for comet C67 to be about 1 MPa. We derived a relation between the surface compressive strength and its dielectric properties for ice rich cometary surface using dry-snow as an analog. This correlation allows us to use the dielectric constant as will be retrieved from the CONSERT to reduce the ambiguities on the surface compressive strength of different areas of the comet.

References:

[1] Mellor, M., and J. H. Smith. 1966. *Cold Regions Research and Engineering Lab, Hanover NH,* No. CRREL-RR-168 [2] Berlin, D. L. R. 2004.Modeling the structure and activity of comet nuclei. *Comets II*: 359. [3] Cumming, WA. 1952. *Journal of Applied Physics* 23 (7), 768-73. [4] Kührt, E., J. Knollenberg, and HU Keller. 1997.. *Planetary and Space Science* 45 (6), 665-80.