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Compressive strength and elastic modulus of Comet 67P interpreted from a material science point of view

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Abstract

The analysis of Cometary Acoustic Surface Sounding Experiment (CASSE) data yielded values of surface compression strength and elastic modulus at the landing site Agilkia. These data are interpreted with fracture mechanical concepts from material science taking into account the high porosity of Comet 67P.

1. Introduction

The lander Philae of the Rosetta Mission carried the Surface Electric Sounding and Acoustic Monitoring Experiment (SESAME) instruments on board [1]. One of them, CASSE, consisted of transmitters and accelerometers as receivers built in the foot soles of the landing gear. They were intended to generate and receive elastic waves and to monitor seismic activity. The accelerometers were operational during the landing on comet 67P in order to record the acceleration signals caused by the landing shock.

2. Results

We reported recently an analysis of these acceleration data obtained at Philae's first touch-down site Agilkia on comet 67P [2]. First the amplitudes of the signals were analyzed. Based on calibration tests at the LAMA test facility of the DLR, and a theoretical analysis of the transfer function of the legs of the landing gear for external forcing via the foot-soles, the impact forces acting on the soles at the first touch-down site Agilkia were determined [3]. They ranged from 7 N to 23 N. Depending on the contact area between the soles and the comet surface, the compression strength calculated extended from 0.5 kPa as a lower limit to 12 kPa as an upper limit.

Furthermore, the signals contained distinct frequency bands which were analyzed regarding the soles as mechanical contact oscillators which were excited due to the landig shock. Their frequencies depend on the contact stiffness of the lander foot soles to the comet surface regolith determined by the contact area, elasticity and compression strength. In a spherical contact, the stiffness k^* is given by $k^* = 2aE_r^*$ where a is the contact radius and E_r^* is the reduced Young's modulus of the sole material and of the comet surface material. Calibrating again the response of the sole contact-oscillator to an external force, a calibration curve for the sole's contact oscillations was obtained. This translates into an elastic surface modulus of about 3 – 25 MPa.

3. Discussion

In view of the various results obtained for strength values of comet 67 P which cover some 10 Pa to 4 MPa, we would like to discuss and explain these rather different values by using relations known from material science and from rock mechanics.

Large porosity is a dominant factor which reduces all strength parameters and elastic moduli of a given material. Besides, large pores can be viewed as stress concentrators which limit the strength upon external loading, here the forces exerted by the Lander Philae. There are strength-elastic modulus relations for foam-like structure with open cells [4]:

$$\sigma_c/E_c = 0.03\left(\rho_p/\rho_s\right)^2\left(1+\sqrt{\rho_p/\rho_s}\right)^2 \qquad (1)$$

Here, σ_c is the elastic stress for compression failure, and for our case ρ_p and ρ_s are the mass densities of the comet material with porosity and for the pore free material, respectively. E_c is its Young's modulus. Inserting for the porosity $(1-\rho_p/\rho_s) = 0.7$ to 0.8 for 67P at Agilkia, one obtains $2.5\times10^{-3} < \sigma_c/E_c < 6.5\times10^{-3}$ For $\sigma_c = 8$ kPa [2], this yields $1.2 \text{ MPa} < E_c < 3.2 \text{ MPa}$.

Similar expressions like Eq. 1 have been derived for other cellular materials. Considering the high porosity, the comet surface material may be viewed as a cellular material with the ice being the walls between the regolith particles [5,6]. There are experimentally determined master curves for cellular materials for the ratio of the elastic collapse strength/elastic modulus of the cells by cell-wall buckling. i.e. crushing [7]. Again for a porosity of 0.7

to 0.8, this ratio is $1.7\times10^{-3} < \sigma_c/E_c < 7.9\times10^{-3}$ i.e. for $E_s = 8$ GPa (ice) [8] we get 13 MPa $< \sigma_c <$ 63 MPa.

Independent of the question whether ice serves as glue between the regolith particles, brittle cellular porous materials fail in compression by crushing after elastic deformation. There is a plateau regime of stress versus strain during which energy is absorbed upon further straining the material and eventually densification sets in at larger strains ε. Such a scenario has taken place according to the analysis of the energy balance of the landing events [9,10].

The fracture of a material is sensitive to defects such as pre-existing cracks, inclusions or large cells or voids in cellular materials because, as said, defects act as stress concentrators. This is the basic concept of fracture mechanics [11]. For a porosity of 80% [7]:

$$\sigma \approx 10^{-2}\,\sigma_{\mathrm{wall}} \Big/ \sqrt{d/L_c} \qquad (2)$$

Here, σ is the fracture stress, L_c is the length of the cells and d is the linear defect size, for example a local crack Eq. 2 holds for $d > L_c$. The smallest cell size for the comet regolith is $L_c = 0.4$ mm [12]. Let us assume we have $d = 10$ cm. This yields a fracture stress of 6.5 kPa if we assume again that the cell walls are ice, i.e. $\sigma_{wall} \approx 10$ MPa. It should be mentioned that Greenberg et al. [5] stated, that a fracture mechanics would be the correct way of describing the fracture strength of comet materials.

Similar considerations and relations exist for the elastic moduli and fracture strength of ceramics before sintering which are either slurries or dry-pressed powders, so-called green bodies [13,14]. Green bodies have an appreciable amount of porosity and also, as assumed for the comet material, the individual particles in the unfired material contact each other at certain points, where interatomic forces hold the particle agglomerate together [15]. They deform the particles at the contact points elastically. The energy needed to separate two particles is $a_{cp}^2\times\Gamma$ where a_{cp} is the radius of the contact points and Γ is the surface energy. When the two particles are separated, the elastic energy is released which *reduces* the total energy needed for separation. The number of contacts in the ensemble with a surface area πa_{cp}^2 depends on the overall porosity. In various theoretical descriptions, this dependence was determined to be proportional to $(\rho_p/\rho_s)^z$ with z being 2, 3, and 4 [16] instead of the almost squared power dependence of Eq. 1 and the master curves cited above. Independent which equation describes the experimental situation best, the relation is very sensitive to the porosity at small values of ρ_p/ρ_s.

Summarizing, it is the porosity which determines the elasticity and the strength of a porous material for small ρ_p/ρ_s. On the one hand the porosity reduces the number of contacts or the coordination number between the individual constituents of the agglomerate and on the other hand large pores act as stress concentrator initiating failure upon loading. This holds also for rocks [17]. The large variations of strength values reported on comet 67P (from a few tens of Pa [18, 19] to several MPa [20] can be explained by local variations in porosity.

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