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Experimental study on compression property of regolith analogues

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ABSTRACT

The compression property of regolith reflects the strength and porosity of the regolith layer on small bodies and their variations in the layer that largely influence the collisional and thermal evolution of the bodies. We conducted compression experiments and investigated the relationship between the porosity and the compression using fluffy granular samples. We focused on a low-pressure and high-porosity regime. We used tens of μm-sized irregular and spherical powders as analogs of porous regolith. The initial porosity of the samples ranged from 0.80 to 0.53. The uniaxial pressure applied to the samples lays in the range from 30 to 4×10^5 Pa. The porosity of the samples remained at their initial values below a threshold pressure and then decreased when the pressure exceeded the threshold. We defined this uniaxial pressure at the threshold as "yield strength". The yield strength increased as the initial porosity of a sample decreased. The yield strengths of samples consisting of irregular particles did not significantly depend on their size distributions when the samples had the same initial porosity. We compared the results of our experiments with a previously proposed theoretical model. We calculated the average interparticle force acting on contact points of constituent particles under the uniaxial pressure of yield strength using the theoretical model and compared it with theoretically estimated forces required to roll or slide the particles. The calculated interparticle force was larger than the rolling friction force and smaller than the sliding friction force. The yield strength of regolith may be constrained by these forces. Our results may be useful for planetary scientists to estimate the depth above which the porosity of a regolith layer is almost equal to that of the regolith surface and to interpret the compression property of an asteroid surface obtained by a lander.

1. Introduction

Small airless bodies are remnants of the solar system formation, while they might have metamorphosed by collisional processes in their evolution. The surface of small bodies such as asteroids is covered by regolith consisting of porous and compressive granular matter (Sears, 2015). The relationship between porosity and compression, or strength, of regolith is a key to better understand the collisional evolution of the bodies. For example, the shape of impact craters on simulated regolith is dependent upon the porosity of the regolith, probably because a projectile penetrates more deeply into the regolith target as observed for highly porous solid targets such as sintered hollow glass beads (Wada and Nakamura, 2012; Okamoto and Nakamura, 2017). At an impact velocity lower than 1 km/s, it is experimentally shown that a fraction of a rocky impactor onto regolith can survive as a block (Nagaoka et al., 2014). Impact onto regolith at the surface of a small body occurs not only with projectiles from interplanetary space but also with blocks from the body itself at low collision velocities. Intrusion depths of the blocks ejected by impact and re-accumulated onto the regolith depend on the compression property or mobility of the regolith. Such an intrusion depth may affect the collisional lifetime of blocks (Durda et al., 2011). According to a previous laboratory study, if the velocity of an impacting block onto regolith is so low that the pressure due to the impact is smaller than the compressive strength of the regolith, then the block would rebound, otherwise it would penetrate into the regolith (Machii et al., 2013; Nakamura et al., 2013). Moreover, porosity structure of regolith is crucial for thermal evolution of small bodies (Akiridge et al., 1998). The thermal conductivity of regolith is dependent not only on the grain size but also on the porosity of the regolith (Gundlach and Blum, 2013; Sakatani et al., 2016).

The porosity of regolith is directly measured for the moon, whereas it is estimated using the density obtained by radar observations for asteroids and Martian moons (Mitchell et al., 1974; Magri et al., 2001; Ostro et al., 2004; Busch et al., 2007). However, such measurements can only probe the near-surface density of regolith. It is known that core tube samples obtained from deep layers of lunar regolith have larger densities because of soil pressure and vibration of impact-induced shaking (Mitchell et al., 1974). Similar physical processes and thus the depth dependence of regolith density can be expected on asteroids. The

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porosity estimated for asteroidal surfaces is larger than random close packing of monodisperse particles (∼0.36), namely, the surfaces are still porous enough to be further compressed (e.g., Scott and Kilgour, 1969).

The density gradient of regolith is determined by the compression properties of the regolith and the compression properties of a granular layer like regolith depend on the structure of the layer and the physical properties of the constituent granular particles. A granular layer is compacted by rearrangement, elastic and plastic deformation, and fragmentation of constituent particles. In case of compaction under a low-pressure regime, deformation and fragmentation of the constituent particles are negligible and therefore the macroscopic structure of the granular layer and forces required to rearrange the particles against interparticle forces determine the compression properties of the layer. The macroscopic structure of a granular layer, in other words, how particles are aligned in the layer, depends on the initial porosity of the layer. The initial porosity is determined by a balance between the gravitational force and the interparticle force acting on the constituent particles (Kiuchi and Nakamura, 2014). The initially loose structure is then changed against interparticle forces acting on the particles by applied compression or vibration.

Interparticle forces acting on particles depend on the following factors.

(a) The particle diameter. The particle diameter of lunar regolith was directly measured and the median diameter is 60–80 μm (Heiken et al., 1991). The particle diameters on asteroids were suggested to be tens to hundreds of microns based on polarimetric observations of asteroids (Dollfus and Zellner, 1979). Images taken by Hayabusa showed that smooth terrain consists of millimeter to centimeter sized particles (Yano et al., 2006). Gundlach and Blum (2013) estimated “typical” diameters based on thermal inertia of the asteroid and found to vary within a range from ∼10 μm to cm. The particle diameters of regolith vary from one body to another and is shown to have a negative correlation with the radius of the body or its escape velocity.

Theoretically, interparticle forces (e.g. pull-off force) increase with particle diameter if the particle is a perfect sphere and the gravitational acceleration is of the order of 10^{-3}–10^{-2} m/s^2 on small bodies of ∼10–100 km in diameter (Johnson et al., 1971). A fluffy regolith layer is, therefore, possibly formed under this low gravitational conditions even if the diameter of regolith particles is of the order of millimeters.

(b) The particle shape. The shape of most of regolith particles is expected to be irregular because regolith is formed either by accretion of impact fragments or in-situ thermal fatigue of blocks on small bodies (Delbo et al., 2014). Regolith samples returned from the moon and from the asteroid Itokawa confirmed their irregular shapes (Mitchell et al., 1974; Tsuchiyama et al., 2011).

(c) The material composition. The material composition of asteroid surfaces is mainly silicates with some exceptions. S-and C-type asteroids are considered as parent bodies of ordinary chondrites and carbonaceous chondrites, respectively, which are composed of silicates (Burbine et al., 2002).

(d) The surface chemistry. Interparticle forces of silica particles are reduced by adsorbed molecules on the particles and enhanced under ultra-high vacuum conditions (Perko et al., 2001; Kimura et al., 2015).

It is difficult to measure the compression properties of regolith layer analogues that simultaneously mimic both the particle size and the porosity because we cannot reproduce a porous structure with millimeter sized particles under earth's gravity. We can reproduce a porous structure only with smaller particles.

Compression experiments of granular materials with a relatively high porosity were conducted by several researchers. Yasui and Arakawa (2009) obtained a compression curve of a 1 μm silica powder. The initial porosity of their sample was 0.64. In our previous work, compression curves of silica and alumina powders with different particle sizes were obtained (Omura et al., 2016). The initial porosity of the samples ranged from ∼0.5 to ∼0.8. However, the uniaxial pressure applied to the samples in these studies was higher than ∼10^4 Pa that exceeds the pressure range relevant to a shallow depth of a regolith layer. Compression curves at low pressure showed a regime where the samples kept their porosity almost constant (Blum et al., 2006; Güttler et al., 2009; Machii et al., 2013). The initial porosity was higher than ∼0.75, but it covered only higher part of possible porosity for asteroid regolith, which is expected to be 0.4–0.9 (Kiuchi and Nakamura, 2014). Güttler et al. (2009) proposed an empirical formula to reproduce the compression curve of uniaxial compression. The formula is described by four parameters obtained by laboratory experiments; an initial filling factor under low pressure, an equilibrium filling factor under high pressure, turnover pressure, and a logarithmic width of transition from initial to equilibrium filling factors. However, the initial porosity, size distribution, shape and material composition of constituent particles, and surface conditions of regolith on an asteroid surface differ from those in the laboratory. Therefore, to estimate the compressive strength of a regolith layer on an asteroid, the effects of initial porosity, particle properties, and surface chemistry on the compression curve must be separately evaluated.

To obtain the data on the compressive properties, especially at a low-pressure and high-porosity regime, we conducted compression experiments and investigated the relationship between the porosity and the pressure using particles of different size distribution, shape, and composition with various initial porosity. We determined the threshold pressure below which the porosity of samples remains almost unchanged. We compared our results with a previously proposed theoretical model for granular material and obtained a possible constraint on the threshold pressure beyond which regolith starts to be compacted. A possible application to an estimate of porosity structure in asteroid surfaces is briefly discussed.

2. Experiments

2.1. Samples

We used fine powders to produce fluffy samples that mimic a regolith structure with a relatively high porosity on small bodies. The selection of powders aimed at investigating the effects of particle size distribution, shape, and material composition on the compression properties of the powders. We used irregular alumina particles of three different sizes and spherical silica particles of three different sizes as our sample powders. Fig. 1 shows scanning electron microscope (SEM) images of each sample powder. The physical properties of the powders are listed in Table 1. Fig. 1 also presents a SEM image of fine components of fragments produced by an impact experiment in which a cylindrical iron projectile was shot at a block of basalt. The shapes of “irregular” samples resemble the shape of impact fragments, namely, an important component of regolith. Fig. 2 shows the particle size distributions of our sample powders in the form of cumulative volume fractions versus particle diameter, which were determined by a laser diffractometer (SHIMAZU SALD-3000S). The sample powders have different ranges of particle size distribution. We use the median diameter as a representative particle diameter of the sample powder and the ratio d_{85}/d_{15} as the width of a particle size distribution where d_{85} and d_{15} indicate the diameters at the cumulative volume fraction of 85% and 15%, respectively.

Because it is easier to obtain commercially available irregularly shaped alumina particles with a narrow size distribution than those consist of SiO_2, we used irregular alumina particles with three different median diameters to investigate the size dependence for irregularly shaped particles. Spherical particles were also used in this study for a direct comparison of our experimental results with a theoretical model.