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Compaction and fragmentation of porous gypsum targets from low-velocity impacts

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ABSTRACT

We performed low-velocity impact experiments of gypsum spheres with porosity ranging from 0 to 61% and diameter ranging from 25 to 83 mm. The impact velocity was from 0.2 to 22 m/s. The target was an iron plate. The outcome of gypsum spheres with porosity 31–61% was different from those of non-porous ice [Higa M., Arakawa, M., Maeno, N., 1996. Planet. Space Sci. 44, 917–925; Higa M., Arakawa, M., Maeno, N., 1998. Icarus 133, 310–320] and non-porous gypsum. In between the intact and fragmentation modes, the outcome of the non-porous ice and gypsum was crack growth at the impact point. However, the outcome of the porous gypsum was compaction. We found that the restitution coefficients of the porous gypsum spheres were all in a similar range, in spite of the difference of the porosity and size at impact velocities up to about 10 m/s where they begin to be fragmented in pieces. Moreover, there is not a large difference between the restitution coefficient of porous and non-porous gypsum. These results collectively indicate that restitution coefficient of gypsum spheres of cm-size is not strongly dependent upon the porosity and compaction process.

1. Introduction

Collisions of small Solar System bodies play an important role in their formation and evolution. Impact velocity is of the order of several km/s in the present asteroid main belt (Bottke et al., 1994). Laboratory impact experiments at impact velocities of km/s range, numerical simulation, and development of scaling theory have been performed to clarify the collisional outcome of the high velocity impact processes (Holsapple et al., 2002). Collisional processes with much lower velocity relevant to the phase of planetesimal growth and dynamical and collisional evolution of particles in the rings of giant planets have also been studied by laboratory experiments (Blum and Muench, 1993; Wurm et al., 2005; Hatzes et al., 1988). Re-accumulation of ejecta from impact cratering or impact disruption of small bodies is another situation where low-velocity impact process play an important role. For example, whether or not the re-accumulated pieces break up at the re-impact on the surface influences the population of boulders and regolith on the surface of small bodies (Nakamura et al., 2008).

Collision outcomes at velocities from 1 to 50 m/s were investigated by laboratory experiments for basalt and other igneous rocks, H_2O ice, and dirt clods (Hartmann, 1978). Impact velocities of catastrophic disruption (defined by largest fragment equaling half original mass) were found to be 37, 9, and 2 m/s, respectively. Higa et al. (1998) conducted low-velocity impact experiments of non-porous ice spheres and showed that the outcome is size-dependent.

Since the recent spacecraft explorations and ground-based observations have revealed that small bodies are generally porous in structure (Britt et al., 2002), understanding of impact process of porous bodies at low velocity is of more significance. There are large varieties in the structure of porous bodies (Richardson et al., 2002; Nakamura et al., 2009). Ryan et al. (1991) studied impact strength of porous aggregate targets at low and high velocities. From the result of low-velocity drop experiment of pebble aggregates, where strong pebbles were connected together by weak glue, it was shown that pebble aggregate having similar static strength to ice showed higher resistance to impact fragmentation.

In this study, we performed low-velocity impact experiments of gypsum spheres. Gypsum has macroscopically more homogeneous structure than the pebble aggregates and was used in previous impact disruption experiments at higher velocity (Kawakami et al., 1991; Nakamura et al., 1992; Stewart and Ahrens, 1999). Mechanical properties of gypsum—modulus, strength, fracture toughness, etc.—as a function of porosity were investigated in a previous work (Vekinis et al., 1993) and we also investigated the physical properties of the samples used in our impact experiments in order to

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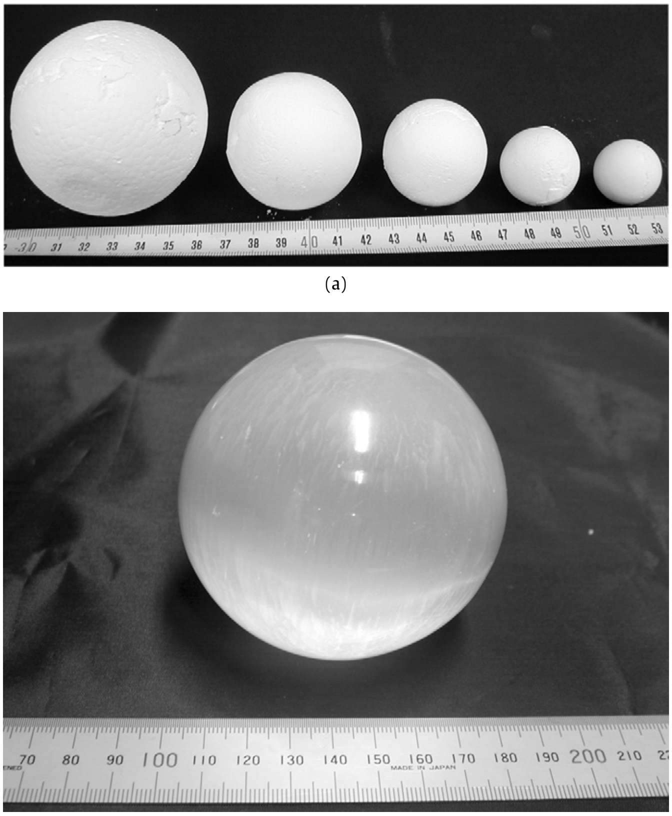
be useful for the future theoretical or numerical works on impact process of porous bodies at low velocity.

2. Physical properties of the samples and experimental method

We prepared two different kind of spheres of dihydrate gypsum ($CaSO_4 2H_2O$). One is self-made gypsum spheres. Powders of hemihydrate were mixed with water at three different weight ratios at room temperature and placed into spherical silicon molds. The porosity of the samples was 31 ± 1 (G31), 47 ± 3 (G47), $61 \pm 4\%$ (G61). The samples were dried for more than 5, 7 and 10 days, respectively. For G47, spheres of 25, 30, 40, 50 and 70 mm were prepared in order to investigate the size dependence of the impact process. On the other hand, for G31 and G61, we fixed the diameter to 50 mm, in order to investigate the porosity dependence. The other is natural crystalline gypsum, called Satin spar. Spheres of diameter ranged from 72 to 83 mm and the porosity less than 3%, respectively were machined out of pre-existing material. Fig. 1 shows the samples. Porous gypsum has an internal structure of coherent aggregates (Richardson et al., 2002). The sizes of void and particles are nearly comparable. Therefore, this structure is similar to the microporosity observed in chondrites (Britt et al., 2002; Nakamura et al., 2009).

We measured physical properties of the samples; velocity of the longitudinal wave, uniaxial compressive strength, Young's modulus, shear modulus, and static compaction curve, called crush curve, which is one of pressure–volume curve. Velocity of the longitudinal wave was measured for cylinders varying its length using a piezoelectric device. The uniaxial compressive strength of the samples was measured for cylinders of 13 mm in diameter and 17 mm in height at a loading rate of 0.1 mm/s. Young's modulus and shear modulus were determined by measurements of natural resonance frequencies of bending and torsional vibration of plates of $6 \times 20 \times 42$ and $6 \times 12 \times 42$ mm^3 in size, whereas the Young's modulus was determined by four-point bending test in the previous work (Vekinis et al., 1993). The crush curves were measured for cylindrical samples of 10 mm in diameter and 12 mm in height. The samples were put into a hollow stainless steel cylinder and compressed by a stainless cylinder of diameter 10 mm at a loading rate of 0.1 mm/s. Fig. 2 shows the crush curves. Samples behave quasi-elastic under the load corresponding to the compressive strength. The samples behave plastic over the load level of compressive strength and lose porosity rapidly. The plastic regimes of the three different samples overlap and converge into single curve. Table 1 summarizes the measurement results. Similarly to the previous results (Vekinis et al., 1993), all the mechanical properties increase with the decrease of porosity. The longitudinal wave velocity can be also derived from the Young's modulus and shear modulus. The calculated values are shown in Table 1. They are in agreement with the values with those determined by piezoelectric device if we take the scatter of the values of the individual specimens into account. Although the values of compressive strength measured for our samples are similar to those of previous determination, the Young's moduli are higher than the previous data. This may be due to the different measurement methods.

The spheres were impacted against an iron plate of $40 \times 400 \times 300$ mm^3. Free falling method was used to accelerate the samples with impact velocity up to 6 m/s. A spring gun was used to obtain impact velocity higher than about 6 m/s. The impact velocity of G47 spheres with different size was from 0.2 to 22 m/s. It was from 0.3 to 6 m/s for G31 and G67. We impacted Satin spar parallel to its crystal orientation with velocity from 0.2 to 6 m/s. The velocities of the samples were measured on the images taken by a high-speed video camera at 500 or 1000 frames/s with exposure duration equal to or less than 100 μs. More than three frames were used for a velocity determination. Fig. 3 shows an example of the image sequence.


(a)

(b)

Fig. 1. Gypsum samples. (a) Self-made gypsum spheres (G47). The diameter is 70, 50, 40, 30 and 25 mm from left to right, respectively. (b) Satin spar sphere. The diameter is about 75 mm.

3. Results

The outcome of Satin spar is similar to the ice spheres' (Higa et al., 1998) as shown in Fig. 4. Under impact velocity lower than about 0.6 m/s, the sample is intact. When impact velocity exceeds about 2 m/s, the sample is broken along the crystal orientation. In between, visible cracks develop in any direction from the impact point.

On the other hand, the outcome of G31, G47, and G61 is different from the non-porous ice and Satin spar. There are no visible cracks and fractures in the intermediate regime between intact and fractured states. The intermediate outcome is characterized by a flattened surface at the impact point as shown in Fig. 5. Fig. 6 shows the largest fragment mass ratio to the original sample mass versus impact velocity for G47. The data points on or near the line of unity in the vertical axis correspond to the intact and intermediate modes of the outcome described in the above. Although some amount of dusts was ejected at the impact as shown in Fig. 3 and the impact point was flattened, the after-impact gypsum samples had almost the similar mass with the original mass. The disappeared part of the sphere was not really lost from the original sample. This fact indicates that the flattened part of the samples is made by compaction. Direct evidence of compaction, i.e., change in porosity, will be given later. There are no largest fragment having mass between 0.7 and 0.95 of the original mass. That is, when samples of G47 broke, they broke into only a few large pieces and very small pieces without fragments of intermediate size. In fact, the number of the major fragments increased from 2 to 5 according to the increase of impact velocity. Fig. 5b shows the example