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# Size dependence of the disruption threshold: laboratory examination of millimeter–centimeter porous targets

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ABSTRACT

The outcome of collision between small solid bodies is characterized by the threshold energy density $Q_S^*$, the specific energy to shatter, that is defined as the ratio of projectile kinetic energy to the target mass (or the sum of target and projectile) needed to produce the largest intact fragment that contains one half the target mass. It is indicated theoretically and by numerical simulations that the disruption threshold $Q_S^*$ decreases with target size in strength-dominated regime. The tendency was confirmed by laboratory impact experiments using non-porous rock targets (Housen and Holsapple, 1999; Nagaoka et al., 2014).

In this study, we performed low-velocity impact disruption experiments on porous gypsum targets with porosity of 65–69% and of three different sizes to examine the size dependence of the disruption threshold for porous material. The gypsum specimens were shown to have a weaker volume dependence on static tensile strength than do the non-porous rocks. The disruption threshold had also a weaker dependence on size scale as $Q^*_s \propto D^{-\gamma}$, $\gamma \le 0.25-0.26$, while the previous laboratory studies showed $\gamma = 0.40$ for the non-porous rocks. The measurements at low-velocity lead to a value of about 100 J kg$^{-1}$ for $Q_S^*$ which is roughly one order of magnitude lower than the value of $Q_S^*$ for the gypsum targets of 65% porosity but impacted by projectiles with higher velocities. Such a clear dependence on the impact velocity was also shown by previous studies of gypsum targets with porosity of 50%.



## 1. Introduction

Collisional cratering and disruption play an important role in the evolution of the asteroid population (Bottke, et al., 2005; O'Brien and Greenberg, 2005). The impact process is also responsible for the production of dust in the asteroid main belt (Tomeoka et al., 2003; Ishiguro et al., 2011), Kuiper belt (Yamamoto and Mukai, 1998), and in debris discs around young stellar objects (Takasawa et al., 2011; Johnson et al., 2012).

The outcome of collision between small solid bodies whose disruption is dependent on material strength rather than self-gravity is characterized by the threshold energy density $Q_S^*$, the specific energy $Q$ required to shatter, which is defined as the ratio of projectile kinetic energy to target mass (or the sum of the target and projectile) needed to produce the largest intact fragment of mass $M_L$ that contains one-half the target mass $M_t$ (Holsapple, et al., 2002). Small bodies in the solar system are generally brittle with some exceptions; e.g., metals at a temperature higher than the brittle–ductile condition (Katsura et al., 2014), and fragmentation of brittle solids occurs by growth and coalescence of cracks. The static strength of a brittle material is known to be dependent on its volume (e.g., Housen and Holsapple, 1999). Larger bodies tend to have a greater probability of including weaker parts or cracks that can begin to grow at lower stress. The volume-dependent static strength is described by a power-law form:

$$Y(V) = Y_0 \left(\frac{V}{V_0}\right)^{-1/m}, \tag{1}$$

where $Y(V)$ and $Y_0$ are the static strength of specimens of volume $V$ and $V_0$, respectively. The material constant $m$, called the shape factor or Weibull modulus, describes the degree of homogeneity of the material such that larger $m$ corresponds to greater homogeneity and lower volume dependence (Weibull, 1939).

In dynamic fragmentation, the strength or the resistance to fragmentation, which is represented by $Q_S^*$, is not only dependent directly on the size scale but also indirectly on it through the duration of loading (Holsapple, 1994; Housen and Holsapple, 1999). Collision between larger bodies generates a longer duration of loading, which allows weaker cracks to extend a greater distance, resulting in a larger degree of fragmentation under a given energy density than in the case of shorter duration loading. Numerical simulations show that the value of $Q_S^*$ is dependent on

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the size scale and that it decreases with increasing target size in a strength-dominated regime (Benz and Aspaug, 1999; Asphaug et al., 2002). This tendency has been confirmed experimentally for a non-porous brittle material by laboratory collision experiments performed under conditions designed to examine the target-size effect (Housen and Holsapple, 1999). It was shown that the specific energy required to delivering the same value of $M_L/M_t$ decreases with increasing target diameter $D$:

$$Q^*_s \propto D^{-\gamma}, \tag{2}$$

where $\gamma = 0.405 \pm 0.023$ for granite targets with diameters between 1.9 and 34.4 cm. Impact disruption experiments aimed at examining the tendency for smaller non-porous targets have been conducted using pyrophyllite targets which were previously used in impact disruption experiments (Takagi et al., 1984) with sizes down to 0.1 cm (Nagaoka et al., 2014). The threshold energy density was shown to have a similar power-law dependence on target size with $\gamma = 0.404 \pm 0.035$. Although impact disrupted iron meteorite specimens of millimeter–centimeter at room temperature showed large deformation probably due to ductility, the largest fragment mass fraction has been shown to be dependent on the size of the specimen for this material, too (Katsura et al., 2014).

The purpose of this study was to examine the size dependence of $Q^*_S$ for porous material. The macroporosity of C-class asteroids ranges up to 0.6, and that of some comet nuclei is estimated to be more than 0.8 (Consolmagno et al., 2008). However, the internal structure of porous materials is not determined exclusively by porosity (Richardson et al., 2002; Nakamura et al., 2009). For example, pumice and formed plastics consist of pores surrounded by walls, whereas aggregate-type porous materials, such as sand piles and sintered beads, consist of particles and inter-particle spaces. In the former, cracks may grow to some extent in the walls; therefore, $Q^*_S$ may be dependent on the target size as for non-porous brittle materials. Numerical simulation of collisional disruption of a pumice-like porous target shows a dependence of $Q^*_S$ on target size, as for a non-porous basalt target, in the strength regime (Jutzi et al., 2010). However, sintered bead targets tend to break at necks, the connecting parts between the beads (Machii and Nakamura, 2011), and continuous cracks cannot extend to great distances. The value of $Q^*_S$ in such a material may exhibit little or no size dependence.

In this study, we used gypsum targets, which have been used in previous impact experiments as an analog for porous small bodies. Kawakami et al. (1991) conducted impact experiments with gypsum ellipsoids having axial ratios similar to those of Phobos and discussed the resulting fracture pattern. Nakamura et al. (1992) investigated the velocity and spin of fragments from a gypsum target and compared the results with those for basalt and alumina targets. The velocity in the center-of-mass system of given mass fragments was shown within the range of an order of magnitude, despite the different material strengths and porosities. Stewart and Ahrens (1999) showed that the threshold energy density of a 65% porosity gypsum target is similar to that of basalt (Fujiwara et al., 1977) may be because of the steeper decay of the shock wave. They showed that the fragment size distribution for the two materials is similar. Okamoto and Arakawa (2009) showed that the threshold energy density of a 50% porosity gypsum target is about threefold that of basalt (Fujiwara and Tsukaoto, 1980), but that the antipodal fragment velocity at given specific energy is markedly lower than that of basalt. Yasui and Arakawa (2011) showed that the threshold energy density of 50% porosity gypsum at low-velocity impact is about 20% of that of high-velocity (Okamoto and Arakawa, 2009).

In this study, we performed low-velocity impact disruption experiments using porous gypsum targets (porosity 65–69%) of different sizes to investigate the size dependence of $Q^*_S$ and compared the results with those for non-porous targets. Additionally, we conducted high-velocity impact disruption experiments of the gypsum targets. Scaling theory of impact disruption based on point-source approximation derives a relationship between the largest fragment mass fraction and the impact conditions and material properties (Housen and Holsapple, 1990, 1999; Holsapple, 1994):

$$Q^*_s \propto U^{-3\mu+2} D^{-9\mu/(2m-3)} \left(\frac{Y}{\rho_t}\right)^{-3\mu/2}, \tag{3}$$

where $U$, $\rho_t$, and $\mu$ are impact velocity, target density, and a material constant, respectively. Our results were compared with the previous study (Stewart and Ahrens, 1999) conducted at impact velocity between our low and high-velocity conditions to more thoroughly discuss the size dependence in relation with the velocity dependence of $Q^*_S$ for porous bodies.

## 2. Experiments

We prepared cylinders of dihydrate gypsum ($CaSO_2 2H_2O$). Powders of hemihydrate were mixed with water at the weight ratio of 10 (dehydrate): 9 (water) at room temperature. The mixture was placed into plastic molds having diameters of 11–74 mm and dried in an oven at 100 °C for more than 1 day. The porosity of the samples was calculated to 65–69% using the density of 2320 kg m$^{-3}$ as was done in previous study (Fujii and Nakamura, 2009). Fig. 1 shows a scanning electron microscope (SEM) image of a fragment from a specimen. It consists of grains that have sizes of ~10 μm and similarly sized void spaces (Fujii and Nakamura, 2009). Cylindrical specimens with diameters of 72.5 and 73.7 mm are here called “large” (L) targets, and those with diameters of 11 and 16 mm are called “medium” (M) targets. Smaller blocks were cut from the “medium” targets and are called “small” (S) targets.

Impact experiments were conducted using a vertical powder gun with a 15-mm-diameter bore and a gas gun with a 3.2-mm-diameter bore at Kobe University (Nagaoka et al., 2014). The experimental conditions are summarized in Table 1. The velocity of the projectile was determined from images taken at 10–67 ms interval by a high speed camera from a direction orthogonal to the projectile trajectory (Photron FASTCAM SA1.1). Hereafter we call this camera as “side camera.” The target to projectile mass ratio was kept almost constant between three different sized targets to minimize the possible effect of target/projectile size ratio.

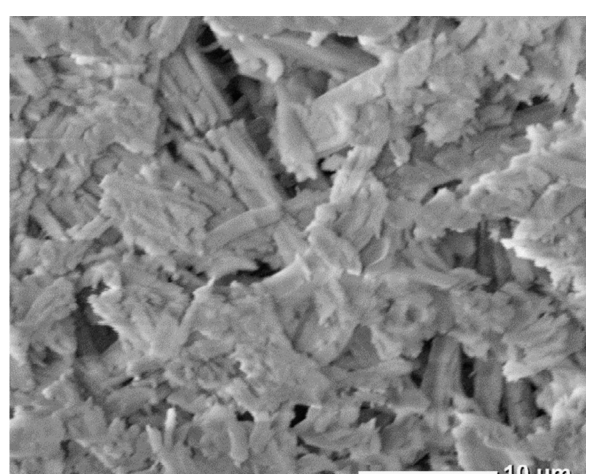


**Fig. 1.** SEM image of a gypsum fragment.