POROSITY EFFECTS ON IMPACT PROCESSES IN SOLAR SYSTEM MATERIALS. Sarah T. Stewart, Thomas J. Ahrens, *Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, CA 91125, USA (sstewart@gps.caltech.edu).*

We will present calculations and experiments on the effect of porosity on the shock wave attenuation, dynamic strength and fragment distribution of porous, brittle materials. These results are part of our developing theory of porosity effects on impact processes in solar system materials. We will also examine the effects of porosity on crack propagation in ice and comet analog materials.

The strength of comets, porous aggregates of ice and dust, is basically unknown with only one data point from the tidal breakup of Comet Shoemaker-Levy 9, which had an extremely low tensile strength of order 100 Pa. The porosity of comets has never been measured directly and models predict a wide range from 40-80%. Planned spacecraft missions, ESA's Rosetta and NASA's Deep Space 4, will measure the porosity and other physical properties of a couple of comets, and there is probably a large range of porosities found in comets. To isolate the effects of porosity on impact processes, we are conducting experiments on Plaster of Paris, a gypsum plaster, from which targets may be made with porosities ranging from 30-80%. The static tensile strength of the plaster is similar to solid ice, ranging from 2-4 MPa, depending on the porosity [1].

The outcome of impacts into icy bodies depends on the material strength and attenuation profile of the shock wave. Porosity will steepen the decay of the shock wave, reducing the volume effected by an impact compared to a solid of the same material. To disrupt a given volume of porous material compared to the same volume of solid of the same material strength, a stronger initial shock wave is necessary. In this way, a porous material may have stronger effective dynamic strength than a solid with similar static material strength.

Shot #	101	102	103	104
M_t [g]	976.8	468.29	250.05	97.78
M_p [g]	0.743	0.741	0.732	0.722
V_i [m/s]	889	913	976	941
Q [10^6 erg/g]	3.0	6.6	14	33
F_L [%]	0.997	0.552	0.213	0.140

Table 1: Experimental parameters for shots into Plaster of Paris with 65% porosity (density=0.81 g/cm^3). M_t and M_p denote the mass of the target and projectile, respectively. The projectile is a pure Al bullet. The impedence match shock pressure is about 1.5 GPa.

We have conducted impact experiments in 65% porous plaster. The experimental parameters are detailed in Table 1. The critical specific energy for total disruption of a target is usually defined as the specific energy required to disrupt the target such that the largest fragment remaining contains half the mass of the total target. The specific energy, Q, is the ratio of the kinetic energy of the projectile to the total mass of the target. See Figure 1 for the mass fraction of the largest fragment, F_L, vs. the specific energy for the impacts into gypsum plaster. The data may be fit by

$$F_L = 4.3 \times 10^5 Q^{-0.87}, \qquad (1)$$

shown as the solid line in Figure 1.

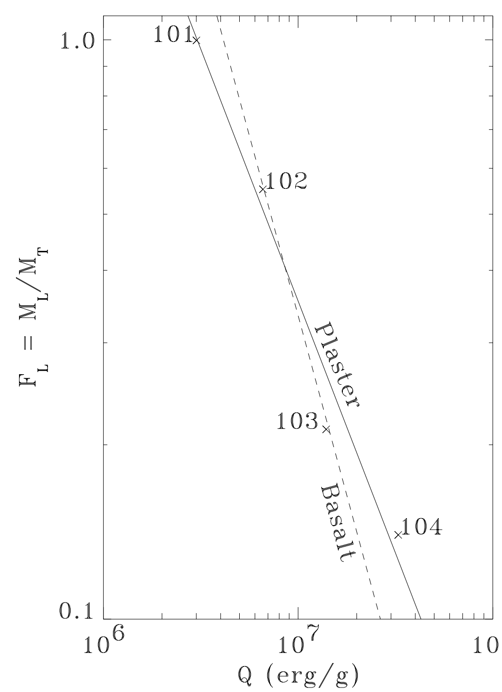

Figure 1: Mass fraction of largest fragment vs. specific energy. The critical specific energy required to disrupt the plaster target is similar to the disruption energy for basalt [2].

The critical specific energy for total disruption of the plaster is about 6.7×10^6 erg/g. For comparison, Fujiwara *et al.* [2] fit the largest fragment from high velocity (2.6 km/s) impacts into basalt with

$$F_L = 1.66 \times 10^8 Q^{-1.24}, \qquad (2)$$

shown as the dashed line in Figure 1. Although the slope of the largest fragment size is slightly shallower for the plaster than for basalt, the critical disruption energy of basalt, $7 - 8 \times 10^6$ erg/g [2], is similar to the plaster. We have found that the disruption energy of a porous matrix with static tensile strength of a few MPa is similar to the disruption energy of basalt with a static tensile strength an order of magnitude larger and a dynamic tensile strength about two orders of magnitude larger [3].

In addition to the critical disruption energy, the fragment size distribution is similar for the basalt and plaster impacts. The cumulative number of particles follows a power law, $N_c = r^{-b}dr$ where $b = 2.7$ (Figure 2), similar to basalt despite the very porous matrix of the plaster. The drop in number of particles in the smallest size bins is due to loss of particles in the sifting process and occurs at a similar size as the basalt data [2].

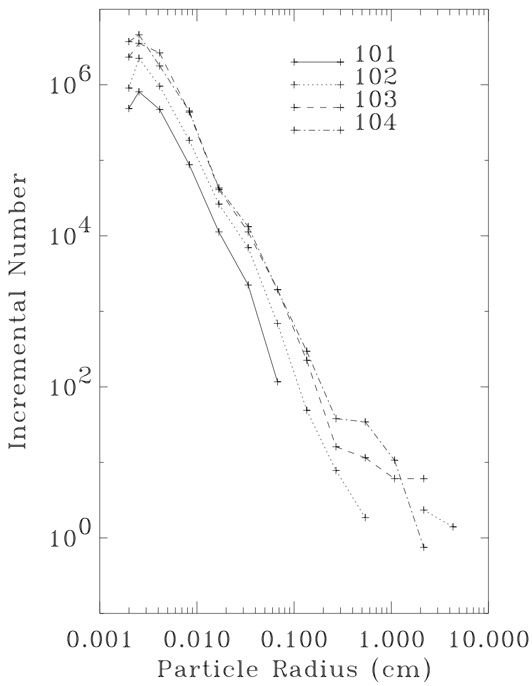

Figure 2: Fragment size distribution for impacts into Plaster of Paris.

The similarity of the critical disruption energy for plaster and basalt may be explained by a steeper shock wave attenuation in the porous plaster than the solid basalt. Mizutani *et al.* [4] developed an intuitive scaling law for impact fragmentation in the strength regime based on a nondimensional impact stress, P_I, with the general form:

$$P_I = \frac{P_0}{Y_t}\left(\frac{L_p}{L_t}\right)^{\alpha} \quad (3)$$

where P_0 is the peak shock pressure, Y_t is the target material strength, L_p is the length of the projectile, L_t is the length of the target, and α is the attenuation profile of the shock wave. Intuitively, the target is completely disrupted when the pressure throughout the target exceeds the appropriate material strength. This parameter has been used to describe the disruption of basalts and pyrophyllites [5] and solid ice [6].

Using the correlation of the largest fragment to the nondimensional impact parameter from impacts into basalt by Takagi *et al.* [5], we estimate that in our impact experiments on 65% porous gypsum plaster the shock wave attenuation follow $\alpha \sim 3$. Ahrens and O'Keefe [7] and Pierazzo *et al.* [8] have shown that the attenuation profile depends on the impact velocity. Pierazzo *et al.* developed the following relation for impact velocities, V_i, from 10-100 km/s:

$$\alpha = -1.84 + 2.61 \log_{10}(V_i) \quad (4)$$

Extension from the attenuation profiles developed for solids at higher velocities is not valid for the gypsum plaster impacts at 900 m/s. We are currently constructing a model to account for the steeper shock wave attenuation profile in porous materials.

In addition to the shock wave attenuation profile, the material strength is needed. The dynamic tensile strength of the target is the appropriate material strength to use in an impact calulation. It requires, however, knowledge of the dependence of the tensile strength on strain rate. The only published data on the dynamic tensile strength of ice is by Lange and Ahrens [9] and more data are needed (see correction [10]). We plan to conduct experiments to measure the dynamic tensile strength of both solid and porous ice.

Although shock damage from multiple impact events may render large icy bodies in the outer solar system effective ''rubble piles,'' similar to Comet Shoemaker-Levy 9, where the outcome of impact events are dominated by the gravity regime, a better understanding of the impact effects in the strength regime is necessary for a full collisional model of the icy bodies in the outer solar system. A model of the effects of porosity on the outcome of impacts on icy bodies will be an important part of the study of the collisional history of the Kuiper Belt, the source of short period comets, which will be visited by the NASA's Pluto-Kuiper Express spacecraft mission in the next century. The strength properties of comets are necessary to understand the transition zone to gravity scaling and also to interpret the cratering history that will be observed on the icy surfaces of outer solar system objects.

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