# INVESTIGATION OF IMPACT CRATERING PROCESSES INTO POROUS TARGETS THROUGH HYPERVELOCITY EXPERIMENT AND SIMULATIONS.

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**ABSTRACT**

The goal of these studies is to obtain a better comprehension of the impact processes on solid body surface (specifically asteroids, comets, icy satellites of giant planets, Kuiper belt objects) and for the data interpretation of remote sensing observations.

We focus on the study of impact processes on porous targets both by experimental and theoretical approach in order to complement and extend the available data to ranges of velocity and physical conditions not yet explored.

Dedicated hypervelocity impact experiments into low density materials and numerical simulations by using Smooth Particle Hydrodynamics technique have been performed and results are presented in this paper.

## 1. INTRODUCTION

The surface of the solid bodies of the Solar System is exposed to impacts of cosmic objects of different dimensions and composition.

A better understanding of impact processes is needed to further our understanding of the surface evolution of the solid bodies in the Solar System and to allow remote sensing data from forthcoming missions as Smart1, MarsExpress, VenusExpress, BepiColombo, Cassini/Huygens, Rosetta to be correctly interpreted.

New data from observations of asteroids and spacecraft encounters revolutionized our understanding of asteroid bulk density [1]. Most asteroids appear to have bulk densities that are well below the grain density of their likely meteorite analogs [4]. This indicates that many asteroids have significant porosity. High porosity attenuates shock propagation, strongly affecting the nature of cratering and greatly lengthening the collisional lifetimes of porous asteroids.

A peculiar example is the C-type, main-belt asteroid 253 Mathilde recently imaged by the Near Earth Asteroids Rendesvous (NEAR) spacecraft. The NEAR determination of a bulk density of 1.3± 0.2 g $cm^{-3}$ for Mathilde [13] and the presence of several giant craters larger than conventionally accepted crater size limit for disruption [2] suggests that this asteroid has significant porosity and this porosity must dampen the shock wave propagation waves in the interior of the asteroid. Another more recent example is the asteroid Itokawa, target of the Japanese mission Hayabusa, which shows a typical rubble pile structure [5].

Porosity is an important physical characteristic of the minor bodies, affecting their behaviour during cratering and catastrophic disruption.

Kawakami et al. (1991) [9] performed impact experiments on a gypsum target simulating Phobos and studied the impact origin of grooves radially growing from a central large crater; they concluded that fracture mode was highly dependent on target material properties, in particular on porosity, and that the low shock impedance of the gypsum target induced rapid attenuation of shock pressure during propagation. Love et al (1993) [10] have shown that it requires more projectile energy to produce the same cratering effect in a porous target than in a nonporous target.

Porous targets are likely to have sound velocity lower than those of nonporous targets composed of same material and compaction of initially porous materials can produce rapid attenuation of the shock, thus affecting energy propagation during collisions.

Similar results have been obtained during our hypervelocity tests campaign aimed at analysing hypervelocity impact effects on porous target. Tests descriptions and results are presented in this paper.

## 2. HYPERVELOCITY EXPERIMENTS

Dedicated hypervelocity impact experiments into low density materials have been performed by using a two-stage light-gas gun (see Fig. 1) of the hypervelocity impact facility at CISAS "G. Colombo" of the University of Padova, Italy [11].

These tests have been performed by shooting aluminium and nylon projectiles from 1 to 4.72mm at velocities of 1600-5500 m/s on targets of several dimensions and materials, i.e. glass ceramic foams, pumices with densities from 0.35 to 1.07 g/$cm^3$.

Physical properties of the impacted materials are analysed by visual and photographic investigation before, during (when possible) and after the event by means of the diagnostic instrumentation available at the impact facility. After the impact, targets are analysed in order to evaluate crater morphology, volume, depth-diameter ratio and ejected mass-projectile mass ratio.

In Tab. 1 some physical properties, density and crushing strength, for the tested materials are reported, while

Tab. 2 presents shots parameters, target characteristics and crater depth of cratering experiments performed at CISAS for this campaign.

Examples of craterization on ceramic glass foam, natural pumices and limestone (Vicenza stone) samples are presented in Fig. 2, Fig. 3 and Fig. 4 respectively.

All figures report shot parameters and craters morphology, thus from a first tentative of comparison it can be argued that natural pumices, which have the lowest density, present small and deep craters.

Craterization has been also provided of photographic proofs of impact event inside impact chamber: the detection of flash generated by the impact of projectile onto the target (see Fig. 4) and shadowgraphies (see Fig. 2) a sequence of four shadow images taken with a mean time delay of 15μs obtained by using a system of flashes to detect impact event and to monitor ejecta.

Tab. 1 Type of employed samples. Density, crushing strength and sample shape are reported for each material.

| Material | Density ρ ($g/cm^3$) | Crushing Strength (MPa) | Shape |
|---|---|---|---|
| Glass Ceramic Foam | 0.92 | 15-20 | Geode |
| Natural Pumice | 0.5-0.7 | -- | Irregular Sphere |
| Limestone (Vicenza stone) | 2.01 | 23 | Cube |
| Natural Marble (Rosso Trento) | 2.6 | 137 | Cube |
| Refractory blocks | 0.5 | -- | Cube |

Tab. 2 Summary of shots aimed at craterization performed by using LGG at CISAS. $\rho_T$ is the target density in $g/cm^3$, $D_p$ is the projectile diameter in mm, $V_p$ represents projectile velocity in m/s and Depth *p* in mm is the crater depth.

| Shot No. | Target | $\rho_T$ ($g/cm^3$) | Target dimensions (mm) | Projectile | $D_p$ (mm) | $V_p$ (m/s) | Depth p (mm) |
|---|---|---|---|---|---|---|---|
| 6320 | Ceramic foam geode | 0.73 | ∅ 80 | Al sphere | 1.5 | 3288 | 13.3 |
| 6322 | Ceramic foam geode 1 | 0.73 | ∅ 80 | Al sphere | 1.5 | 4430 | 9.2 |
| 6326 | Ceramic foam geode 1 | 0.73 | ∅ 80 | Nylon Cylinder | 1.5 | 1170 | 14.8 |
| 6327 | Ceramic foam geode 1 | 0.73 | ∅ 80 | Nylon Cylinder | 4.72 | 2400 | 15.9 |
| 6457 | Ceramic foam geode 3 | 1.067 | ∅ 70.5 | Al sphere | 0.8 | 2483 | 3.0 |
| 6458 | Ceramic foam geode 3 | 1.067 | ∅ 70.5 | Al sphere | 1 | 2189 | 4.0 |
| 6459 | Ceramic foam geode 3 | 1.067 | ∅ 70.5 | Al sphere | 1.5 | 1899 | 4.0 |
| 6460 | Ceramic foam geode 3 | 1.067 | ∅ 70.5 | Nylon Cylinder | 2.3 | 1997 | 5.0 |
| 6667 | Refractory block R1 white | 0.850 | 60x60x60 | Polycarbonate | 4.72 | 4923 | 2.0 |
| 6668 | Refractory block R1 white | 0.850 | 60x60x60 | Al sphere | 1.5 | 5100 | 1.07 |
| 6672 | Refractory block R1R red | 0.500 | 57x64x56 | Al sphere | 1.5 | 4770 | 1.1 |
| 6679 | Refractory block R2R red | 0.500 | 56x64x55 | Al sphere | 1.5 | 4800 | 1.1 |
| 6692 | Refractory block R2R red | 0.500 | 56x64x55 | Al sphere | 1.5 | 5156 | 1.26 |
| 7467 | pumice1 | 0.676 | ∅ 73 | Al sphere | 1 | 4100 | 5.0 |
| 7559 | pumice2 | 0.543 | ∅ 55 | Al sphere | 1 | 1644 | 5.5 |
| 7560 | pumice2 | 0.543 | ∅ 55 | Al sphere | 1 | 4180 | 5.7 |
| 7561 | pumice2 | 0.543 | ∅ 55 | Al sphere | 1.5 | 4111 | 10.3 |
| 7603 | pumice3 | 0.600 | ∅ 62 | Al sphere | 1 | 4881 | 5.0 |
| 7605 | pumice3 | 0.600 | ∅ 62 | Al sphere | 1.9 | 5016 | 6.8 |
| 7881 | Marble1 | 2.6 | 70x70x70 | Al sphere | 1.0 | 4916 | 1.5 |
| 7882 | Marble1 | 2.6 | 70x70x70 | Al sphere | 1.9 | 5192 | 4.5 |
| 7883 | Limestone1 | 2.01 | 70x70x70 | Al sphere | 1.0 | 5000 | 2.0 |
| 7884 | Limestone1 | 2.01 | 70x70x70 | Al sphere | 1.9 | 5000 | 4.7 |
| 7886 | Marble1 | 2.6 | 70x70x70 | Al sphere | 1.0 | 5085 | 1.8 |
| 7887 | Marble1 | 2.6 | 70x70x70 | Al sphere | 1.5 | 5085 | 2.4 |

Fig. 1 The two stage light gas gun, the hypervelocity facility at CISAS (left), and the recovery box for targets in the vacuum chamber (right).

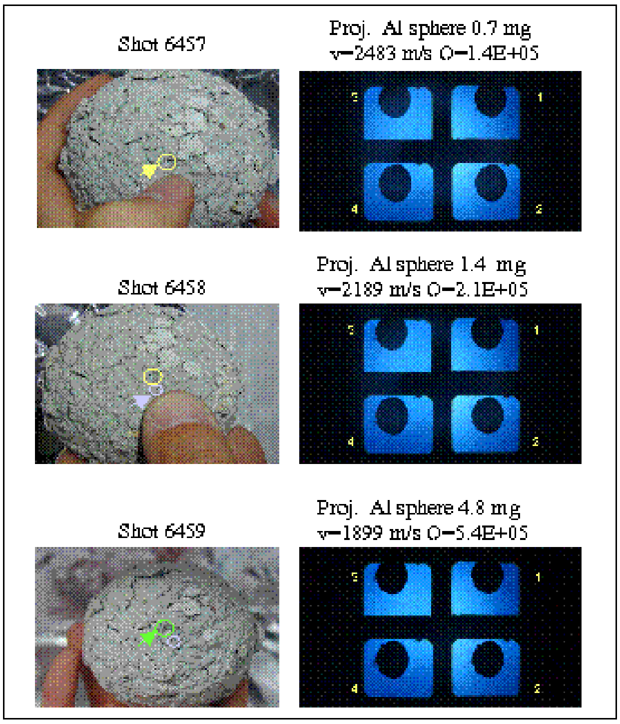


Fig. 2 Examples of tests on glass ceramic foam: in the images on the left pictures of the targets after impact are reported with evidence of crater formation, while on the right the shadowgraphies of the event are presented.

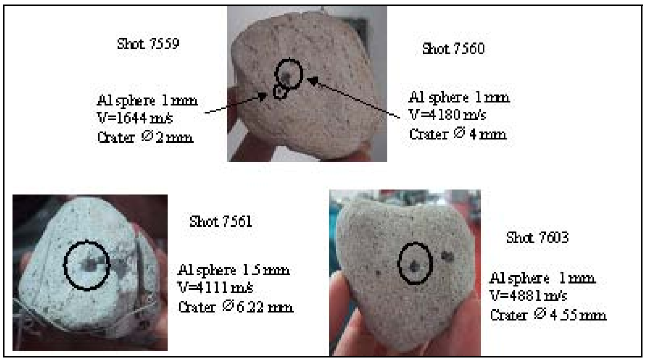


Fig. 3 Examples of craterization impact results on natural pumice.

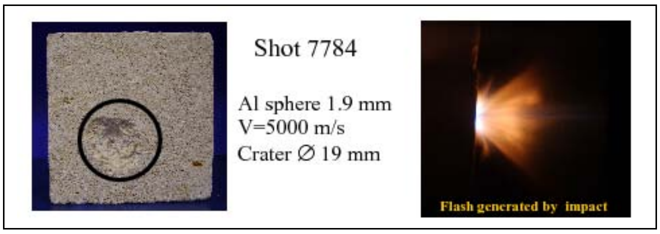


Fig. 4 Craterization results of hypervelocity impacts on limestone target (Vicenza stone) and image of detection of flash generated by projectile impact.

Craterization as function of impact energy has been investigated. Crater dimensions have been then related to impact conditions, and thus compared to published results [7,8].
Crater diameter with respect to projectile diameter, has been studied as function of impact velocity by comparing our experimental results with those obtained by Ishibashi by shooting 7mm nylon projectiles at 0.4-4.3 km/s on polystyrene targets (ρ=0.011-0.079 g/cm$^3$). our results follow Ishibashi's empirical distribution (see Fig. 5), except for refractory blocks results. This may be due to the great uncertainty in crater morphology determination for this kind of material. As observed by Kadono [8] with various types of porous material, the penetration of a dense projectile into these porous target produces a carrot-spindle shaped cavity with a maximum cavity diameter larger than the entrance hole diameter.

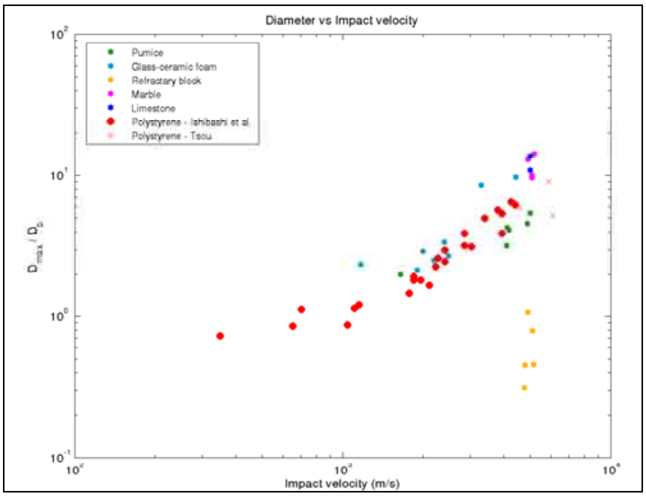


Fig. 5 Crater diameter normalised to projectile diameter vs. Impact velocity: comparison between experimental data obtained at CISAS and Ishibashi et al. (1990) results [5].

Furthermore, the relation between crater depth (penetration *p*) with respect to crater diameter has been

investigated as function of density ratio between projectile and target. Also in this case our results (see Fig. 6) are in good agreement with other experimental data on porous targets.
In particular, they lay within the uncertainty range of the empirical distribution obtained by Kadono [8] described by Eq. 1.

$$p_{max} / D_p = 10^{0.33 \pm 0.31} (\rho_p / \rho_t)^{1.07 \pm 0.17} \qquad (1)$$

The visual inspection of the impacted targets revealed that the effect of the impacts resulted in the compaction of target material as observed by Housen & Holsapple [6].

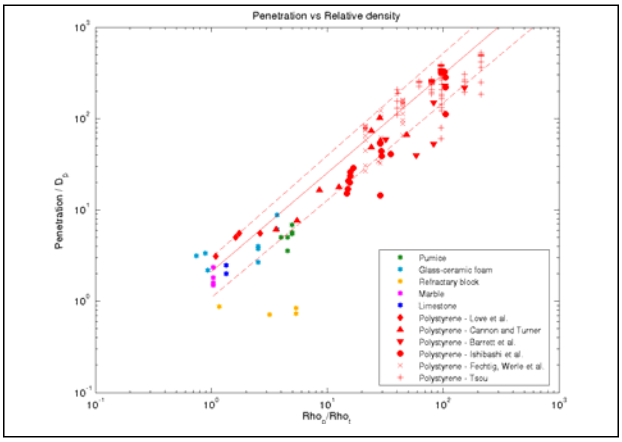

Fig. 6 Penetration as function of relative density: comparison between our experimental values and Kadono results obtained by comparing polystyrene experimental data from literature[8].

## 3. NUMERICAL SIMULATIONS

Numerical modelling is a fundamental tool for understanding of the dynamics of impact cratering, especially at planetary scales [12].
In particular, processes like melting/vaporization and crater collapse, typical of planetary-scale impacts, are not reproduced in the laboratory, and can only be investigated by numerical modelling. The continuum dynamics of impact cratering events is fairly well understood and implemented in numerical codes; however, the response of materials to shocks is governed by specific material properties. Accurate material models are thus crucial for realistic simulation of impact cratering, and still represent one of the major problems associated with numerical modelling of impacts.
In order to validate the experimental data we have performed preliminary numerical simulations by applying Smooth Particle hydrodynamics (SPH) technique, by using Software Autodyn 2D by Century Dynamics.
The code combines finite difference, finite volume, and finite element techniques; meshing is performed by considering each material as composed by spherical particles whose interactions are based on the laws of conservation of mass, momentum and energy.
Our simulations are aimed at investigating the propagation of the shock wave into the targets, the variation of the material physical properties and energy partition. Targets of different materials (concrete, concrete 35MPa, rock, quartz), porosity and dimensions have been considered and impacts of different velocities and different projectile to target diameter ratios have been simulated.
In Fig. 7 simulation results for different materials at the same impact conditions are reported. By comparing quartz or rock samples to more porous samples, as ones made of porous concrete, it can be inferred that the first are more affected by wave propagation reflection, with generation of compression waves which can cause the detachment of big fragments.

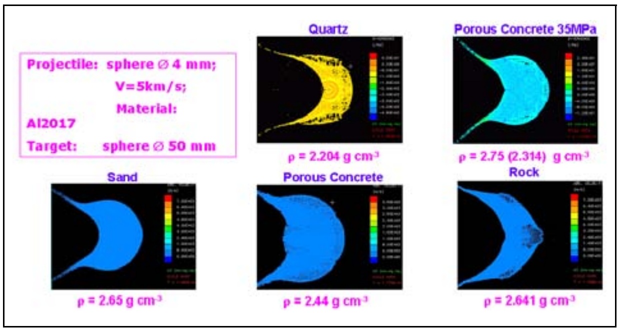

Fig. 7 Comparison between numerical simulations performed by using Smooth Particle Hydrodynamics (SPH) technique in the case of an aluminum projectile of 4mm diameter impinging at 5km/s on a spherical target made of quartz, porous concrete 35MPs, sand, concrete and rock.

In order to estimate scaling effect, projectile dimensions variations with respect to target were studied also by using two different techniques: SPH and Lagrangian mesh; results of the simulations at 1.8e-02 ms in the case of a porous concrete target are reported in Fig. 8. An impact of an Aluminum projectile onto a target of porous concrete at a velocity of 5km/s has been studied; projectile to target diameter ratios of 0.02, 0.04 and 0.08 have been simulated.

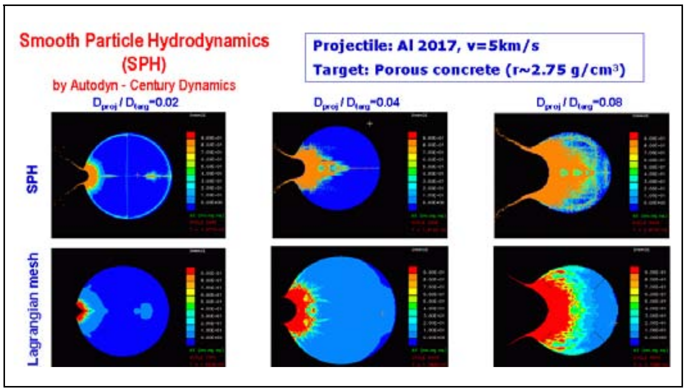


Fig. 8 Comparison between SPH and Lagrangian technique by simulating impacts of different projectile dimensions on the same target at 5km/s. Diameter ratio of 0.02, 0.04, 0.08 were considered.

SPH technique seems to better simulate this kind of hypervelocity impacts as damage and crater shape seems to be quite similar to experimental cases, more than Lagrangian mesh.

Simulations of small projectile impact on porous targets, in particular those using SPH technique, showed a damaged zone quite similar to the carrot shaped cavity produced by hypervelocity impact observed by Kadono [8] and confirmed during our experiments.

## 4. CONCLUSIONS

In order to obtain a better comprehension of the impact processes on solid body surface and for the data interpretation of remote sensing observations we studied impact processes on porous targets both by experimental and theoretical approach simulating ranges of velocity and physical conditions not yet explored.
Dedicated hypervelocity impact experiments into low density materials have been performed by using a two stage Light Gas Gun facility at CISAS “G.Colombo”.
About 25 impact experiments only aimed at craterization have been conducted on several porous material: glass ceramic foam, porous natural pumices, limestone, marble and refractory blocks.
Projectiles with diameter of 0.8 up to 2 mm with a velocity of 2-5 km/s have been used.
The visual inspection of impacted samples revealed on porous targets a carrot shaped cavity, as observed by Kadono et al. 1990 [8], and the effect of the impacts resulted in the compaction of target material as observed by Housen & Holsapple [6].

Crater morphology has then been analysed and results compared to published results, as and Ishibashi et al. (1990) [7] and Kadono et al. (1999) [8] data.
In particular crater diameter normalised to projectile dimensions, for all our shots, has been related to impact velocity and results seem to follow Ishibashi’s empirical distribution. Furthermore the distribution of penetration as function of projectile-target density ratio given by our data agree with the empirical distribution obtained by Kadono [8].

In order to validate experimental results and to infer scale effects, some preliminary numerical simulations by using hydrocodes, in particular the Smooth Particle Hydrodynamics technique, have been performed.
Tests revealed that SPH technique seems to be more suitable than Lagrangian mesh as crater shape and dimensions are quite similar to experimental results.

In conclusion it can be inferred that porous targets revealed to have sound velocity lower than those of non porous target as compaction of initial porous material produces rapid attenuation of the shock, thus affecting energy propagation.

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