Crush Curve Measurements of Porous Materials Used for Laboratory Impact Experiments

Kensuke Hiraoka and Akiko M. Nakamura
(Kobe University)
Porous structure has been found to be common among small bodies in the solar system.

Itokawa: porosity = ~ 40% (Abe et al., 2006)

Wild 2: 30~60% (lower limit) (Davidsson & Gutiérrez, 2005)
Tempel 1: 50~88% (Davidsson et al., 2006)

Various porous materials are used in laboratory impact experiments.

- powders (sands, glass beads etc.) --- no tensile strength
- porous solids (sintered materials, gypsum, pumice etc.) ---
  These objects have tensile strength.
  Sintered materials are maybe good analogues for the icy bodies.
Previous impact experiments on porous material

Laboratory impact experiments at elevated acceleration (500g) to simulate large impact cratering in low gravity (Housen et al., 1999; Housen & Holsapple, 2003)

Crater made by compaction rather than ejection

Compaction is a main process of the cratering on highly porous materials (target initial porosity 60%)

The response of highly porous materials to compaction should be quantitatively investigated.
The approximation by Mie-Grüneisen equation

→ valid only for high pressure
To study the response of porous materials to the compaction

**Purpose of this work**

- Crush curve measurements of porous materials which used for impact experiments
- Dependence of crush curves on the target properties

Crush curve is well studied for porous metal, ceramics powders and SiO2 powders

Is there any difference between powders and solids?

**P-\(\alpha\) model (Herrmann, 1969)**

Simple model describes a compaction of porous materials

\[
\alpha = \frac{\rho_s}{\rho} = \frac{1}{1 - \text{porosity}} = F(P)
\]

\(\rho_s\) : solid material density  
\(\rho\) : porous material density  
\(P\) : pressure  
\(P_s\) : solid pressure  
\(P_e\) : elastic pressure

\(F(P)\) is the parameter for modeling of impacts in porous materials (Juzti, 2004)
Samples

"porous solids"

pumice
porosity = 79 +/- 2%
compressive strength = 5.1MPa

sintered soda lime glass beads
porosity = 39 +/- 2%
compressive strength = 10MPa

gypsum
porosity = 42 +/- 1%
compressive strength = 14MPa

hollow glass beads (boro silica glass)
macro porosity = 87 +/- 2%
micro porosity ~ 82%

"powders"

alumina
porosity = 91 +/- 1%
particle strength ~ GPa

soda lime glass beads
porosity = 39 +/- 2%
particle strength ~ 850MPa
Measurements

• by compression testing machine (Maximum=10 kN)
• loading rate =0.06 mm/min (or 6 mm/min)
• sample diameter=9.95 mm, height=6~12 mm
Results

head speed=0.06mm/min

α (= solid density/porous density)

Pressure in MPa

- pumice
- gypsum
- sintered glass beads
- glass beads
- hollow beads
- alumina

Herrmann, 1969
The crush curve depends on initial target porosity, and the component strength.
Normalized by uniaxial compressive strength

$\alpha = \frac{\text{solid density}}{\text{porous density}}$

- pumice
- gypsum
- sintered glass beads

- almost elastic deformation
- plastic deformation

Pressure/compressive strength

$\alpha$ (almost elastic deformation)
Effect of the strain rate

The strength of brittle material increases with a strain rate.

- Strain rate dependence of crush curve

Compaction of ceramics powder

(Vogler et al., 2007)

\[ \sigma \approx 10^6 \text{s}^{-1} \]

\[ \sigma \approx 10^{-5} \text{s}^{-1} \]
Results (pumice and glass beads)

\[ \alpha = \text{solid density/porous density} \]

\[ \begin{array}{c|c|c}
\text{Pressure in MPa} & \text{6mm/min} & \text{0.06mm/min} \\
\hline
1000 & - & - \\
100 & - & - \\
10 & - & - \\
1 & - & - \\
\end{array} \]

\[ \alpha \]

\[ \Rightarrow \text{No apparent rate dependence effect.} \]

There is no distinguished difference between each loading rate. Relocation is probably a dominant process.
Results (gypsum)

After the first disruption, the pressure of higher strain rate is larger than that of lower strain rate. These difference probably show the strain rate dependence of the gypsum sample.
Summary and future work

We measured crush curves of porous materials.

Crush curve highly depends on the initial porosity of sample.

There is the strain rate dependence for gypsum.

Future Work

• quantitatively discussion about the dependence of crush curve on the target property

• to describe the path from the compression state

• discussion about the difference between static and dynamic compression

• to measure the lateral pressure and describe the stress state accurately
From Mie-Grüneisen equation,

\[ P = P_H + \frac{\gamma}{V}(E - E_H), \]

\[ P = P_H \frac{2 - \rho \gamma (V_0 - V)}{2 - \rho \gamma (V_0^* - V)} \]

- \( E \): internal energy of porous material
- \( E_H \): internal energy of dense material
- \( P \): pressure of porous material
- \( P_H \): pressure of dense material
- \( V_0 \): initial specific volume of dense material
- \( V_0^* \): initial specific volume of porous material
- \( V \): compacted specific volume (=1/\( \rho \))
- \( \gamma \): Grüneisen parameter

(McQueen et al., 1970)
Hugoniot of porous material

From Mie-Grüneisen equation,

$$ P = P_H \frac{2 - \rho \gamma (V_0 - V)}{2 - \rho \gamma (V_0^* - V)} $$

(McQueen et al., 1970)

$P$: pressure of porous material
$P_H$: pressure of dense material
$V_0$: initial specific volume of dense material
$V_0^*$: initial specific volume of porous material
$V$: compacted specific volume ($=1/\rho$)
$\gamma$: Grüneisen parameter

Dynamic compaction of porous silica powder (Borg et al., 2005)

This approximation is only valid for high pressure.
Normalized by uniaxial compressive strength

- Pumice
- Gypsum
- Sintered glass beads
Plastic deformation starts over 1 of vertical axis. (This plastic deformation is caused by a disruption of sintering neck, not of glass bead particles.) Porosity is only slightly decreasing with pressure. The change of the slope is similar to that of gypsum.

Normalized by uniaxial compressive strength
<table>
<thead>
<tr>
<th>Uniaxial compressive strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>6mm/min (8 \sim 16 \times 10^{-3} \text{s}^{-1})</td>
</tr>
<tr>
<td>pumice: (4.1 \pm 2.0 \text{MPa})</td>
</tr>
<tr>
<td>gypsum: (19 \pm 2 \text{MPa})</td>
</tr>
<tr>
<td>s-glass beads: (12 \pm 2 \text{MPa})</td>
</tr>
</tbody>
</table>
Results (hollow beads)

![Graph showing pressure in MPa against α (solid density/porous density) with two lines representing 0.06 mm/min (red) and 6 mm/min (blue)].
### Experiments

<table>
<thead>
<tr>
<th>Sample</th>
<th>Condition</th>
<th>Grain Size</th>
<th>Initial Porosity</th>
<th>Uniaxial Compressive Strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>pumice</td>
<td>solid</td>
<td>μm</td>
<td>79±2%</td>
<td>5.1MPa</td>
</tr>
<tr>
<td>gypsum</td>
<td>solid</td>
<td>μm</td>
<td>50±1%</td>
<td>14MPa</td>
</tr>
<tr>
<td>Sintered soda lime glass beads</td>
<td>solid</td>
<td>50μm</td>
<td>39±2%</td>
<td>10MPa</td>
</tr>
<tr>
<td>Hollow glass beads (boro silica glass)</td>
<td>powder</td>
<td>10 80μm</td>
<td>87±2%</td>
<td></td>
</tr>
<tr>
<td>Alumina</td>
<td>powder</td>
<td>0.1μm</td>
<td>91±1%</td>
<td>GPa</td>
</tr>
<tr>
<td>Soda lime glass beads</td>
<td>powder</td>
<td>50μm</td>
<td>39±2%</td>
<td>850MPa</td>
</tr>
</tbody>
</table>
**Future work**

- Quantitatively discussion about the dependence of crush curve on the target property
- To describe the path from the compression state
- Discussion about the difference between static and dynamic compression
- To measure the lateral pressure and describe the stress state accurately
Results (sintered glass beads)

There is no distinguished difference between each loading rate.

\[ \downarrow \]

This shows that a relocation is probably a dominant process.
Compressive strength

Plastic deformation

Elastic deformation

Pressure

$\alpha$

$\alpha_0$

Compressive strength

Elastic deformation

Plastic deformation