



Experimental Study of the Impact Cratering Process in the Strength Regime

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Doctoral Dissertation

Experimental Study of
the Impact Cratering Process
in the Strength Regime

(強度支配域での衝突クレーター形成過程
に関する実験的研究)

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Abstract

The solar system is composed of several populations of small bodies, such as asteroids and comets. On such small bodies, most crater features are the results of impacts, which can be seen on almost all images that have been obtained by different observations of their surfaces. In order to derive from these observations some information on the physical properties of small bodies, it is important to understand the impact cratering process. When the surface of a small body has a certain degree of strength, the impact cratering is controlled by surface physical properties, in particular the material strength itself. This cratering regime is the so-called strength regime. In this study, the impact cratering process in the strength regime is investigated by impact cratering experiments.

In Chapter 2, the effect of the silicate content in H₂O ice targets on the impact cratering is examined, motivated by the observation that small icy bodies in the outer solar system consist of ice-silicate mixtures. Thus, ice-silicate mixtures whose silicate content was varied from 0 to 50wt% were used as targets.

The crater depth and diameter on brittle materials such as rock and ice is predicted to depend on the different kinds of strength of the target. Thus, the uniaxial compressive and tensile strengths of the targets were measured by uniaxial compressive and Brazilian tests, respectively, in a cold room (263K) at Hokkaido University. The shear strength was then estimated from these measurements. It was found that those strengths increase with silicate content. However, the gradient of increase of the uniaxial compressive strength is different from that of the tensile strength and eventually, the difference between both strengths decreases with the increase of silicate content up to 50wt%.

Impact cratering experiments on ice-silicate mixture targets were performed in the cold room at Hokkaido University. One set of experiments consisted of using a gas gun to perform impacts of a 1.6g ice projectile at velocities between 300m/s and 660m/s. A second set of experiments consisted of using a two-stage light-gas gun to perform impacts of a 7mg nylon projectile at velocities between 1480m/s and 3680m/s. The decrease of crater volume with increasing silicate content in the target was visible in the results from the two-stage light gas gun experiments, as expected from the increase of the target strength with the silicate content. It was also found that the uniaxial compressive strength, and not the tensile and shear strengths, controls the crater depth. As for the crater diameter, it was found that the tensile strength has the major role in its determination. Indeed, the relation between the normalized crater diameter and the normalized tensile strength is not sensitive to the silicate content of the target.

In Chapter 3, the relation between the crater depth and the shock pressure propagation in the target is exposed. The crater depth is probably determined by the relation between the uniaxial compressive strength of the target and the compressive pressure at that depth. Thus, the shock wave propagation in the targets was investigated for the scaling of the crater depth. The shock pressure from a point source is kept near the impact point as an initial peak pressure, and then decays with the propagation

distance, because of the geometrical expansion, the rarefaction wave and other energy dissipation. The depth of the isobaric region depends on both the target and the projectile materials, and the shock attenuation rate in the target depends on both the target's properties (e.g. porosity) and the pressure.

In this study, the shock attenuation rate in the targets was estimated by the measurements of the antipodal ejection velocity and its variation with the target's thickness in a first set of experiments. Those experiments were performed on sintered glass beads-silicate mixtures using the two-stage light-gas gun installed at JAXA/ISAS and nylon sphere projectiles, and the gas gun installed at Kobe University and glass sphere projectiles, respectively. The target porosity was changed from about 32 to 40%, and the silicate content was varied as 0 and 25wt%. The impact velocity was from 1700 to 3390m/s for the two-stage light-gas gun, and about 260m/s for the gas gun. Another set of impact cratering experiments using the two-stage light-gas gun was then performed. The target porosity was changed from about 32 to 40%, and the silicate content was varied as 0, 12.5 and 25wt%. The impact velocity was from 2510 to 3530m/s. Stainless, glass and alumina spheres were used as projectiles in order to change the shock pressure and compare with the previous works. The depth of the isobaric region, which depends on the projectile's material, was estimated by measuring the antipodal ejection velocity for each projectile material and by using the shock attenuation rate measured in the first set of experiments.

From this study, it was found that the shock attenuation rate was almost independent on the silicate content in the target. Although the depth of the isobaric region is predicted to correlate with the density ratio between the target and projectile materials, such correlation was not found in these experiments. The relation between the normalized crater depth and the normalized initial peak pressure is fitted by the same curve as that found in previous experiments on ice. However, the fitting coefficient is not particularly good. Thus, for the scaling of the crater depth, further investigations of the shock pressure propagation are required.

1. General Introduction

1.1. Impact cratering in the solar system

The results of impact processes are readily apparent in almost every image of bodies in our solar system, and are recognized as one of the most important geological processes determining the morphology of those surfaces. The observation of those surfaces is also one of the most important remote sensing procedures for understanding the history and evolution of the solar system. Thus it is important to understand the impact cratering process and how it scales on solar system bodies. Dimensional analysis is the primary tool used to derive scaling theories (e.g. Holsapple, 1993). However, it is necessary to investigate what physics rules the morphology or size of craters on solar system bodies.

1.2. Scaling law in impact cratering

The objective is to predict the volume V of a crater that results from the impact of a spherical body of radius, a , velocity, U and mass density, δ , onto a planet with surface gravity, g , some strength, Y and mass density, ρ . In this case, there are seven parameters, with the three independent dimensions of mass, length and time. Therefore, there is a simpler relation among four (seven minus three) dimensionless combinations. The choice of these groups is not unique, and all results are independent of the forms that are chosen. One form uses the mass, m of the impactor as well as its radius,

$$\frac{\rho V}{m} = f \left[\frac{ga}{U^2}, \frac{Y}{\rho U^2}, \frac{\rho}{\delta} \right], \quad m = \frac{4\pi}{3} \delta a^3. \quad (1.1)$$

These groups are known as π scaling groups.

When $\rho ga \ll Y$, the first term in the brackets of the right hand side of Eq. (1.1) can be disregarded compared with the second term. Thus, in this case the cratering process is controlled by the target's surface strength. This regime is called the strength regime. On the other hand, when $\rho ga \gg Y$, the second term can be ignored and the crater size depends on the target's surface gravity, and this regime is called the gravity regime. When laboratory experiments are carried out on hard targets, or in the case where small solar system bodies have a certain degree of strength, the cratering takes place in the strength regime.

1.3. Strength regime cratering

The morphology of laboratory craters in the strength regime is highly depends on target and projectile properties. The crater on a metal target made in the strength regime is typically a simple bowl-shaped crater. The crater volume in metal targets is well scaled by an ultimate strength of targets (Holsapple and Schmidt, 1982). On the other hand, the morphology of laboratory craters on brittle materials, which are usually rocks or ices and which constitute the surface of most solar system bodies, is typically a

pit-halo structure (Fig. 1.1). The difference of crater morphologies either metals or brittle materials is caused by the ratio of shear and tensile strengths of those materials.

The impact cratering mechanism in the strength regime is considered qualitatively as follows; compressive wave caused by an impact makes shear fracture in the target, and the region where this occurs may correspond to a central pit. The compressive wave reflects as a rarefaction (tensile) wave at a free surface. Because of the rarefaction wave, the geometric expansion and other dissipation mechanisms of the impact energy, the compressive wave decays with propagation distance. In brittle materials, the rarefaction wave detaches thin fragments from the surface region because tensile strength is about 3 times lower than shear strength. This phenomenon is called “spallation” (Melosh, 1984), which makes a halo. Thus, the crater morphology and dimension on brittle targets are expected to depend on different strengths, that is the shear and tensile strengths.

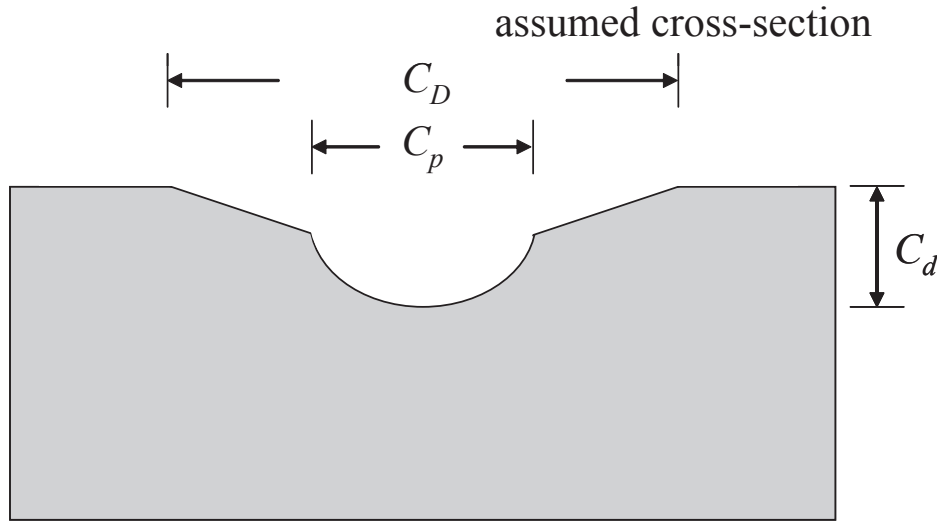


Fig. 1.1. Cross-section of a typical crater made in brittle materials and symbols of each dimension; C_D is the crater diameter, C_p is the pit diameter and C_d is the crater depth.

The size of a crater made in the strength regime is determined by the relation between the stress which propagates in the target with attenuation and the target mechanical strength corresponding to the fracture mode. Thus, in order to scale the crater size each kind of target strength should be measured. In chapter 2, we examine the relation between each crater dimension and each target strength. In chapter 3, we investigate the effect of porosity and shock attenuation rate on impact cratering.

2. Laboratory Impact Cratering Experiments on Ice-Silicate Mixture Targets

2.1. Introduction

Pure ice has often been used in laboratory impact experiments in order to simulate the impact process on icy bodies (e.g. Kato et al., 1995). From data of spacecrafts, however, it has been shown that comets, Saturn's rings and satellites in the outer solar system consist of several kinds of volatiles (N_2 , CO_2 , CH_4 and H_2O) and silicate dusts (e.g. Keller et al., 2005; Estrada and Cuzzi, 1996; Kempf et al., 2005; Porco et al., 2005). Thus impact experiments using ice-silicate mixture as a target are useful for understanding the impact process on icy bodies.

Previous studies using ice-silicate mixture target are as follows; Lange and Ahrens (1982) performed cratering experiments on ice-silicate mixture targets with 35 to 40wt% silicate content. They showed that the crater volume and diameter are smaller than those on a pure ice target. Koschny and Grün (2001) measured the crater volume and size resulting from the impact cratering on targets with silicate content from 5 to 20wt%. They showed a decrease of crater volume with increasing silicate content (see Fig. 9 in their paper), however the silicate content was quite limited. Furthermore, the reason of this decrease was not investigated. Therefore, in our experiments we varied the silicate content more widely from 0 to 50wt% in order to examine the cratering efficiency in a wider range of silicate content and measured the target strength and its dependency on the silicate content.

Laboratory impact craters on ice-silicate mixtures are formed in the strength regime. In this regime, the mechanical strength of the material is a key parameter to determine the crater dimension and morphology. In fact, images taken by the Stardust mission show pit-halo depressions like Rahe crater and flat-floor craters on the surface of Comet 81 P/Wild 2, and similar structures were observed in laboratory hypervelocity impact experiments by using strength controlled targets (Brownlee et al., 2004). They used baked resin-coated sand for the analogue of comet nucleus. Although they succeeded to reproduce the characteristic crater morphologies observed, the experimental condition was unrealistic to represent for the crater made on the comet, because the baked resin-coated sand could have a very different mechanical strength from the comet nucleus. Ice-silicate mixtures are the main components that construct the small icy bodies. Thus it is important to study the mechanical strength of not only pure ice but also ice-silicate mixtures in order to understand the impact cratering on the small icy bodies.

The mechanical strength of ice-silicate mixtures, which controls the cratering process, depends not only on silicate content but also on target porosity. Arakawa and Tomizuka (2004) found that the static compressive strength of sintered ice-silicate mixtures at a strain rate of $5.6 \times 10^{-3} \text{s}^{-1}$ followed an empirical power law equation of the porosity from 12.5 to 37wt%, and the strength was always lower than that of sintered pure ice. However, they examined samples with a silicate content of 50wt% only, and

the porosity was varied between 12.5 and 37wt%. Moreover almost all the previous impact experiments made with ice-silicate mixture targets were conducted using samples with porosity less than 10% and the silicate contents varying until 50wt%. Therefore, it remains necessary to study the mechanical strength of ice-silicate mixtures with a wide range of silicate content and small porosities.

In this study the uniaxial compressive and tensile strengths of ice-silicate mixture targets were measured at a strain rate $\sim 2 \times 10^{-3} \text{ s}^{-1}$ and a temperature of 263K. Then the shear strength of these targets was calculated from the measured values of the two other strengths. The impact cratering experiments were carried out using these same samples at the same temperature. In this chapter target procedure and strength measurements are described at first. Then the experiments of impact cratering are presented. In the end, we examine the relation between the three kinds of strengths and crater dimensions.

2.2. Target procedure

The silicate content of ice-silicate mixtures was changed from 0 to 50wt%. A powder of serpentine was used. In order to mix ice and silicate powder homogeneously in the targets, we made those targets in the following procedure at 263K. At first, we broke a commercial ice block into small powders (snow) by an electric mixer. Then, we mixed the snow into the silicate powders. These mixed powders were put into the target container, and then pushed with small quantity of purified water. We did the last process over again until all prepared water was used. The ratio of snow to water was 6:4 or 7:3. The target of 0wt% silicate content was made by the same procedure. Cross-sections of the target samples were inspected with a microscope and were found to be homogeneous mixtures with some air bubble inclusions as shown in Fig. 2.1. The porosity of the targets used by Koschny and Grün (2001) were assumed to be zero, but that of our target is estimated to be of several percents. The diameters of our snow particles were in the order of 100 μm and that of Serpentine was several μm in most of the experiments. In order to investigate the effect of the difference of size and kind of silicate powder, 50wt% ice-silicate mixtures were made by serpentine powder of 200-500 μm in diameter and dunite powder. The error of the silicate content was largest at the silicate content of 50wt%, which was about 2wt%, and then became smaller at lower silicate content. The bulk density of ice and serpentine was 910 and 2600 kg/m^3 , respectively.

Longitudinal sound velocities in targets with silicate content of 0, 12.5 and 50wt% were measured with varying sample thickness by using acoustic emission sensors. The results are listed in Table 2.1. The longitudinal sound velocity in pure ice is consistent with the results of Kato et al. (2001), and is about 3670-4100m/s. The bulk sound velocity in serpentine is $5290 \pm 165 \text{ m/s}$ (Tyburczy et al., 1991) and the longitudinal sound velocity is larger than the bulk sound velocity. Thus, the longitudinal sound velocity in serpentine is larger than 5000m/s. However, the longitudinal sound velocities in mixtures are even smaller than that in pure ice.

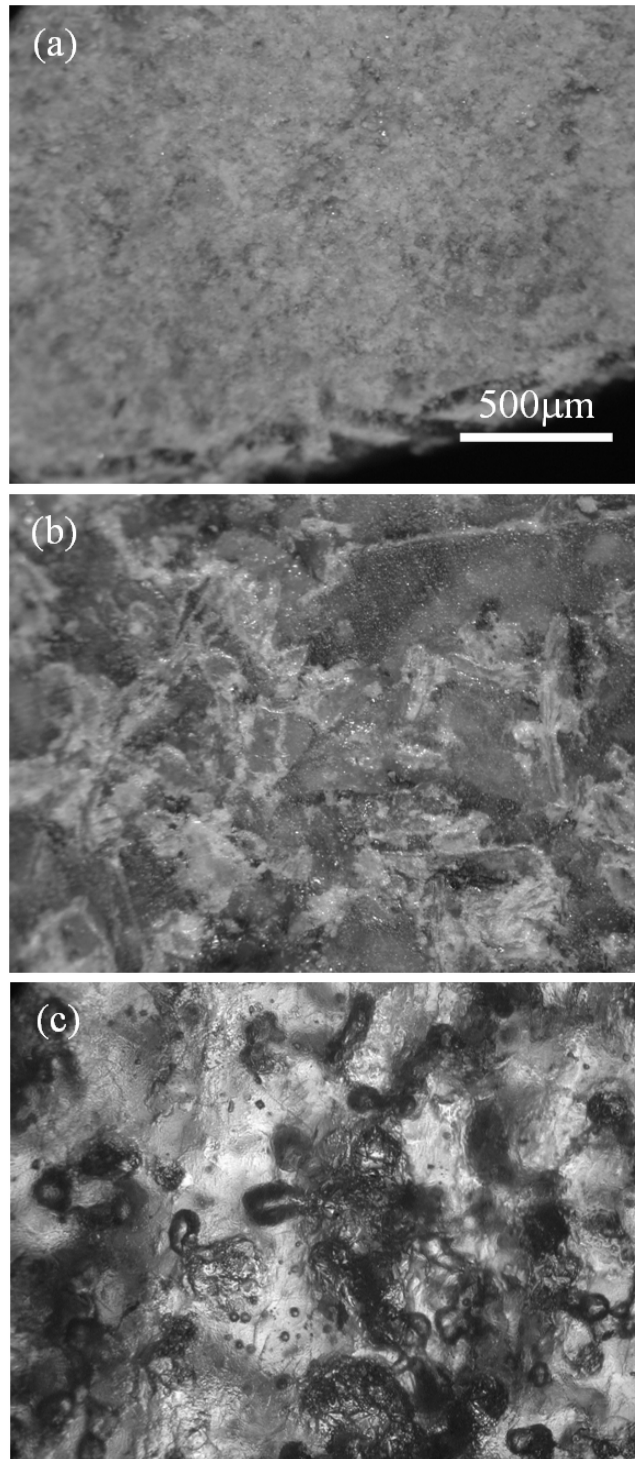


Fig. 2.1. Microscopic image of the cross-section of a target sample. Each image is in the same scale. Images (a) and (b) are ice-silicate mixture with 50wt% and taken by reflection light. The diameter size of silicate powder in image (a) is of the order of μm and about $500\mu\text{m}$ in image (b). The white part is serpentine content and the dark part is ice. Image (c) is pure ice and taken by transmitting light. The bubbles in ice can be seen.

2.3. Target strength measurements

The target uniaxial compressive and tensile strength are measured at a strain rate ($\sim 2 \times 10^{-3} \text{s}^{-1}$) by uniaxial compression and Brazilian tests (Mellor and Hawks, 1971), respectively, in the cold room (263K). Note that the results here might be quite different at the temperatures of comets and satellites of the outer solar system. In the uniaxial compressive test, cylindrical specimens were loaded uniaxially without confining pressure and the specimen fractured with vertical cracks, which is one of the typical fracture morphology of brittle materials in uniaxial compression tests. The Brazilian test is one that compresses disc-shaped specimen diametrically inducing a stress that causes the sample to yield in tension. The tensile strength, σ_T is calculated using the following equation,

$$\sigma_T = \frac{2F}{\pi \cdot d \cdot l}, \quad (2.1)$$

where F is the maximum compressive load during the measurement, d is the diameter of the sample and l is the thickness (height) of the test specimen. Based on the concept postulated by Griffith, the diameter of the maximum stress circle through σ_T -point on Mohr's diagram is equal to $4\sigma_T$. Consequently, the Mohr's envelope is expressed in a common tangent of the $4\sigma_T$ -stress circle and a σ_C -stress circle, which represents the uniaxial compressive strength. In this case, the shear strength, σ_S is approximately obtained from an intersection of the shear τ -axis in the diagram and the common tangent, and can be calculated by the following equation (Kobayashi and Okumura, 1971). If $\sigma_C > 3\sigma_T$,

$$\sigma_S = \frac{\sigma_C \cdot \sigma_T}{2\sqrt{\sigma_T(\sigma_C - 3\sigma_T)}}. \quad (2.2)$$

Table 2.1.
Target properties

Silicate content in wt%	Uniaxial compressive strength in MPa	Tensile strength in MPa		Shear strength in MPa		Longitudinal sound velocity in m/s	
0	5.23 ± 0.92	0.736	± 0.036	1.29	± 0.06	3860	± 7
5	6.65 ± 0.69	0.83	± 0.25	1.51	± 0.35	3860	± 7
12.5	7.04 ± 0.79	0.83	± 0.25	1.51	± 0.35	3860	± 7
25	7.64 ± 0.27	1.18	± 0.25	2.05	± 0.41		^a
37.5	6.76 ± 0.86	1.86	± 0.20	4.2	± 1.6		^a
50	8.55 ± 0.45	2.12	± 0.37	4.2	± 1.4	3500	± 83
50 ^{C.S.}	8.23 ± 0.17		^a	-			^a
50 ^{C.D.}	8.77 ± 0.18	1.40	± 0.10	2.43	± 0.41		^a

Note. Silicate content with ^{C.S.} and ^{C.D.} mean the samples made from coarse serpentine and coarse dunite, respectively. ^a means that the value was not measured.

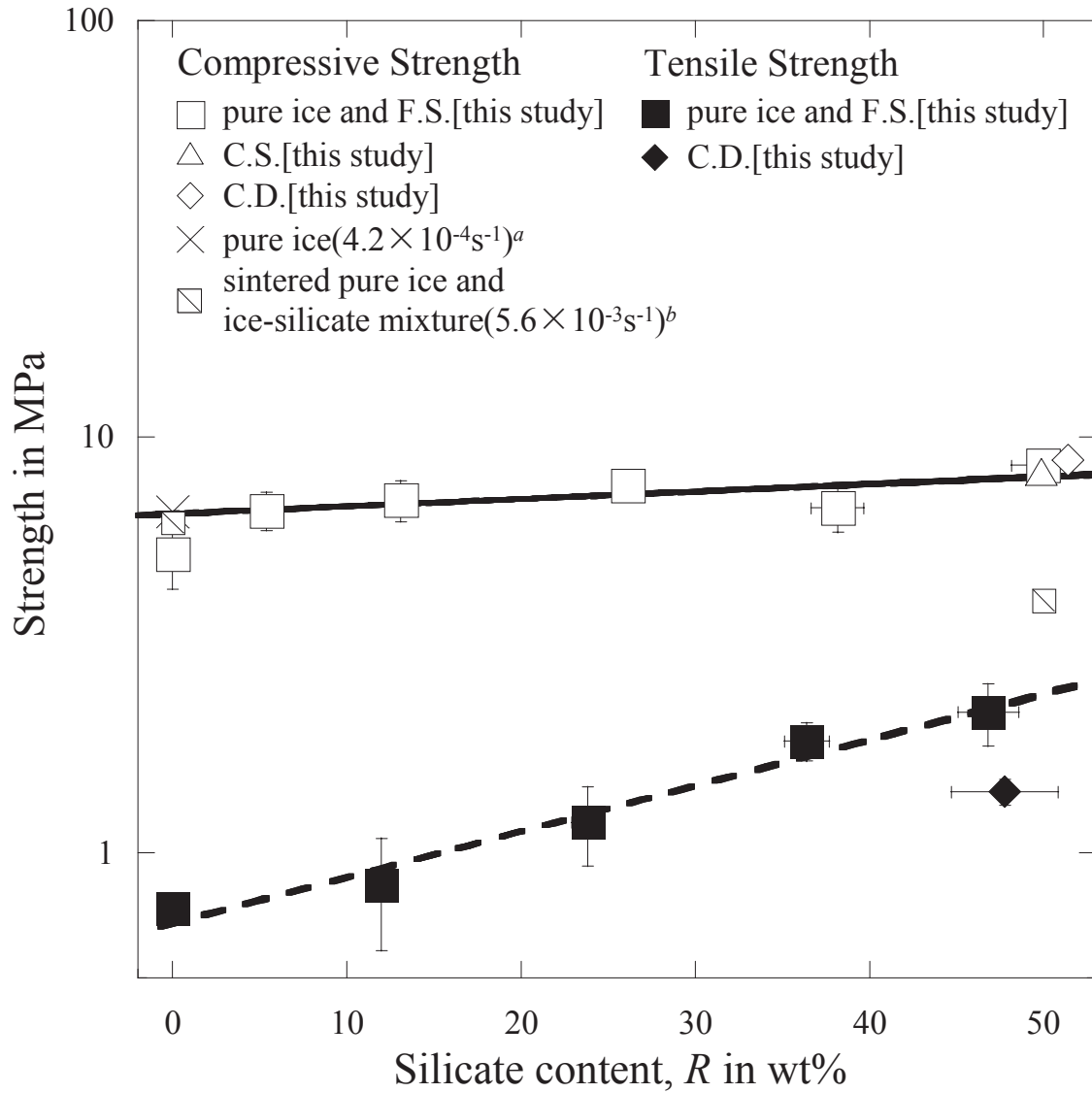


Fig. 2.2. The relation between the silicate content and the uniaxial compressive and tensile strengths. Symbols represent the sample type. The characters *F.S.*, *C.S.* and *C.D.* mean the sample made by silicate powders of fine serpentine, coarse serpentine and coarse dunite, respectively. Solid line shows the exponential fitting line of the uniaxial compressive strength for the mixture samples made by fine serpentine powders (Eq. (2.3)). Dashed line shows the exponential fitting line of the tensile strength for pure ice and the mixture samples made by fine serpentine powders (Eq. (2.4)). ^a and ^b denote the results of Arakawa and Maeno (1997) and Arakawa and Tomizuka (2004), respectively.

The test specimens were 32mm in diameter and 43-48mm in height for the uniaxial compression test, and 20-35mm in height for the Brazilian test. The loading rate was 5 and 3mm/min for the uniaxial compressive and Brazilian test, respectively. Thus, the strain rate of the uniaxial compressive test was 1.7 to $2.2 \times 10^{-3} \text{ s}^{-1}$. On the other hand, since the loading direction is perpendicular to the strain direction in the Brazilian test, it is not straightforward to calculate actual strain rate of the Brazilian test. However, the

strain rate should be close to the value of sample diameter/loading rate, $1.5 \times 10^{-3} \text{s}^{-1}$. The results of the uniaxial compressive and Brazilian tests are shown in Fig. 2.2 with the results of the previous measurements. Both strengths increase with silicate content

Since ductile deformation was observed for ice and ice-silicate mixtures, the uniaxial compressive and tensile strength were defined by the maximum values of the stress of each stress-strain curve when we observed large cracks. For the uniaxial compressive test the stress of ice decreased rapidly after the maximum stress, and that of ice-silicate mixtures also decreased but the stress only gradually changed. In the Brazilian test the amount of plastic deformation of ice-silicate mixture samples increased with increasing silicate content. Since the contact between the loading head and the sample changed from linear to planar with increasing amount of plastic deformation, the tensile strength of the specimens with the highest silicate content might not be measured precisely. However, the error due to the planar contact is probably smaller than several % according to an error estimate for an arch-like contact (Mellor and Hawkes, 1971), then within the scatter of our measurements.

2.3.1. Uniaxial compressive strength

The uniaxial compressive strength did not differ among the samples of fine, coarse serpentine, and dunite particles. It gradually increased as the silicate content increased, with perhaps a more rapid rise for silicate contents between 0 and 5wt%. The uniaxial compressive strength of the specimen with 37.5wt% silicate content was lower than expected. The reason of this inconsistency is not clear. An empirical expression of the uniaxial compressive strength for the mixture samples made by fine serpentine powders is

$$\sigma_c = (6.5 \pm 0.5) e^{(0.004 \pm 0.002)R}, \quad (2.3)$$

where R is the silicate content and the correlation coefficient of this fitting is 0.71. Arakawa and Maeno (1997) measured the uniaxial compressive strength of pure ice at 263K, which was 6.6MPa at lower strain rate ($4.2 \times 10^{-4} \text{s}^{-1}$). This pure ice sample was bubble free, which would explain why its uniaxial compressive strength was higher than those of our samples. Arakawa and Tomizuka (2004) measured the uniaxial compressive strength of sintered ice and ice-silicate mixtures at 263K at $5.6 \times 10^{-3} \text{s}^{-1}$. Although their silicate content and one of the porosity values were almost the same as in our samples, the uniaxial compressive strength of the sintered ice-silicate mixture, whose porosity was 12.5%, was smaller than that of the sintered pure ice and our results. This maybe indicates that the cohesion between ice and silicate of our samples is stronger than that of the sintered ice-silicate mixtures of Arakawa and Tomizuka (2004).

Although the sample height/diameter ratio (l/d) was different among the samples (from 1.2 to 1.6), the effect of this variation was small compared with the scatter caused by the individual difference among the samples as shown in the following. It is well known for the uniaxial compressive test that the uniaxial compressive strength of brittle materials is affected by the strain rate and l/d . Because the variation of the strain rate due to the difference of the sample height is very small, it would not have any

significant effect on the uniaxial compressive strength. Hawkes and Mellor (1970) showed that uniaxial compressive strength of rocks decreased up to 30% with increasing value of l/d between 1 and 2.5 or 3.0. However, our measurement results do not show this trend. This indicates that the effect of the difference of l/d is within the scatter of our measurements caused by other aspects, such as the difference in the internal structure of the samples due to the preparation process.

2.3.2. Tensile strength

The tensile strength increased with silicate content differently from the uniaxial compressive strength. Thus, the ratio between the uniaxial compressive and tensile strengths changes with silicate content. Tensile strength of the specimen with dunite coarse powders 50wt% was smaller than that of the serpentine fine 50wt%, while the coarse serpentine 50wt% continued plastic deformation without fracture. We could not determine the tensile strength of the coarse serpentine sample. An empirical relationship of the tensile strength for the samples made by fine serpentine powders is as follows:

$$\sigma_T = (0.68 \pm 0.07) e^{(0.026 \pm 0.003)R}, \quad (2.4)$$

where the correlation coefficient of this fitting is 0.99.

Tensile strength is controlled by growth of cracks in the sample. Since silicate powders block off crack growth in the sample, the increase of the tensile strength is enhanced. This is consistent with the less high number of cracks observed around the crater on ice-silicate mixture targets. The lack of spallation for the higher silicate content targets is also consistent with the increase of the tensile strength with silicate content. The difference in tensile strength among different sample types, i.e., with serpentine and dunite, may be caused by the different volume of the silicate grains and/or different grain shapes. Since the grain density of dunite is larger than that of serpentine, the total volume of the serpentine powders is larger than that of the dunite powders even if the specimens have the same silicate content in weight. Furthermore, serpentine grains have needle like structures which correspond to larger cross-sections. Thus the serpentine powders have an advantage in prevention of crack growth.

2.4. Impact cratering experiments

Laboratory impact experiments were carried out using a gas gun and a two-stage light-gas gun in the Institute of Low-Temperature, Hokkaido University. The room temperature was 263K. Cylindrical projectiles (pure ice, 15mm in diameter, 10mm in height and 1.6g in weight) were used for the gas gun and corn shaped projectile (nylon, 1mm and 2mm in diameter, 2.5mm in height and 7mg in weight) for the two-stage light-gas gun. The projectile trajectory was vertical for the gas gun, and horizontal for the two-stage light-gas gun. The range of impact velocity was from 299 to 657m/s and from 1480 to 3684m/s, respectively. The impact velocity was measured by the flight time of the projectile between two laser beams. In our experiments, the estimated peak pressure at impact is from 0.31 to 15.6GPa as described in Appendix I.

Table 2.2.

Experimental parameters and crater dimensions

Shot no.	Silicate content, R in wt%	Impact velocity in m/s	Crater volume, V in cm^3	Crater diameter, C_D in cm	Pit diameter, C_P in cm	Crater depth, C_d in cm	Initial peak pressure, P_0 in GPa
01 <i>i</i>	0	309	37.8	^a	^a	0.585	0.314
02 <i>i</i>	0	470	132	^a	^a	2.4	0.593
03 <i>i</i>	0	1480	12.2	6.07 ± 0.25	4.35	0.908	1.71
04 <i>i</i>	0	3310	9.40	4.87 ± 0.15	^b	1.12	6.06
05 <i>i</i>	0	3850	28.9	^a	^a	^a	7.80
06 <i>i</i>	12.5	300	7.30	5.8 ± 2.0	1.43	0.315	0.319
07 <i>i</i>	12.5	316	20.0	8.3 ± 1.4	2.81	0.305	0.343
08 <i>i</i>	12.5	353	14.5	6.53 ± 0.04	2.73	0.523	0.398
09 <i>i</i>	12.5	454	57.6	8.59 ± 0.58	3.57	0.615	0.593
10 <i>i</i>	12.5	473	10.7	6.11 ± 0.59	3.06	0.685	0.598
11 <i>i</i>	12.5	551	83.7	7.82	4.19	0.815	0.632
12 <i>i</i>	12.5	564	31.1	8.59 ± 0.82	3.67	1.28	0.639
13 <i>i</i>	12.5	636	142	13.9 ± 0.8	5.24	0.903	0.688
14 <i>i</i>	12.5	654	117	9.27	4.35	0.915	0.702
15 <i>n</i>	12.5	1970	7.50	5.68 ± 0.55	1.47	0.686	2.80
16 <i>n</i>	12.5	2990	7.57	5.73 ± 0.51	4.08	0.714	5.42
17 <i>n</i>	12.5	3210	7.66	5.15 ± 0.34	2.57	1.02	6.08
18 <i>i</i>	25	300	2.45	4.33 ± 0.82	2.50	0.235	0.335
19 <i>i</i>	25	312	3.28	4.50 ± 0.05	3.00	0.22	0.353
20 <i>i</i>	25	357	16.2	10.0 ± 1.3	3.41	0.64	0.424
21 <i>i</i>	25	446	17.5	6.8 ± 1.4	3.79	0.355	0.596
22 <i>i</i>	25	458	24.2	7.78 ± 0.71	3.35	1.12	0.599
23 <i>i</i>	25	473	25.6	6.61	3.00	0.545	0.605
24 <i>i</i>	25	563	71.5	8.12 ± 0.61	4.01	1.51	0.650
25 <i>i</i>	25	567	50.2	10.5 ± 0.4	4.12	1.08	0.652
26 <i>i</i>	25	634	25.1	6.8 ± 1.4	4.46	1.14	0.702
27 <i>i</i>	25	657	57.5	10.5 ± 0.4	4.71	1.33	0.722
28 <i>n</i>	25	2910	6.92	4.81 ± 0.39	2	0.698	5.73
29 <i>n</i>	25	3670	7.70	5.22 ± 0.35	1.97	0.943	8.33

Note. Shot numbers with the extension *i* were performed by the gas gun using ice projectiles, those with *n* were performed with the two-stage light-gas gun using nylon projectiles and *R* were the targets made by ca. 500 μm silicate powder. ^a means that we could not measure the value because the crater led to the frame of target container. ^b means no individual halo around the crater. Crater depth of all craters made with the gas gun was measured using a caliper while a laser displacement meter was used for the others.

Table 2.2. (continue)

30 <i>i</i>	37.5	302	1.08	3.38	±0.01	2.38	-0.03	0.358
31 <i>i</i>	37.5	466	22.5	7.72	±0.70	3.51	1.315	0.609
32 <i>i</i>	37.5	569	65.7	9.99	±0.44	4.07	1.35	0.668
33 <i>i</i>	37.5	575	18.9	5.98	±0.11	2.89	1.61	0.672
34 <i>i</i>	37.5	644	82.8	8.96	±0.43	5.06	1.78	0.729
35 <i>n</i>	37.5	3120	6.01	4.70	±0.33	2.02	0.853	6.91
36 <i>n</i>	37.5	3580	5.99	4.65	±0.77	1.93	0.798	8.63
37 <i>n</i>	50	2780	1.63	2.93	±0.15	^b	0.726	6.39
38 <i>nR</i>	50	2820	2.26	3.15	±0.15	1.67	0.686	6.53
39 <i>nR</i>	50	3120	3.38	4.06	±0.24	1.77	0.768	7.65
40 <i>n</i>	50	3250	3.64	4.05	±0.24	1.57	0.684	8.16
41 <i>n</i>	50	3570	2.15	3.52	±0.16	1.49	0.585	9.48
42 <i>nR</i>	50	3840	3.61	3.82	±0.66	1.53	0.865	10.7
43 <i>n</i>	100	2890	0.149	1.37	±0.24	^b	0.213	14.1
44 <i>n</i>	100	3130	0.217	1.30	±0.16	^b	0.302	15.6

Note. Shot numbers with the extension *i* were performed by the gas gun using ice projectiles, those with *n* were performed with the two-stage light-gas gun using nylon projectiles and *R* were the targets made by ca. 500 μ m silicate powder. ^a means that we could not measure the value because the crater led to the frame of target container. ^b means no individual halo around the crater. Crater depth of all craters made with the gas gun was measured using a caliper while a laser displacement meter was used for the others.

Cylindrical targets were used for all experiments. The target size was tuned as a function of the accelerator: 20 or 30cm in diameter and 5 or 10cm in height for the gas gun and 10cm in diameter and 5 cm in height for the two stage light gas gun. Furthermore, we used two Serpentine blocks, whose dimensions were 10×10cm wide and 5cm in height, in order to compare with the experiments on other targets. The frame speed of the high-speed camera was 2000 or 4000 frames/s. Table 2.2 lists the experimental conditions.

2.5. Results and discussions

The crater diameter, the pit diameter and the crater central depth were the average of several measurements by caliper. We took the depth profiles of some craters. These were obtained by moving a laser displacement meter across the surface, at 1mm horizontal interval, measuring the depth from a fixed height. One or two depth profiles were obtained for each crater. The crater profiles are shown in Fig. 2.3. We measured the crater volume by subtracting the fragment mass after impact from the target mass before impact.

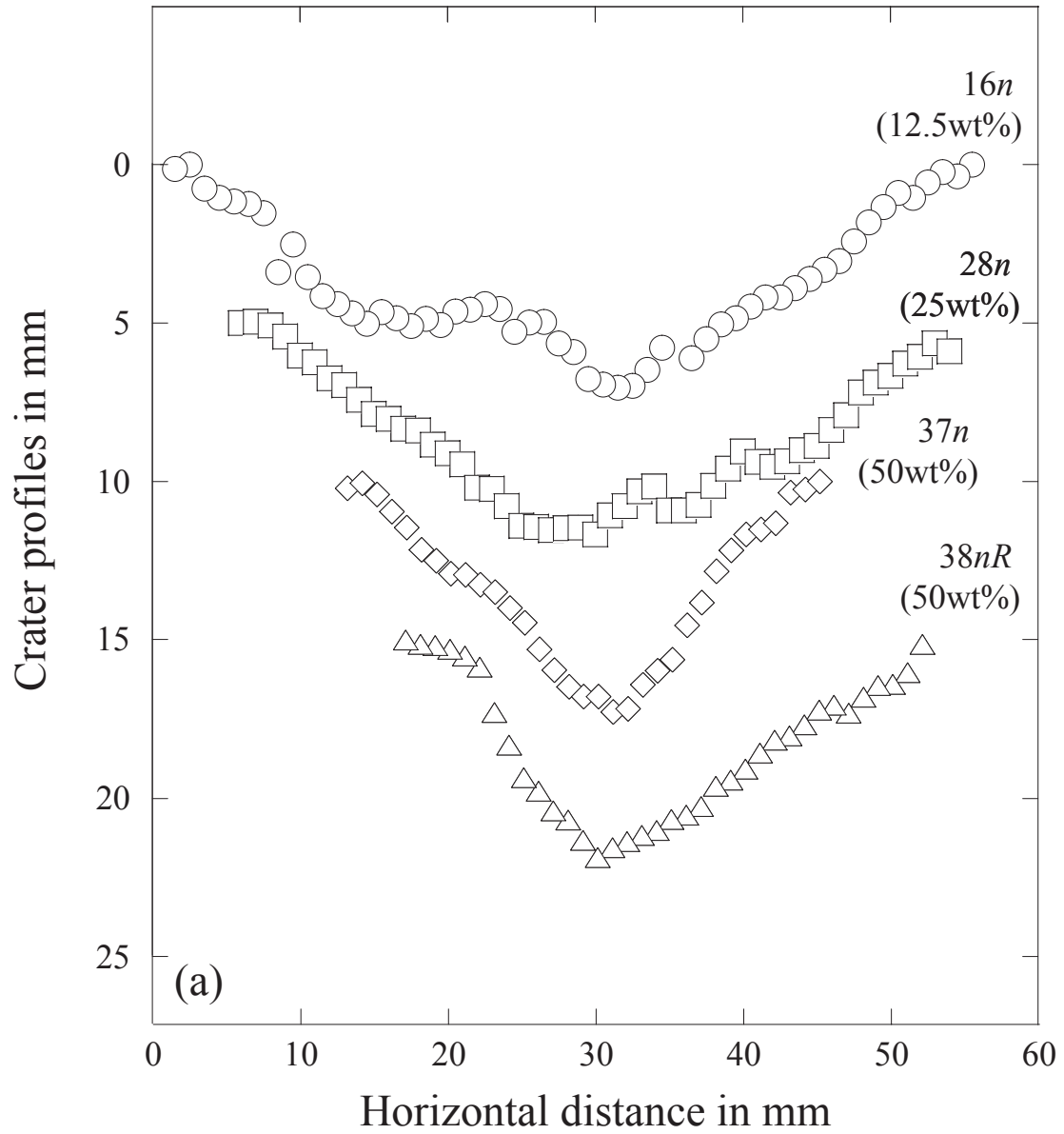


Fig. 2.3 (a). Crater profiles at impact velocity of 2720 to 2990m/s. The measurement error is less than 0.03mm.

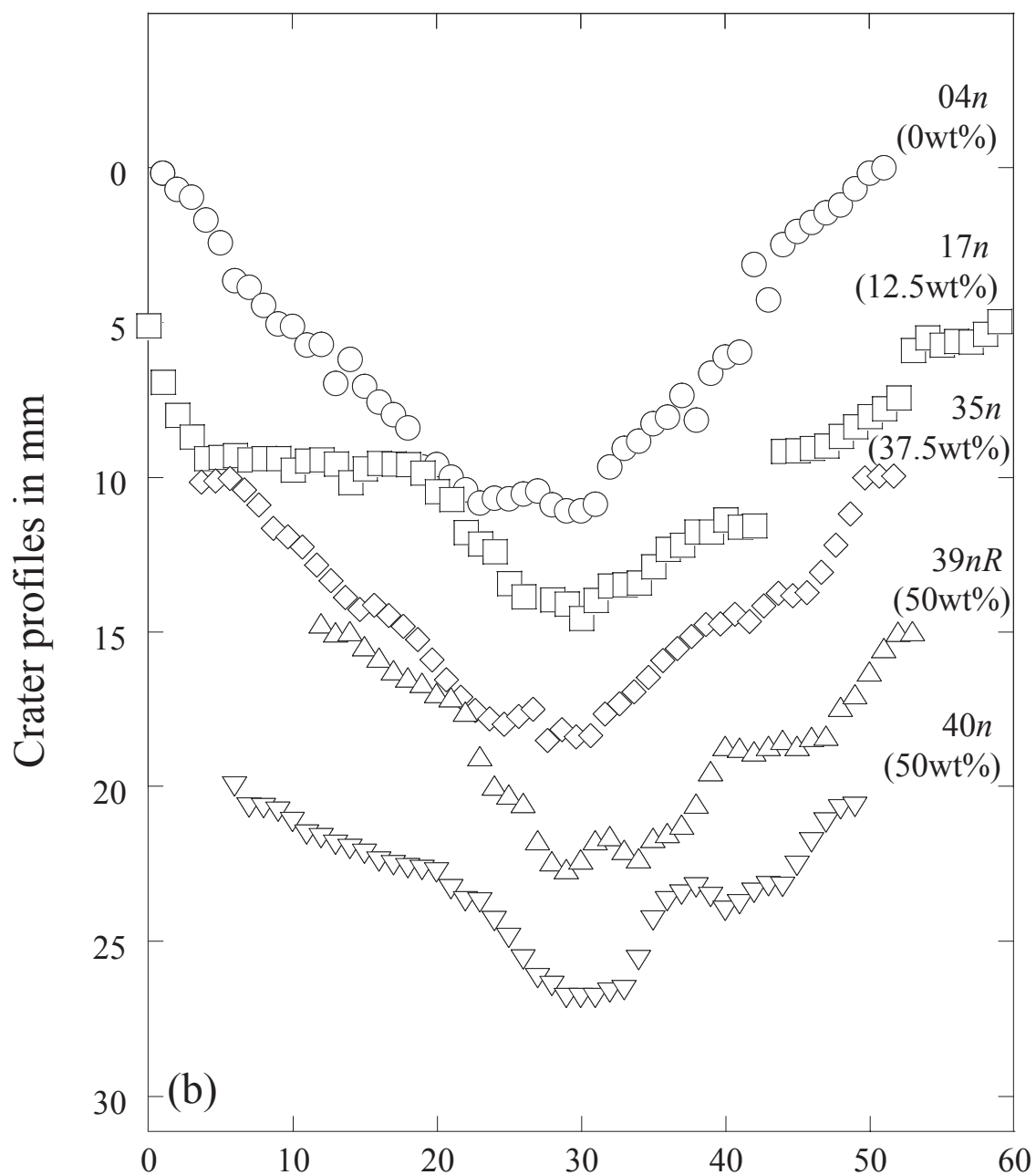


Fig. 2.3 (b). Crater profiles at impact velocity of 3120 to 3310m/s. The measurement error is less than 0.03mm.

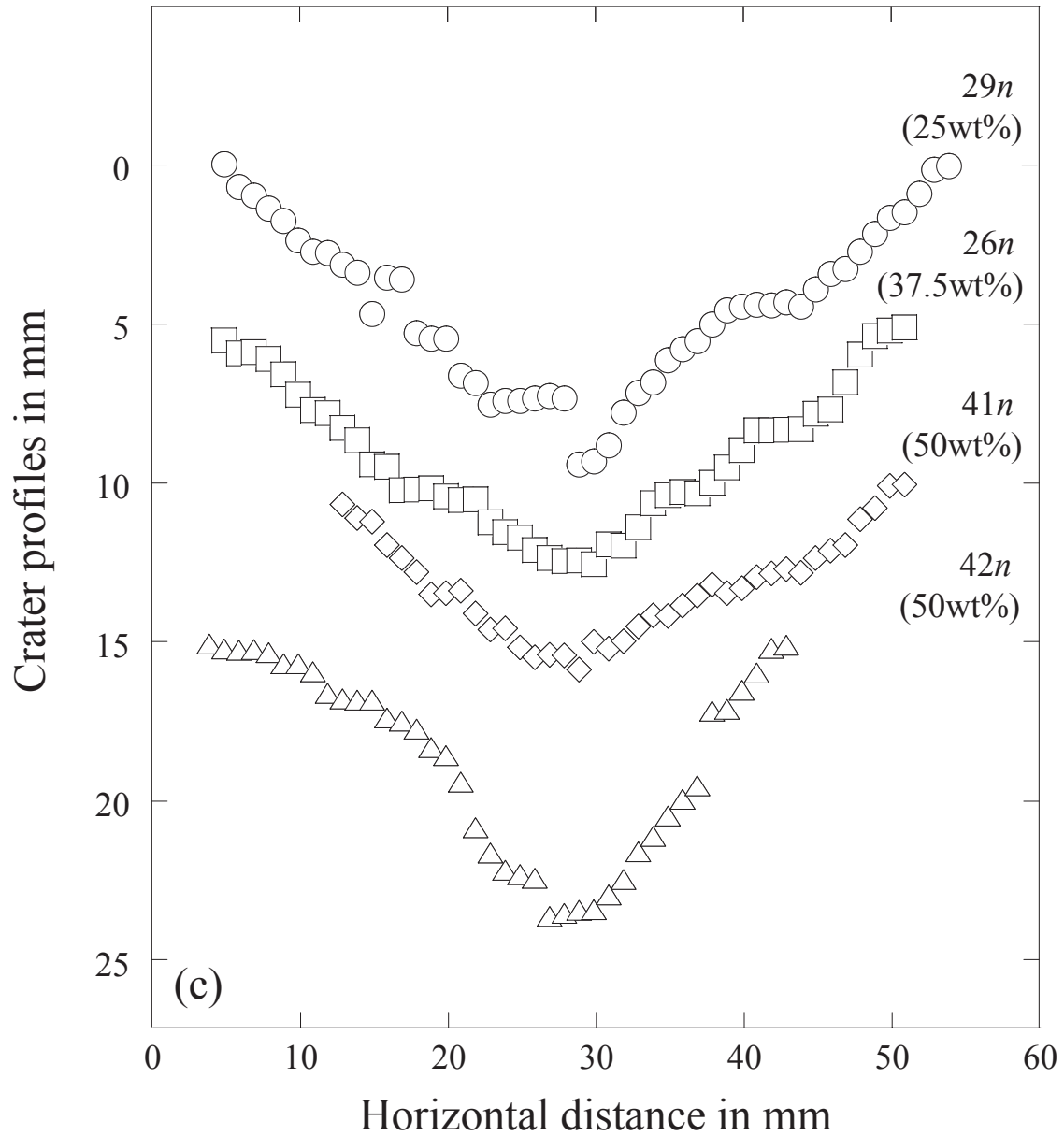


Fig. 2.3 (c). Crater profiles at impact velocity of 3570 to 3840m/s. The measurement error is less than 0.03mm.

For a pure ice target, the impact produced many cracks in a radial pattern around the crater and the central pit crater surrounded with a shallow halo made by spallation. This is consistent with the results of Kato et al. (1995). The halo was also observed for low silicate content targets. However, no crack could be observed for mixture targets. That may be because powders of silicate in the target prevent the growth of cracks. As can be seen in Figs.2.3 (a), (b) and (c), the crater profiles of 50wt% have much less visible brake, and the inclination of their crater walls are steeper than those with the other silicate content. These are because of the lack of spallation (halo) in 50wt% target. Figs.2.3 show a higher impact velocity makes sharper crater profiles than lower impact velocity. The central area of the crater was brighter than the rest. The change of the

brightness was a result of the surface structure. The central area experienced high compressive pressure. Thus, it became rough, but bright. The change of brightness was also reported in Koschny and Grün (2001).

No clear dependency of the crater volume on silicate content was found in the results of experiments with the gas gun. The relation between the crater volume and the silicate content in the results of the two-stage light-gas gun experiments is shown in Fig. 2.4. As Koschny and Grün (2001) indicated, the decrease of the crater volume with the increase of the silicate content is visible. In their paper, they found this tendency for silicate content between 0 and 20wt%. We show that this tendency continues up to silicate content 50wt%. In Fig. 2.4 the crater volume in samples with silicate content between 12.5 to 37.5wt% is almost constant, but the crater volume in samples with silicate content of 50wt% is especially smaller than the others. This fact indicates that the physical property of a mixture target may largely change at 50wt%. In the range of this kinetic energy, the crater volume is more sensitive to the silicate content than to the projectile impact velocity and this is similar to the results of Koschny and Grün (2001).

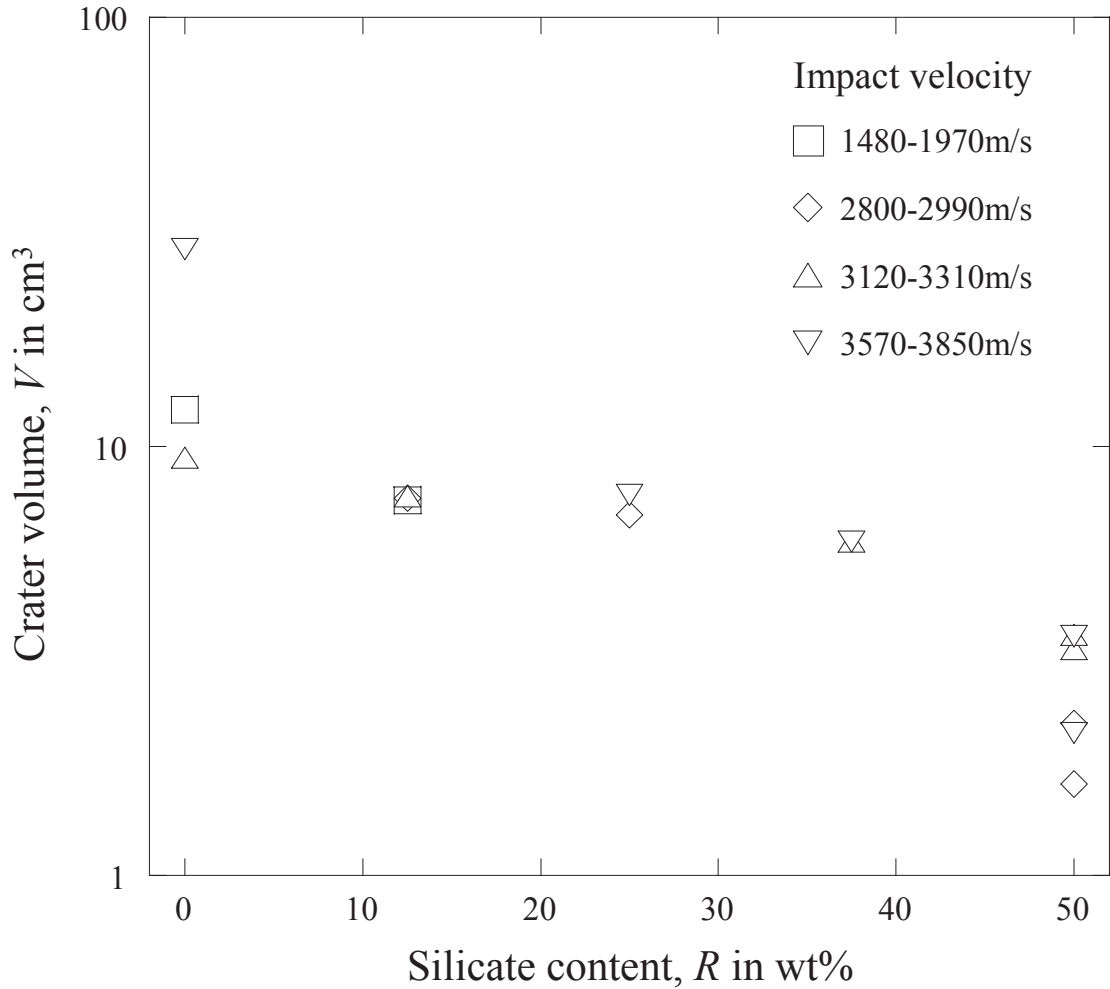


Fig. 2.4. Crater volume V versus silicate content R . Symbols represent the range of impact velocity. The silicate content should have a certain value of error, which is expected to be smaller than 2wt%.

In Eq. (1.1), the left term can be changed into dimensionless crater depth or diameter. We discuss the most appropriate strength among uniaxial compressive, tensile and shear strength, for the dimensionless crater depth, diameter and volume. Since the density ratio of the projectile and the target in this study was changed only over factor 1.7, it is difficult to discuss and determine the dependence on this ratio. Thus, the index of the density ratio is fixed to -0.4 (Holsapple and Housen, 2007). The density of mixtures is calculated by the following equation,

$$\frac{1}{\rho_{mixture}} = \frac{1 - R/100}{\rho_{ice}} + \frac{R/100}{\rho_{silicate}}, \quad (2.5)$$

where R is the silicate content in wt% and $\rho_{mixture}$, ρ_{ice} and $\rho_{silicate}$ are the density of mixtures, ice (910kg/m³) and serpentine (2600kg/m³), respectively.

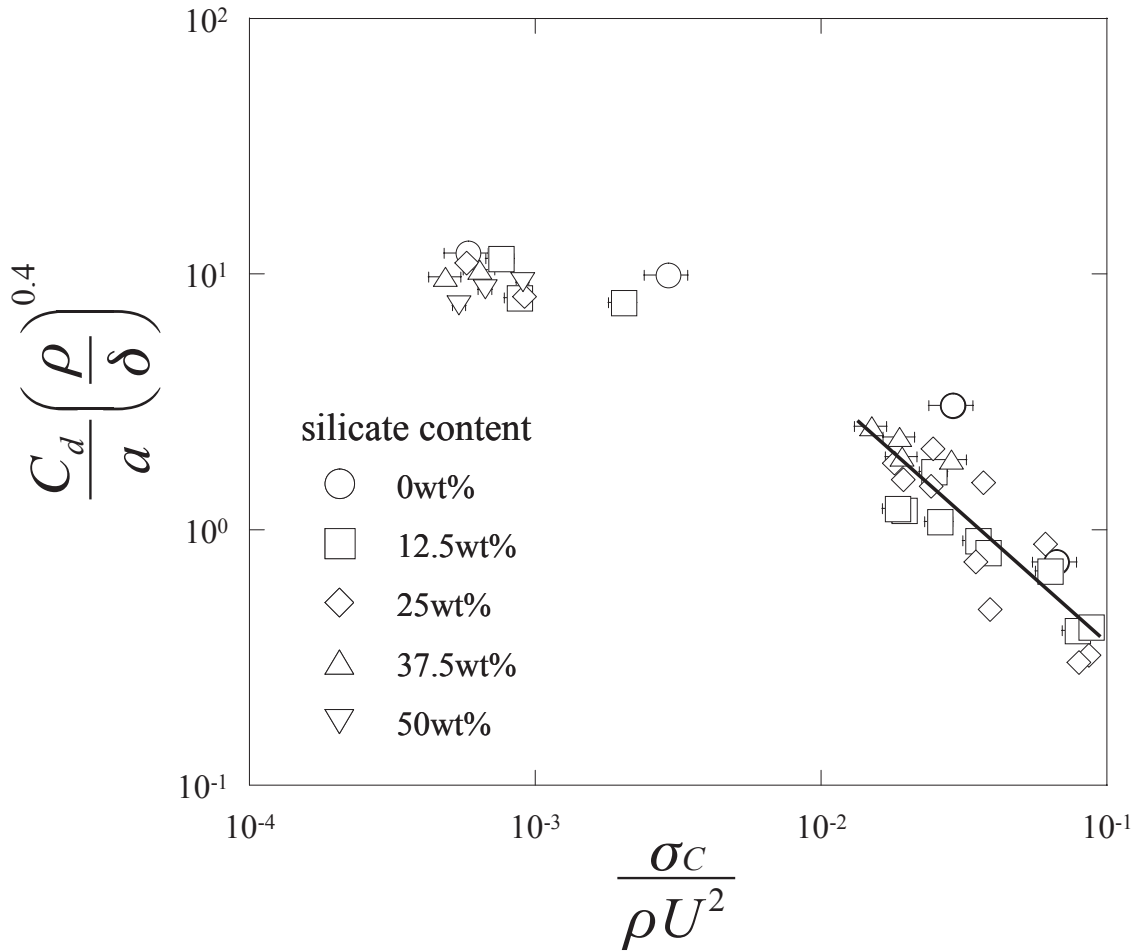


Fig. 2.5. The relation between the dimensionless uniaxial compressive strength and the crater depth normalized by the projectile radius. The solid line shows the fitting line of the results at lower impact velocity

Table 2.3.

Correlation coefficients of the fitting curves when the uniaxial compressive, tensile or shear strengths are used for the scaling.

	Crater depth/ projectile radius (impact velocity ranged below 700m/s)	Crater diameter/ projectile radius	Crater volume/ (projectile radius) ³
Uniaxial compressive strength	0.74	0.91	0.73
Tensile strength	0.43	0.93	0.82
Shear strength	0.36	0.93	0.81

2.5.1. Crater depth

Fig. 2.5 shows the relation between the dimensionless uniaxial compressive strength and the crater depth normalized by the projectile radius. The crater depth increases with the impact velocity as long as the velocity is below 700m/s. On the other hand, the results obtained with an impact velocity between 1.5km/s and 3.6km/s are almost constant. This feature can be also seen in impact experiments with rock and metal targets (Kadono and Fujiwara, 2005). The crater depth is well scaled by the uniaxial compressive strength, especially for lower impact velocities. Table 2.3 shows the correlation coefficients of the fitting curves when the uniaxial compressive, tensile or shear strengths are used for the scaling. A least square fit of all results at lower impact velocity in Fig. 2.5 gives,

$$\frac{C_d}{a} = 10^{-1.4 \pm 0.2} \left(\frac{\sigma_c}{\rho U^2} \right)^{-1.0 \pm 0.1} \left(\frac{\rho}{\delta} \right)^{-0.4}, \quad (2.6)$$

where C_d , a , σ_c , U , ρ and δ are the crater depth, the projectile radius, the uniaxial compressive strength, the impact velocity, the target density and the projectile density, respectively.

2.5.2. Crater diameter

Figs.2.6 (a), (b) and (c) show the relation between the dimensionless uniaxial compressive, tensile and shear strengths, and the crater diameter normalized by the projectile radius. When the normalized crater diameter is scaled by the uniaxial compressive strength, the crater diameter of the higher silicate content is still smaller than that of the lower silicate content (see Fig. 2.6 (a)). In the case of the normalized crater diameter scaled by the shear strength, the fitting lines in Fig. 2.6 (c) are still scattered. On the other hand, there is no difference between the fitting lines for the silicate contents when the crater diameter is normalized by the tensile strength (see Fig. 2.6 (b)). This is consistent with the model that the crater diameter is determined by the spallation. However, the correlation coefficients of the fitting curves shown in Table 2.3

are almost the same. A least squares fit of all results in Fig. 2.6 (b) gives

$$\frac{C_D}{a} = 10^{-0.02 \pm 0.07} \left(\frac{\sigma_T}{\rho U^2} \right)^{-0.46 \pm 0.02} \left(\frac{\rho}{\delta} \right)^{-0.4}, \quad (2.7)$$

where C_D , and σ_T are the crater diameter and the tensile strength, respectively.

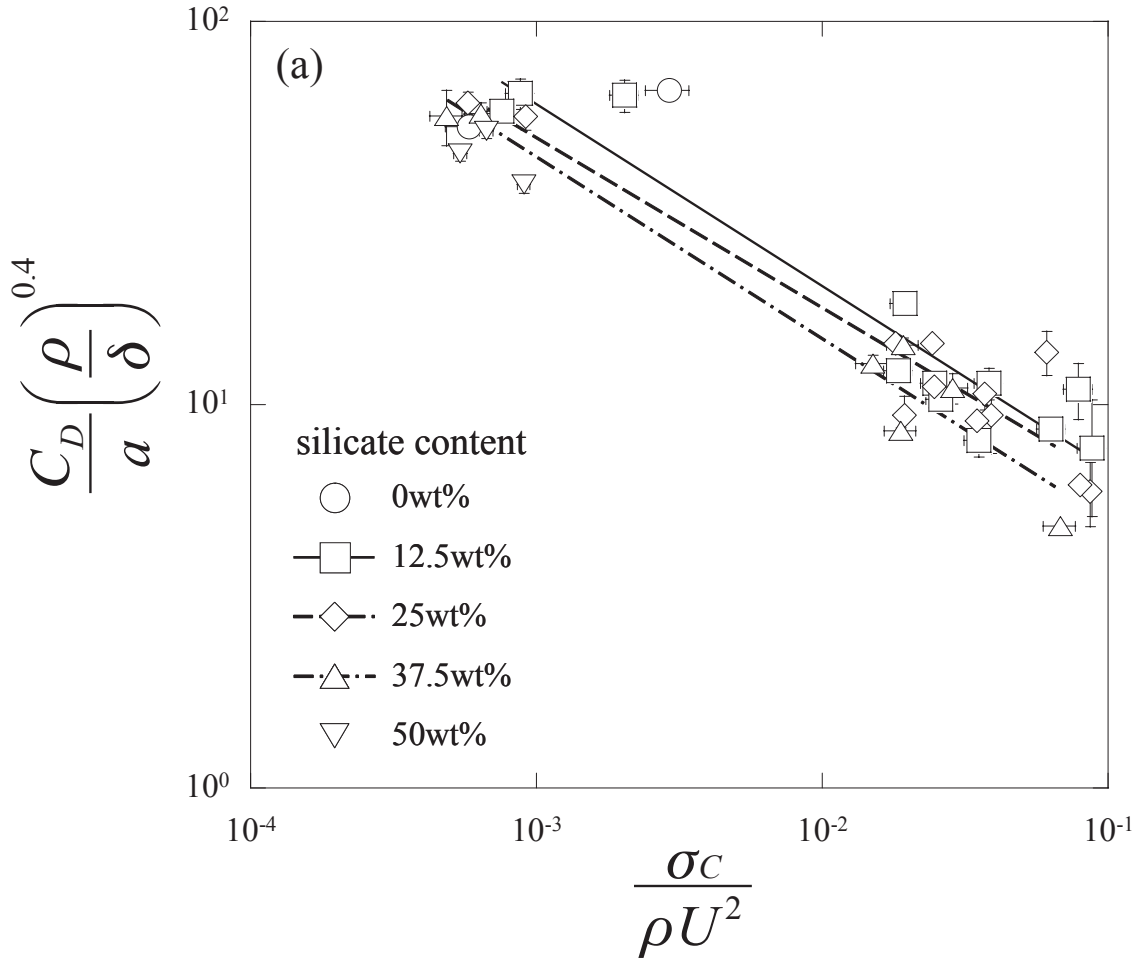


Fig. 2.6 (a). The relation between the dimensionless uniaxial compressive strength, σ_C , and the crater diameter, C_D normalized by the projectile radius, a . The fitting lines of the results for 12.5, 25 and 37.5wt% silicate contents are shown.

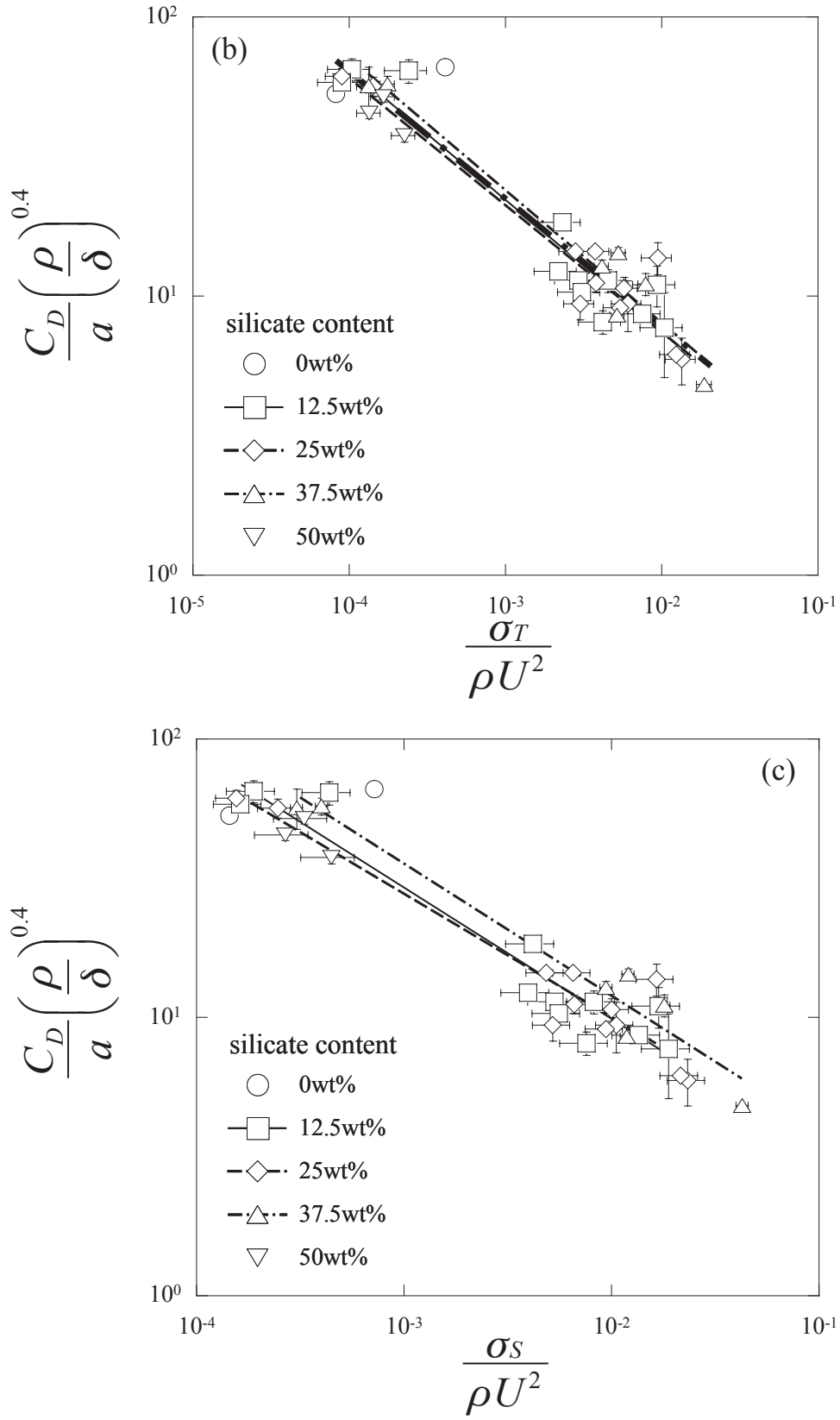


Fig. 2.6 (b) and (c). The same as Fig. 2.6 (a), but for the tensile and shear strength, σ_T and σ_s , respectively. The bold-dashed-dotted line shows the fitting line of all results.

2.5.3. Crater volume

Figs.2.7 (a), (b) and (c) shows the relation between the dimensionless uniaxial compressive, tensile and shear strength, and the normalized crater volume. The normalized crater volume is better scaled by the tensile strength, that is similar to the crater diameter (see Figs.2.7 (a), (b) and (c)). The correlation coefficients of the fitting curves shown in Table 2.2 are almost the same. A least squares fit of all results in Fig. 2.7 (b) gives,

$$\frac{V}{a} = 10^{-1.4 \pm 0.2} \left(\frac{\sigma_T}{\rho U^2} \right)^{-1.15 \pm 0.07} \left(\frac{\rho}{\delta} \right)^{-0.4} \quad (2.8)$$

where V is the crater volume.

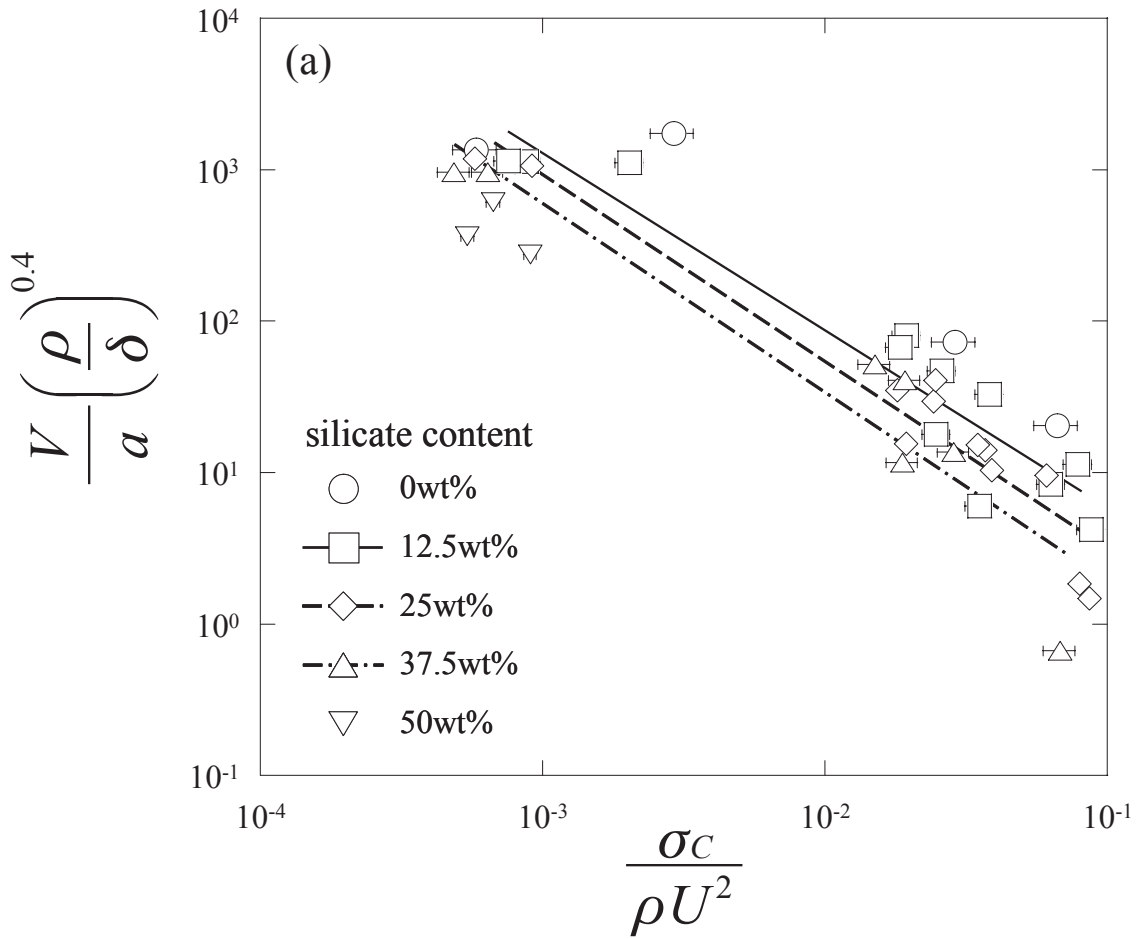


Fig. 2.7 (a). The relation between the dimensionless uniaxial compressive strength, σ_c , and normalized crater volume, V . The fitting lines of the results for 12.5, 25 and 37.5wt% silicate contents are shown in each figure.

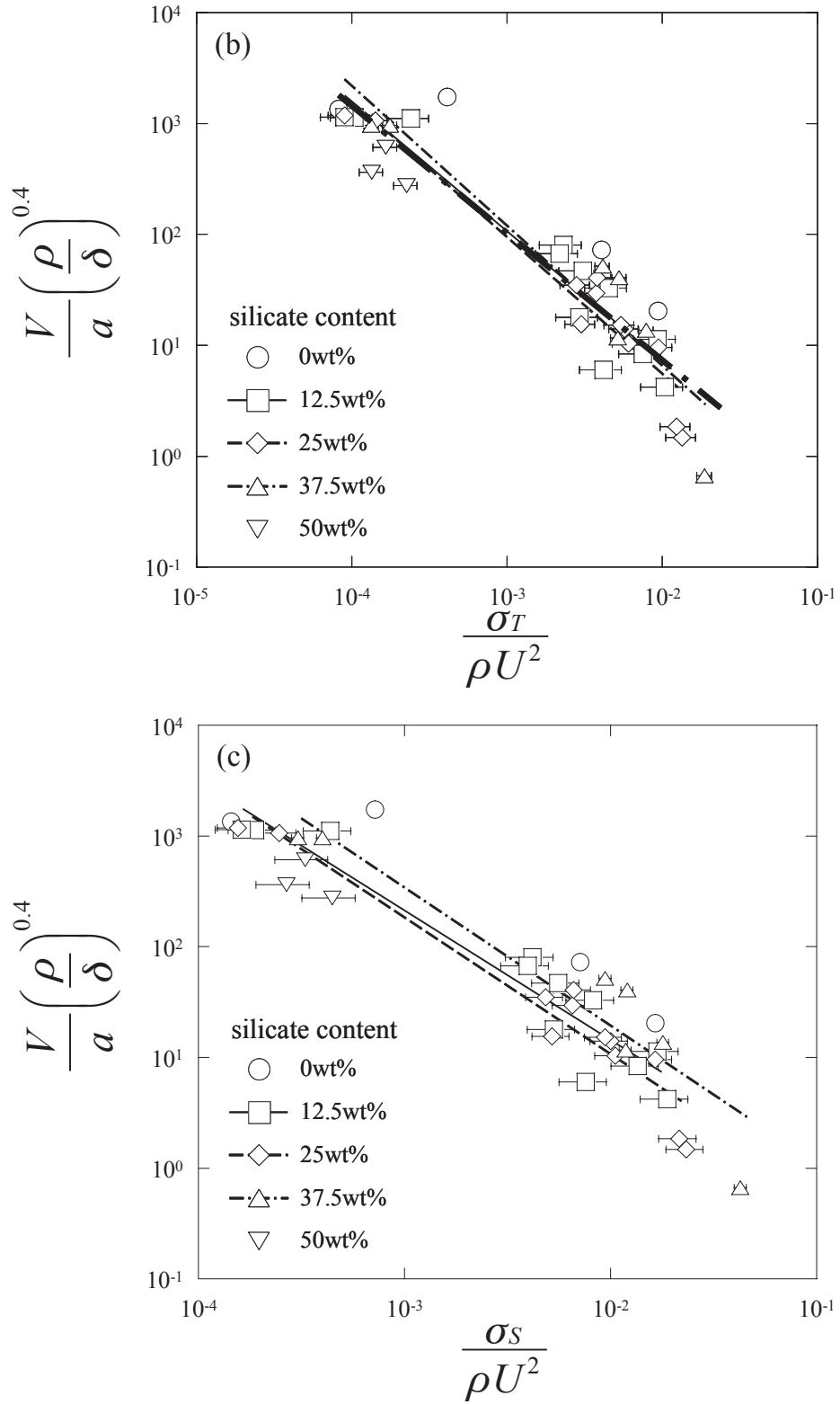


Fig. 2.7 (b) and (c). The same as Fig. 2.7 (a), but for the tensile and shear strength, σ_T and σ_S , respectively. The bold-dashed-dotted line in Fig. 2.7 (b) shows the fitting line of all results.

3. Experimental Study of the Compressive Stress Propagation for the Scaling of the Crater Depth

3.1. Introduction

As described in Chapter 2, the crater depth is controlled by the uniaxial compressive strength of the targets. Thus the crater depth is determined by the relation between compressive stress at the crater depth and the uniaxial compressive strength of the targets. In this chapter, we estimate the compressive stress at the crater depth, and compare that with the uniaxial compressive strength of the targets. In order to discuss about the compressive pressure at the crater depth, the shock attenuation rate in the target and the size of isobaric region have to be investigated.

3.1.1. Shock wave propagation and scaling of the crater depth

As described in Section 1.3, shock wave propagates with attenuation in the target. Decay of pressure can be described by

$$\frac{P(x)}{P_0} = \left(\frac{x}{d_i} \right)^{-b}, \quad (3.1)$$

where $P(x)$ is the pressure at propagation distance, x , P_0 is the initial peak pressure, d_i is the depth of the isobaric region and b is the shock attenuation rate. The shock attenuation rate depends on the pressure (Holsapple, 1993), the target materials and the projectile shape (Kato et al., 2001; Nakazawa et al., 2002). When the impact occurs normal to the target surface, the depth of the isobaric region is the sum of the burrowed depth of the projectile and the size of the isobaric core. In Melosh (1984), the size of the isobaric core was about projectile radius, and the burrowed depth of the projectile d_b was estimated by

$$d_b \approx 2a \left(\frac{\delta}{\rho} \right)^{1/2}. \quad (3.2)$$

The shock attenuation rate which propagates along the impact direction was measured to be 0.89 for ice at a pressure below 1GPa and 1.7 to 1.8 for Kinosaki basalt at a pressure of 30 to 0.02GPa by Kato et al. (2001) and Nakazawa et al. (2002), respectively. They examined the shock wave attenuation by employing piezoresistive gages which set in a certain depth of the targets. Kato et al. (2001) reported that the depth of the isobaric region was about 0.36 projectile radii. They used cylindrical aluminum projectiles. Nakazawa et al. (2002) concluded that the depth of the isobaric region is the depth where the rarefaction wave reflected at the free surface caught up with the shock wave. In their experiments, the depth of the isobaric region is almost the same as the projectile radius. The shock wave generated using thin flyer plate was attenuated by the rarefaction wave generated on the back surface of the plate and by geometrical expansion effects. The shock wave generated using thick projectile was attenuated by edge-wave and by geometrical expansion effects. The rarefaction wave

velocity depends on materials and pressure. Thus, the depth of the isobaric region depends on the projectile shape and target and projectile materials.

When the shock attenuation rate and the depth of the isobaric region are established, the pressure at a certain depth can be calculated. The crater depth can be determined by using the relation between compressive stress at the crater depth and the uniaxial compressive strength of the targets expressed by the following simple equation

$$P_0 \left(\frac{C_d}{d_i} \right)^{-b} = K \sigma_c, \quad (3.3)$$

where K is a constant. In Eq. (3.3), the left part represents the pressure at the crater depth, and the right part represents constant times the uniaxial compressive strength. When the crater depth on ice of Kato et al. (1995) which was produced by a cylindrical aluminum projectile is scaled by Eq. (3.3), Fig. 3.1 is obtained. In Kato et al. (2001) similar cylindrical aluminum projectiles were used to measure the shock pressure propagation.

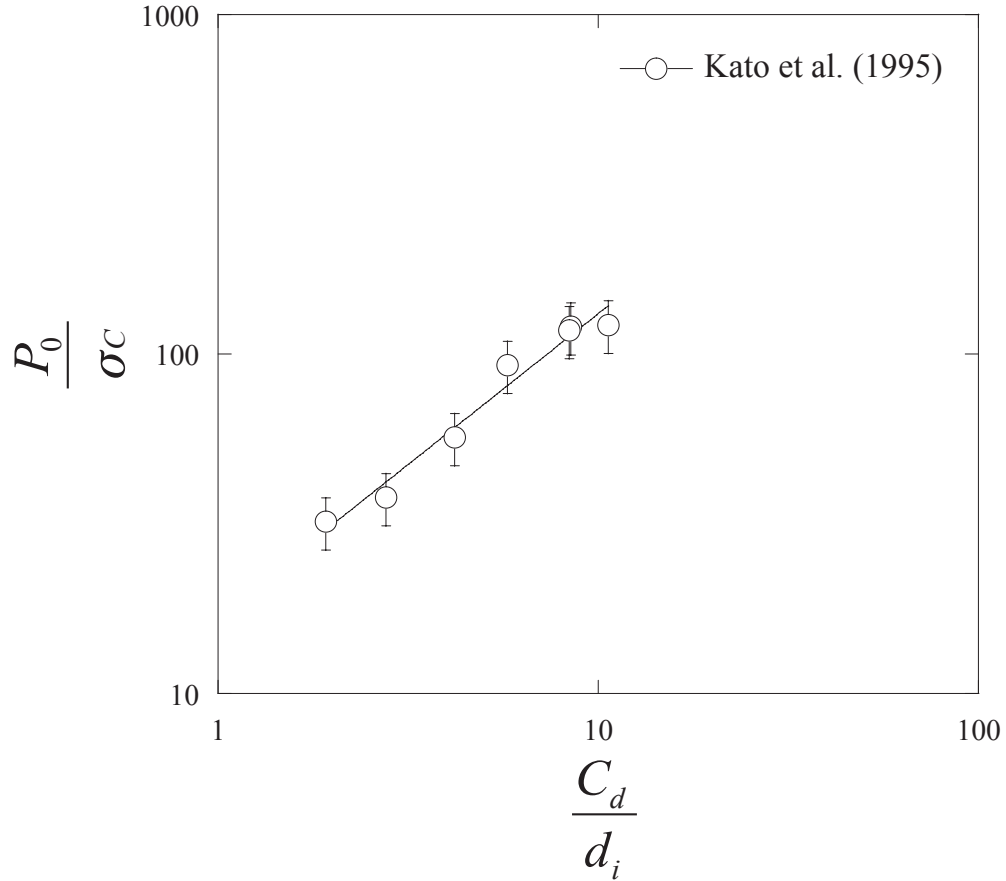


Fig. 3.1. The relation between the crater depth, C_d in ice normalized by the depth of the isobaric region, d_i of Kato et al. (2001) and the initial peak pressure, P_0 normalized by the uniaxial compressive strength, σ_c in the results of Kato et al. (1995). The value of the uniaxial compressive strength of ice is adopted from Chapter 2. The initial peak pressure is calculated by the Hugoniot data obtained by Stewart and Ahrens (2003). The solid line is the fitting curve for all plots.

In Fig. 3.1, if the crater depth can be scaled by Eq. (3.3), the slope corresponds to the value of the shock attenuation rate. In fact, the slope, 0.89 ± 0.07 is extremely consistent with the results of Kato et al. (2001). From this figure, the constant value of K is estimated to be 17 ± 2 . However, direct measurements of the shock pressure by piezoresistive gauges are technically difficult to perform. Thus estimations of the antipodal shock pressure are used to estimate the shock attenuation rate and the depth of the isobaric region.

3.1.2. Antipodal shock pressure

The shock attenuation rate and the depth of the isobaric region can be derived from the measured antipodal ejection velocity. When the particle velocity, u_p in the target is low enough relative to the bulk sound velocity, C_L of the target material, the shock pressure, P is calculated by the equation,

$$P = \rho C_L u_p, \quad (3.4)$$

where C_L is the longitudinal sound velocity of the target material. The target particle velocity at the antipodal point, u_a can be estimated from the antipodal ejection velocity, V_a by using the free-surface approximation,

$$u_a = \frac{1}{2} V_a. \quad (3.5)$$

Then, the antipodal shock pressure, P_a in the targets can be obtained by the equation,

$$P_a = \rho C_L V_a / 2. \quad (3.6)$$

When impact experiments are performed with varying the target size, the shock attenuation rate, b can be derived from the relation between the antipodal shock pressure normalized by the initial peak pressure and the target size, which corresponds to the propagation distance.

Fujiwara and Tsukamoto (1980) and Nakamura (1993) measured the antipodal ejection velocity of Yakuno basalt targets whose size was varying. In Fujiwara and Tsukamoto (1980) the shape of targets was either a cube or a sphere, and they changed impact angles for sphere targets from 90 to 55 degrees. The targets of Nakamura (1993) were spheres, and the impact angle was also changed from 90 to 30 degrees. The projectile of Fujiwara and Tsukamoto (1980) was polycarbonate cylinder and the initial peak pressure was fixed about 11GPa. Nylon spheres were used as projectile in Nakamura (1993), and the initial peak pressure was about 15GPa. The relation between the antipodal shock pressure normalized by the initial peak pressure and target size normalized by projectile radius is shown in Fig. 3.2. The longitudinal sound velocity of Yakuno basalt was measured by Takagi et al. (1984) to be 4640 ± 140 m/s. The shock attenuation becomes large when the normalized target size is larger than 10. This corresponds to the transition from complete disruption to core disruption in Fujiwara and Tsukamoto (1980). Since the antipodal fragments from the core disruption are spalled off as a plate, they are larger than those from the complete disruption. Due to

these large fragments, the free-surface approximation (Eq. (3.5)) was not valid, and then the shock attenuation is probably steeper than that of Nakazawa et al. (2002). Thus, this method to estimate the shock attenuation rate is not appropriate for hard targets. If the antipodal shock pressure in the impact of completely disruption is valid, the depth of the isobaric region is almost the same as that of Nakazawa et al. (2002). When the impact angle was smaller than 45 degree, the effect of oblique impact became noticeable.

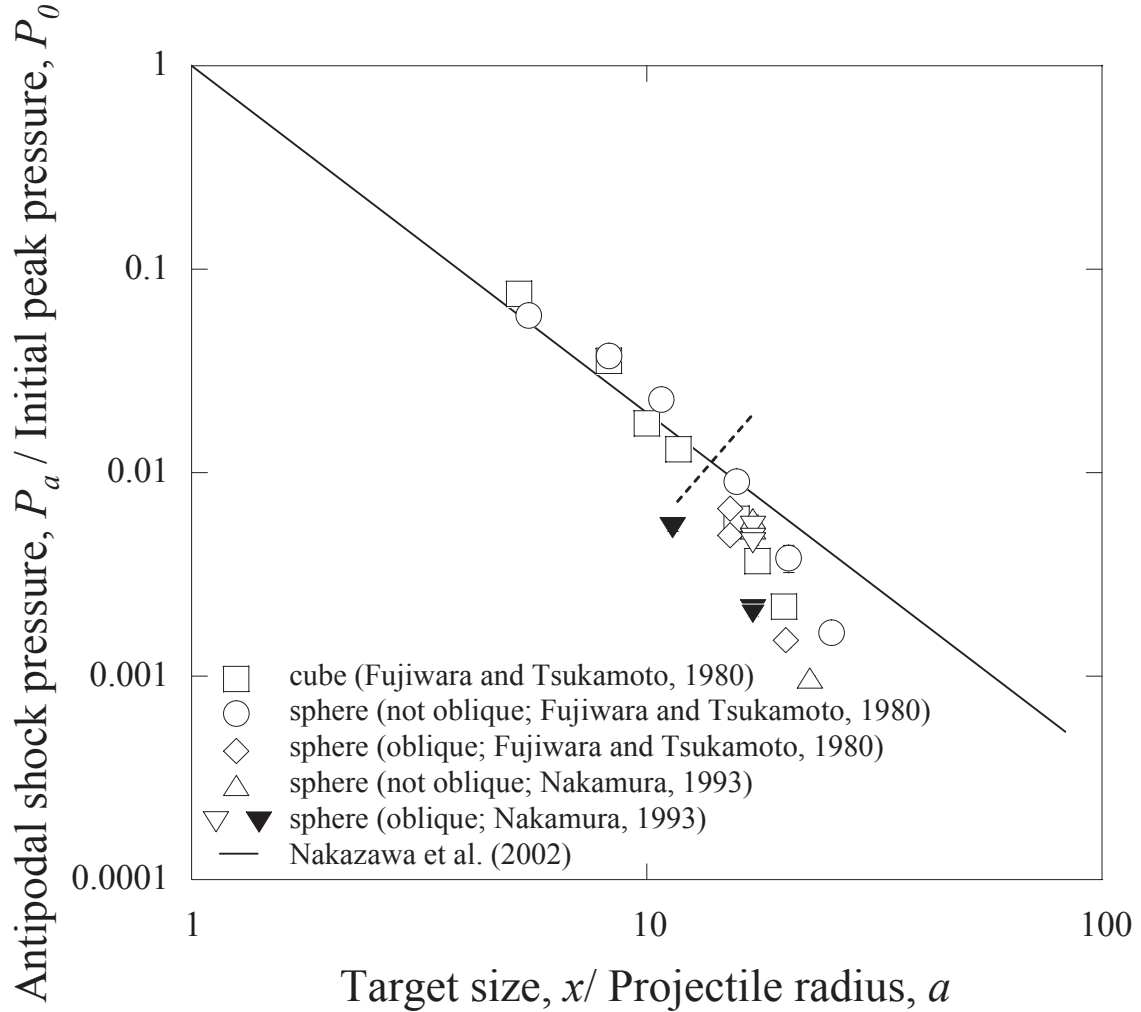


Fig. 3.2. The relation between the target size, x normalized by the projectile radius, a and the antipodal shock pressure, P_a normalized by the initial peak pressure, P_0 for the results of Fujiwara and Tsukamoto (1980) and Nakamura (1993). The open and filled plots of oblique impacts of Nakamura (1993) show the results with an impact angle of 60 degrees and 45 to 30 degrees, respectively. The solid line is the result of Nakazawa et al. (2002). The dashed-line shows the transition from complete disruption to core disruption in Fujiwara and Tsukamoto (1980). Almost all error bars are smaller than the plots.

Arakawa (1999) measured the antipodal ejection velocity in ice targets with varying target sizes. They used cone-shaped nylon as projectile. The shock attenuation

rate in ice derived from measurements of the antipodal shock pressure was 2.0 ± 0.3 which is larger than the value of Kato et al. (2001). The initial peak pressure in the experiments of Arakawa (1999) is an order of magnitude larger than that of Kato et al. (2001). This probably explains that the shock attenuation rate in ice derived from the antipodal shock pressure of Arakawa (1999) is larger than the value of Kato et al. (2001). The depth of the isobaric region was not determined, because the error of the fitting was quite large.

In this chapter, we discuss the crater depth in porous targets using the shock attenuation rate and the depth of the isobaric region derived from the antipodal shock pressure. The shock wave stress in porous targets generally decays more rapidly than in dense targets because of a larger dissipation of the impact energy (Melosh, 1989). The sintered glass beads-silicate mixtures are used as porous targets. The porosity and strength of sintered mixtures can be changed by the mixing ratio, the heating duration and the temperature. As a result, the shock attenuation rate can be probably varied. Furthermore, when we change the density ratio of projectile to target, we can examine the dependence of the burrowed depth of the projectile on the density ratio, and Eq. (3.2). Then we compare our results with those of previous studies and discuss whether our simple scaling for the crater depth can be adapted to different experiments in which the shock attenuation rate and the depth of the isobaric region were measured.

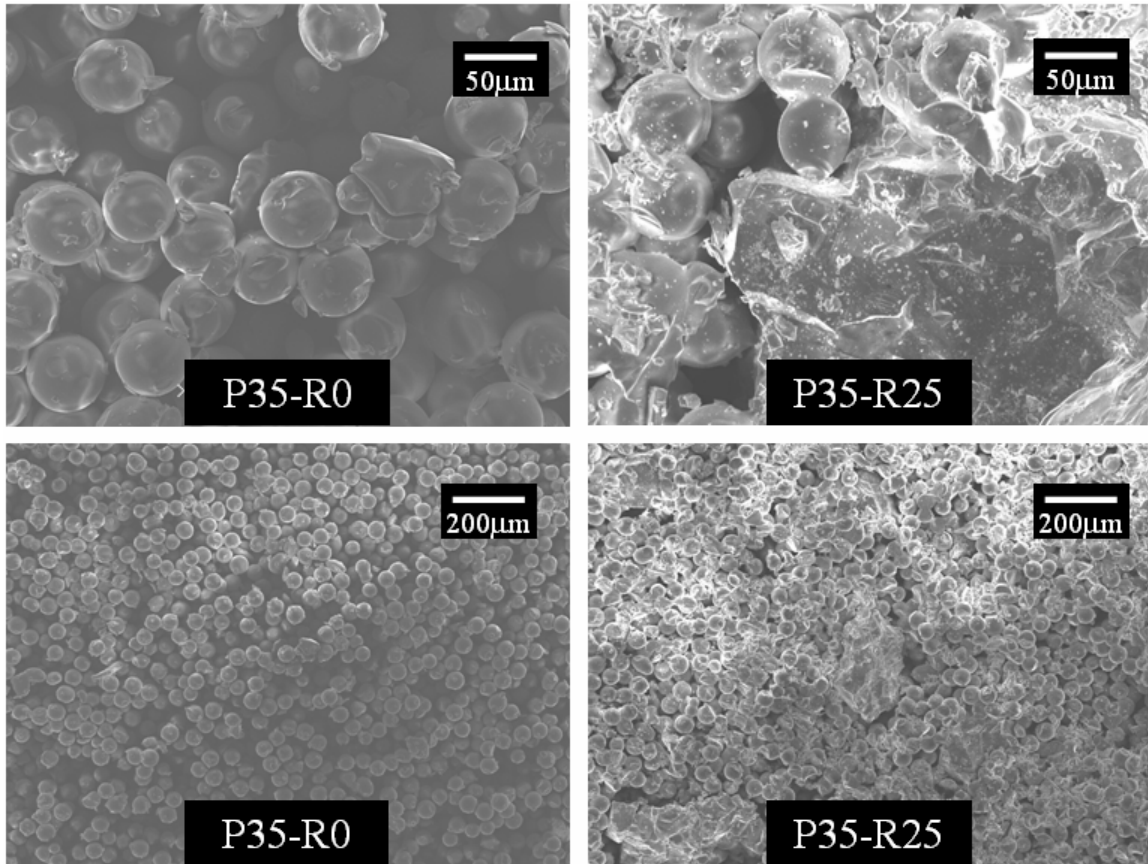


Fig. 3.3. The images taken by scanning electron microscope of P35-R0 and P35-R25.

3.2. Targets

Soda lime glass beads were used in this study (diameter: 63-53 μ m (FGB300); nominal density: 2.5g/cm³, softening point: 734°C, particle strength: ~850MPa, Fujikihan, Japan) (Love et al., 1993; Michikami et al., 2007). The powder of dunite was used as silicate content (size: 200-500 μ m in diameter, nominal density: 3.3g/cm³).

The sintering process consisted of mixing the glass beads into the dunite powders, pouring the mixtures powders into a cylindrical mold (inner diameter: 10cm, inner height: 6cm) and then positioning the mold at the center of an oven which was subsequently heated from room temperature to maximum temperatures of 625 and 620 °C in a 30-min interval. The duration of the baking process at the maximum temperature was 4 h, at which point the heater was switched off. The oven was not opened for about 10 h, until the internal temperature had returned to room temperature. This long cooling time was employed to minimize possible internal thermal stress in the targets. Fig. 3.3 shows scanning electron microscope images of sintered soda lime glass-silicate mixtures. The target properties are summarized in Table 3.1.

Table 3.1.
Target types and properties

Target type	Porosity in %		Uniaxial compressive strength in MPa		Tensile strength in MPa		Shear strength in MPa		Longitudinal sound velocity in m/s	
P35-R0	36.5	±0.3	12.1	±3.4	1.81	±0.46	3.16	±0.72	2178	±27
P35-R12.5	34.3	±1.0	15.3	±6.3	2.07	±0.70	3.6	±1.1	1944	±80
P35-R25	32.3	±1.6	17.5	±5.9	3.52	±0.11	6.24	±0.61	1958	±148
P40-R0	40.3	±1.8	1.91	±0.51	0.365	±0.045	0.638	±0.096	1297	±137

Note. Target types of P35 were made by sintering process at maximum temperature of 625°C. Target type of P40 was made by sintering process at maximum temperature of 620°C. Uniaxial compressive and tensile strengths were measured by uniaxial compressive and Brazilian tests, which are described in Section 2.3. Shear strength were calculated by Eq. (2.2).

Target strengths were measured and calculated in the same way as that described in Section 2.3 at Kobe University. Several cylindrical cores (height: 1.2 to 1.7cm, diameter: 1.0cm) were drilled from each targets. Because of the large mold, there was a gradient of the strength; the strength of the inside was weaker than that of the surface, and that of the upper side was weaker than that of the base side. The impact experiments were performed at the base side of targets. Thus the strength at a depth of about 3cm from the base side was measured for each target type. The head-speed of the compression machine was 1mm/min, thus the strain rate was about 10⁻³s⁻¹. The results of target strength measurements and calculations are listed in Table 3.1. The strengths of mixtures are correlated with the silicate content, and this tendency is consistent with the

strength of ice-silicate mixtures. The longitudinal sound velocities in each target are measured by acoustic emission sensors, and the results are also listed in Table 3.1. The longitudinal sound velocity in soda lime glass and dunite was reported as 5840 ± 30 m/s (Bourne et al., 1995) and 8770 m/s (Marsh, 1980), respectively..

3.3. Experiments

Impact experiments were performed by a two-stage light-gas gun installed at ISAS/JAXA. We used spherical stainless projectiles (SUS-440C, diameter: 1.6mm, nominal density: 7.75 g/cm^3), spherical soda lime glass projectiles (diameter: 3.2 or 0.94mm, nominal density: 2.5 g/cm^3) and spherical alumina projectiles (Al_2O_3 99%, diameter: about 1.18mm, nominal density: 3.7 g/cm^3) for impact cratering experiments and spherical nylon projectile (diameter: 7mm, nominal density: 1.16 g/cm^3) for measurements of antipodal ejection velocity. Except for nylon projectiles, we have to use sabots. In previous works of impact cratering on sintered glass beads, spherical soda lime glass of 1.6mm in diameter and spherical alumina of about 1mm in diameter were used in Love et al. (1993) and Michikami et al. (2007), respectively. Experiments were observed by the high-speed camera from two directions. The frame rate of high-speed camera was 2000 or 3000 frames/s, and 3000 or 31000 frames/s for different direction.

3.3.1. Impact cratering experiments

The impact velocity was from 2510 to 3530 m/s. The nominal target size is 10cm in diameter and 5cm in height for impact cratering experiments. The impact angle is normal to the target surface. Targets were put on a floor of a target chamber. Some craters were obtained in the measurement experiments of antipodal ejection velocities using low porosity targets. In order to examine the effect of target thickness on impact cratering, impact experiments were performed on targets that were stuck with a low porosity sample (about 32% porosity) at target antipodal surface. The experimental conditions and results are listed in Table 3.2. The estimation of the initial peak pressure for porous material is described in Appendix I.

3.3.2. Measurements of antipodal ejection velocity

The antipodal ejection velocities of sintered soda lime glass beads, whose porosity is $40.7 \pm 1.2\%$ (Setoh et al., 2007) and about 32% (Setoh et al., personal communication) were measured. In this study, we measured the antipodal ejection velocity of P35-R25 targets. These measurements were performed with varying the thickness of disc-shaped targets whose diameter was 10cm, from about 10 to 40cm. Most experiments were performed by the two-stage light-gas gun by using nylon projectiles of 7mm in diameter at JAXA/ISAS. Since these experiments need many shots to achieve the required accuracy to measure the shock attenuation rate, we chose to make shots without sabots. Setoh et al. (2007) also measured the antipodal ejection velocity of sintered glass beads of 40.7% porosity at low impact velocity, about 260 m/s, using the gas gun installed at Kobe University (spherical glass projectiles of 3.2mm in diameter). From these measurements, the shock attenuation rate and the depth of the isobaric region can be

measured. In the experiments made with the two-stage light-gas gun, the antipodal ejection velocity was measured by high-speed camera whose frame rate was 32000 or 64000 frames/s. The experimental conditions and results of measurements are shown in Table 3.3. The estimation of the initial peak pressure for porous is described in Appendix I. However, since this estimation is only valid for high pressure, the initial peak pressure for the experiments of low impact velocity was estimated by Eq. (3.4).

Table 3.2.
Experimental conditions of impact cratering and crater dimensions

Shot no.	Target type	Impact velocity in m/s	Crater diameter, C_D in cm	Pit diameter, C_P in cm	Crater depth, C_d in cm	Initial peak pressure, P_0 in GPa
01s	P35-R0	3160	4.65 $\pm$ 0.44	2.37 $\pm$ 0.06	1.411 $\pm$ 0.01	17.4
02s	P35-R0	3050	4.54 $\pm$ 0.47	2.31 $\pm$ 0.11	1.51 $\pm$ 0.06	16.2
03s	P35-R0	2810	4.77 $\pm$ 0.61	2.07 $\pm$ 0.03	1.87 $\pm$ 0.03	14.0
04s	P35-R12.5	2730	3.35 $\pm$ 0.91	1.70 $\pm$ 0.19	1.86 $\pm$ 0.01	14.8
05s	P35-R12.5	2760	4.38 $\pm$ 0.31	2.11 $\pm$ 0.09	1.36 $\pm$ 0.01	14.8
06s	P35-R25	2510	4.63 $\pm$ 0.38	2.11 $\pm$ 0.08	1.32 $\pm$ 0.01	12.7
07s	P35-R25	2860	4.16 $\pm$ 0.42	1.93 $\pm$ 0.22	1.34 $\pm$ 0.01	17.7
08g3.2	P35-R0	2940	4.24 $\pm$ 0.22	2.33 $\pm$ 0.07	1.45 $\pm$ 0.04	7.19
09g3.2	P35-R0	3270	4.84 $\pm$ 0.50	2.32 $\pm$ 0.12	1.59 $\pm$ 0.05	8.82
10g3.2lp	P35-R0	3060	<5.1	<2.8	1.5 $\pm$ 0.03	7.77
11g3.2lp	P35-R0	2740	<5.3	<3	<1.54	6.26
12g3.2	P35-R12.5	3530	4.91 $\pm$ 0.23	2.26 $\pm$ 0.04	1.43 $\pm$ 0.01	11.1
13g3.2	P35-R12.5	2510	3.37 $\pm$ 0.27	1.92 $\pm$ 0.05	1.21 $\pm$ 0.01	5.61
14g3.2	P35-R25	3190	3.58 $\pm$ 0.14	2.05 $\pm$ 0.03	1.311 $\pm$ 0.01	9.78
15gl	P35-R25	2830	1.12 $\pm$ 0.11	0.52 $\pm$ 0.02	0.30 $\pm$ 0.07	7.74
16gl	P40-R0	3300	2.00 $\pm$ 0.06	1.29 $\pm$ 0.07	0.73 $\pm$ 0.01	8.48
17gl	P40-R0	2940	1.79 $\pm$ 0.06	1.30 $\pm$ 0.10	0.68 $\pm$ 0.01	6.77
18a	P40-R0	3040	3.06 $\pm$ 0.15	1.79 $\pm$ 0.07	1.10 $\pm$ 0.03	13.6
19a	P40-R0	3460	3.64 $\pm$ 0.23	2.08 $\pm$ 0.04	1.16 $\pm$ 0.03	17.0
20a	P40-R0	3180	2.98 $\pm$ 0.08	1.89 $\pm$ 0.10	1.22 $\pm$ 0.03	14.7
21n	S-H2	2120	5.31 $\pm$ 0.59	2.23 $\pm$ 0.16	1.03 $\pm$ 0.01	4.40
22n	S-H2	<2700	4.67 $\pm$ 0.50	1.76 $\pm$ 0.18	0.75 $\pm$ 0.01	6.49
23n	S-H2	1900	3.52 $\pm$ 0.21	1.97 $\pm$ 0.05	1.13 $\pm$ 0.01	3.70

Note. Shot numbers with the extension *s* used stainless projectiles, *g3.2* used glass projectiles of 3.2mm in diameter, *gl* used glass projectiles of about 1mm in diameter, *a* used alumina projectiles, *n* used nylon projectiles of 7mm in diameter, and *lp* correspond to the experiments in which a less porous target was placed at the antipodal surface. Because the target was disrupted, some values of *lp* shots were measured as an upper limit. The target types except for S-H2 are the same as in Table 3.1. The target properties of S-H2 target type are listed in Table 3.3.

3.4. Results and discussions

3.4.1. Crater dimensions and morphologies

Fig. 3.4 shows some examples of pictures of the crater. The crater diameter and the pit diameter were the average of several measurements by caliper. The crater profiles were obtained by moving a laser displacement meter (KEYENCE, LK-080, spot size: about 70 μ m in diameter) across the surface, at 0.5mm or 0.2mm horizontal interval, measuring the depth from a fixed height. The crater depth was determined by the deepest point of the crater profiles. The results of the crater dimensions are summarized in Table 3.2. Some target edge was disrupted, and there was spallation at the antipodal surface of some targets. When a low density target was put at the antipodal surface of targets, the targets were disrupted. This is probably caused by the reflected shock wave at the antipodal interface of both targets. However, the crater dimensions were not changed drastically.

The crater profiles are shown in Fig. 3.5. The filled plots of each figure show the edge of the pit. From crater profiles, it is difficult to distinguish the clear difference of crater morphologies made in different silicate contents or by different projectile materials. Crater morphologies on S-H2 target types (~32% porosity targets) are extremely unique. The edge of the pit is higher than the outer region for the crater of shot 22*n*. On the other hand, the crater morphology from shot 23*n* is similar to that of higher porosity targets. The crater from shot 21*n* has an intermediate shape has that from shots 22*n* and 23*n*; the right-hand side is similar to the crater shape from shot 22*n*, and the left-hand side is similar to that from shot 23*n*. This unique shape is appreciably similar to the Rahe crater, which is on Comet 81 P/Wild 2 and whose pit edge seems to be higher than the terrace region. This shape is made by ejection of thick spall fragments. Since spallation is considerably irregular, the difference of morphologies is likely to be observed even on similar targets. However, the reason that this shape is only observed on lower porosity targets is unclear. The images from shots 21*n*, 22*n* and 23*n* are shown in Fig. 3.6.

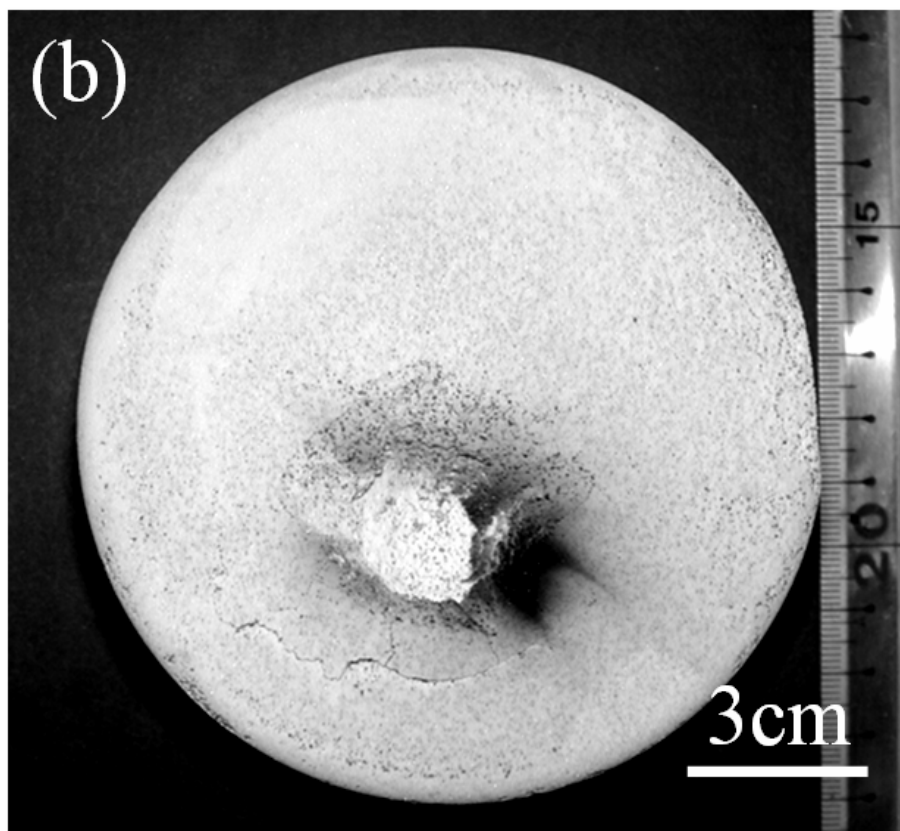
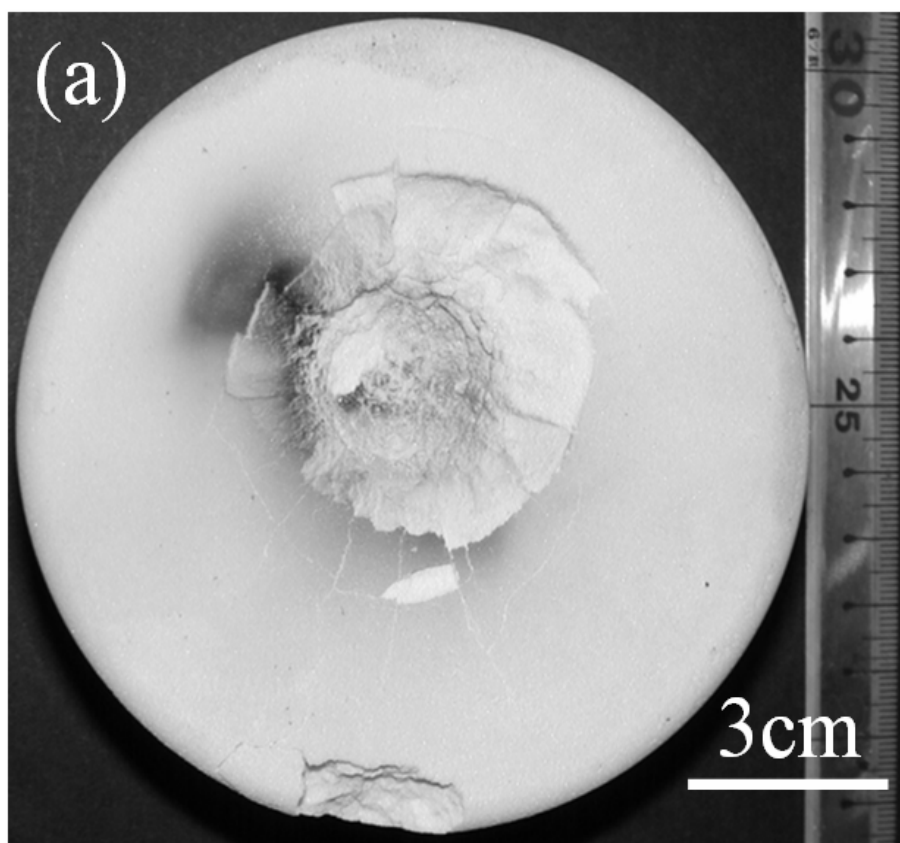


Fig. 3.4. Pictures of the crater of shots (a) 08g3.2 (b) 14g3.2.

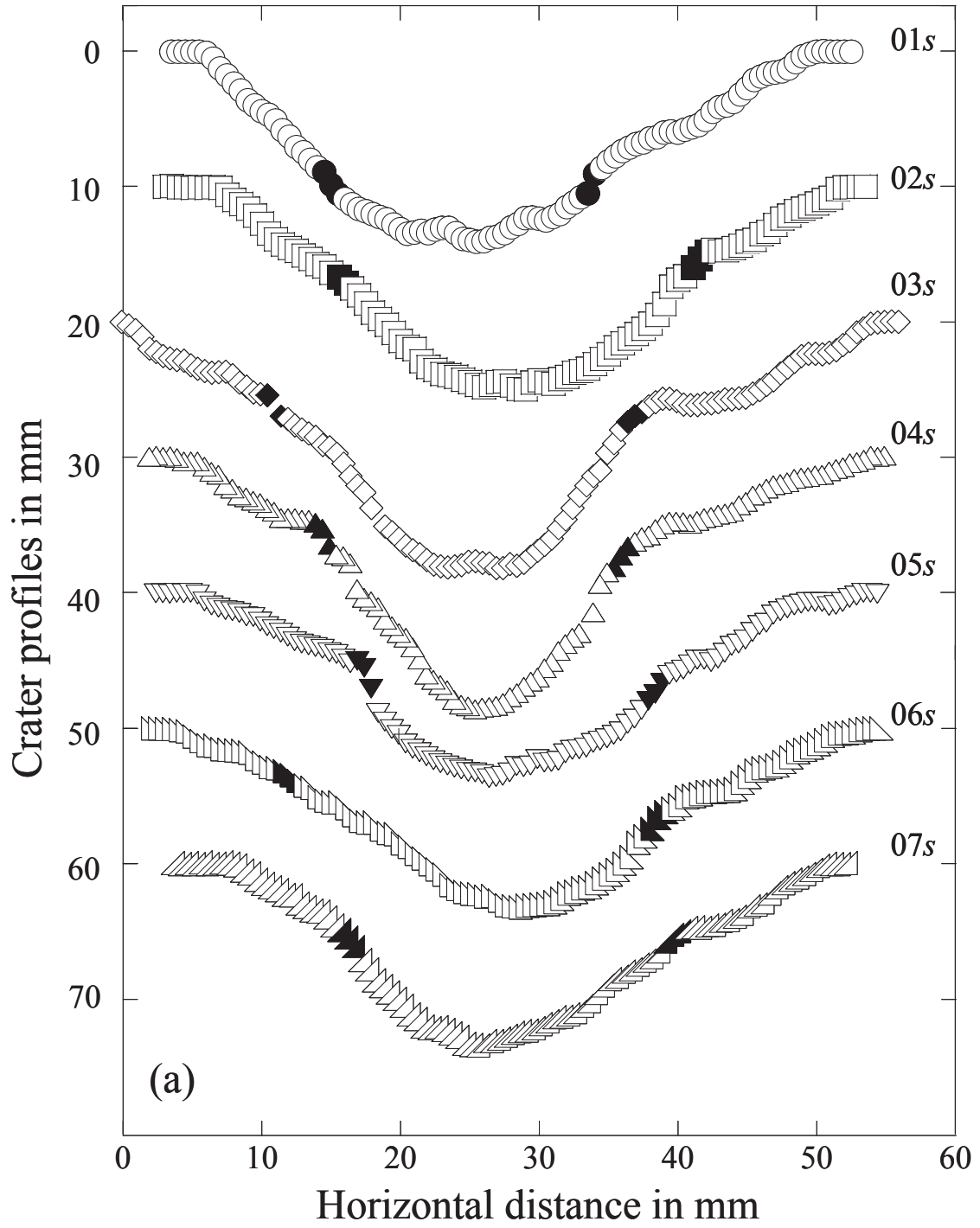


Fig. 3.5 (a). Crater profiles made by stainless projectiles. Shot no. are the same as those in Table 3.2. The measurement error is less than 0.03mm. Filled zones correspond to the edge of the pit.

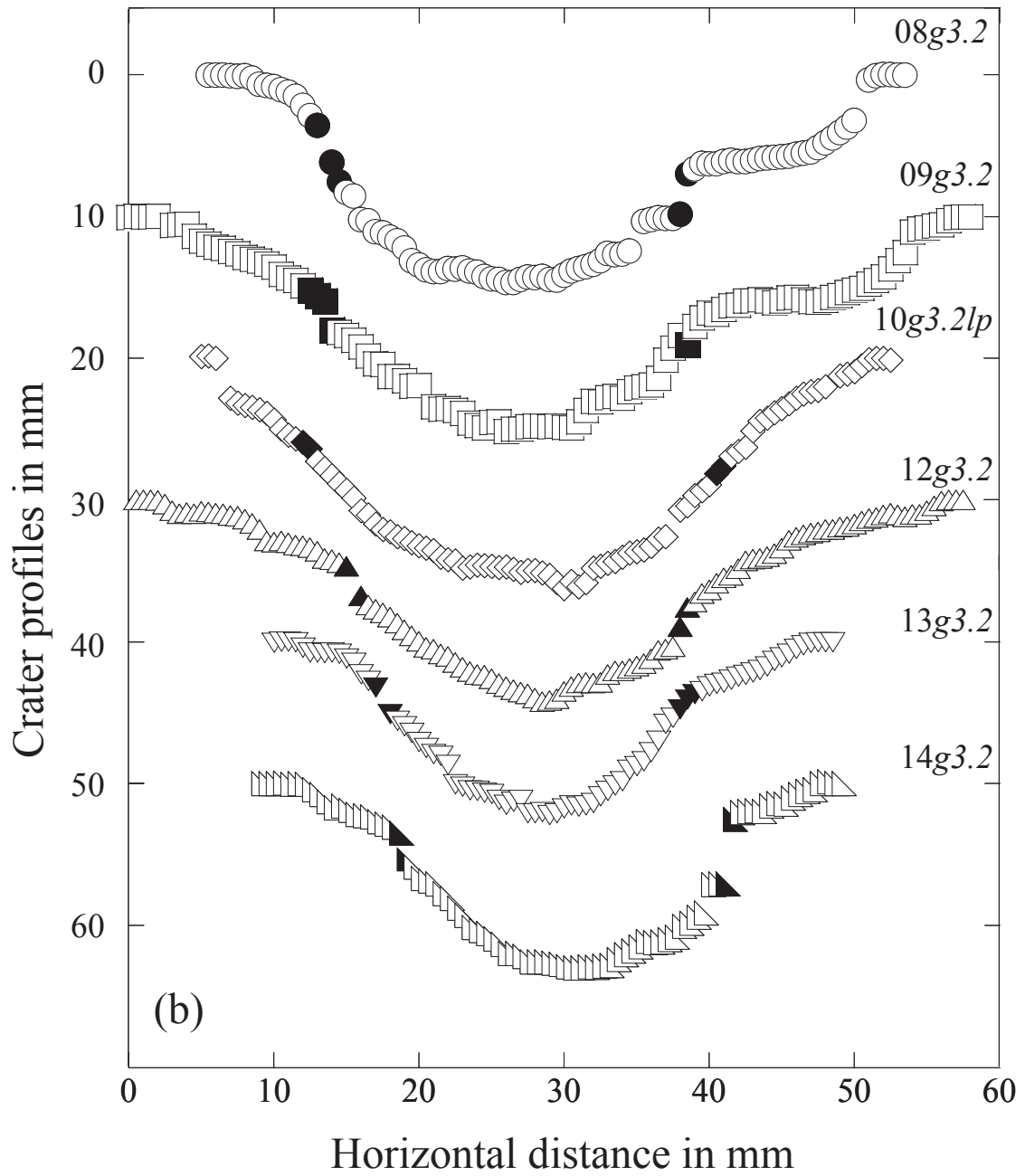


Fig. 3.5 (b). Crater profiles made by glass projectiles of 3.2mm in diameter. Shot no. are the same as those in Table 3.2. The measurement error is less than 0.03mm. Filled zones correspond to the edge of the pit.

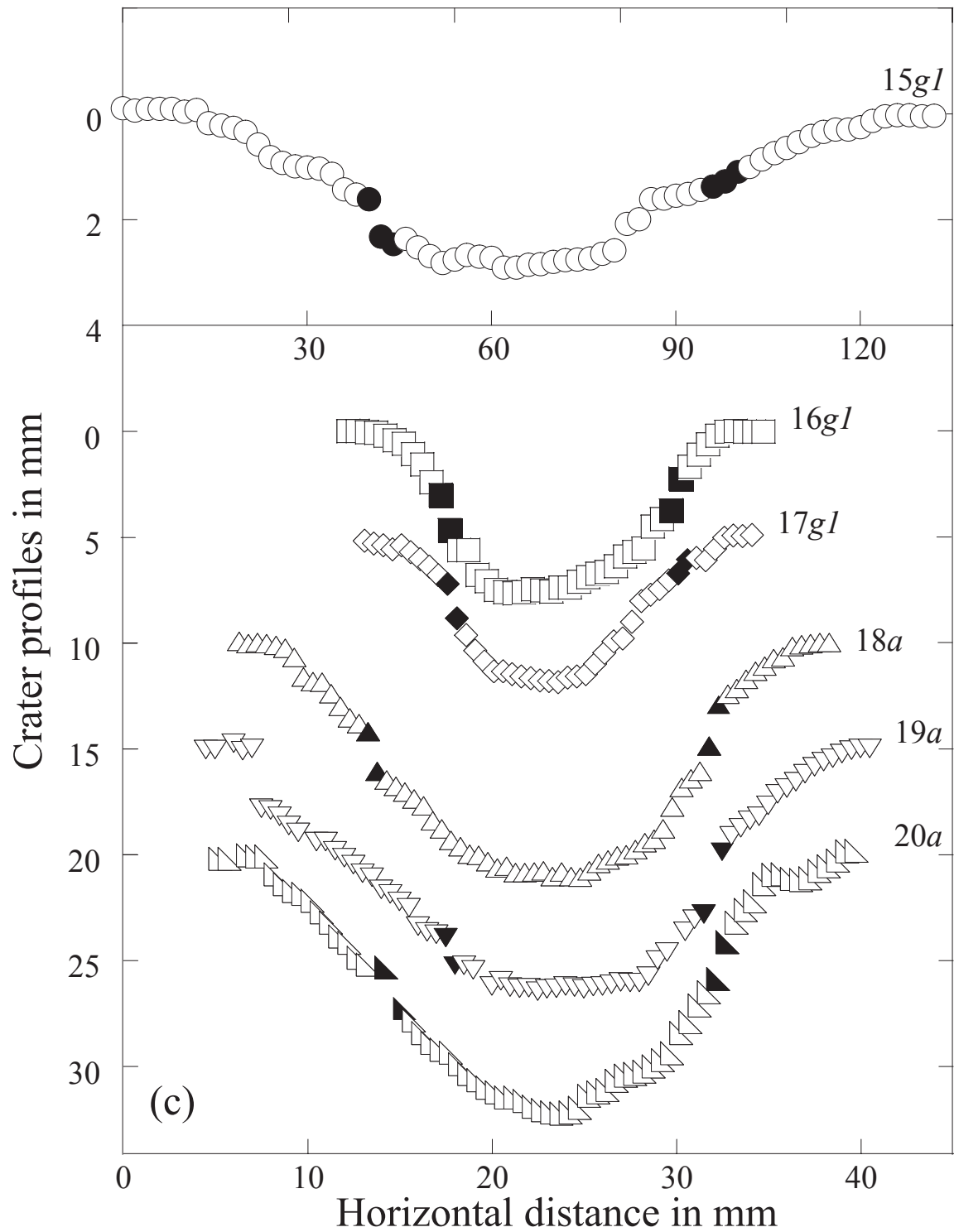


Fig. 3.5 (c). Crater profiles made by glass projectiles of 1mm in diameter and alumina projectiles. Not that the scale of 15gl is not the same as that of other profiles. Shot no. are the same as those in Table 3.2. The measurement error is less than 0.03mm. Filled zones correspond to the edge of the pit.

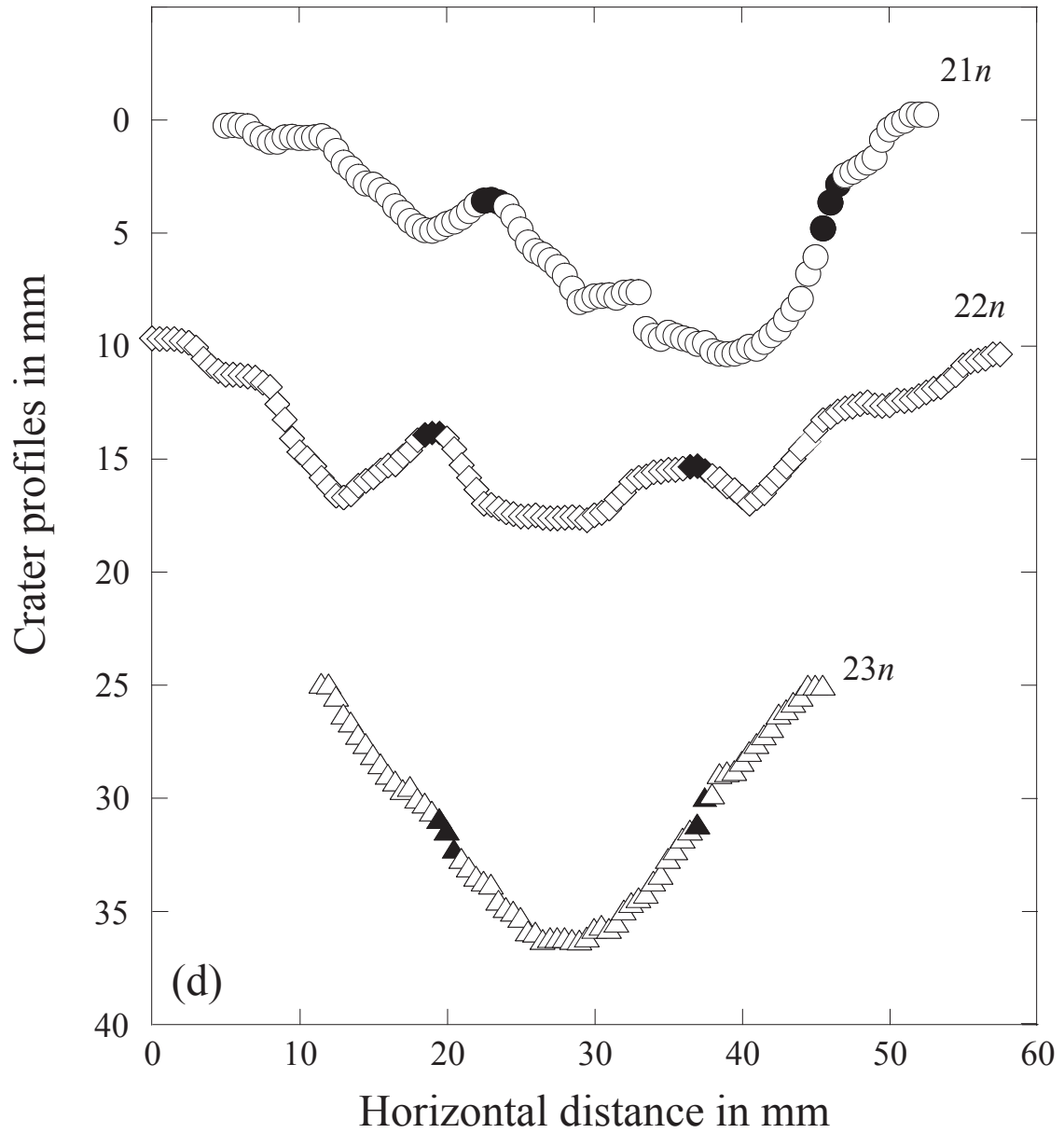


Fig. 3.5 (d). Crater profiles made by nylon projectiles of 7mm in diameter on S-H2 (low porosity) targets. Shot no. are the same as those in Table 3.2. The measurement error is less than 0.03mm. Filled zones correspond to the edge of the pit. The target thickness is ~38mm for 21n and 22n, and 29mm for 23n.

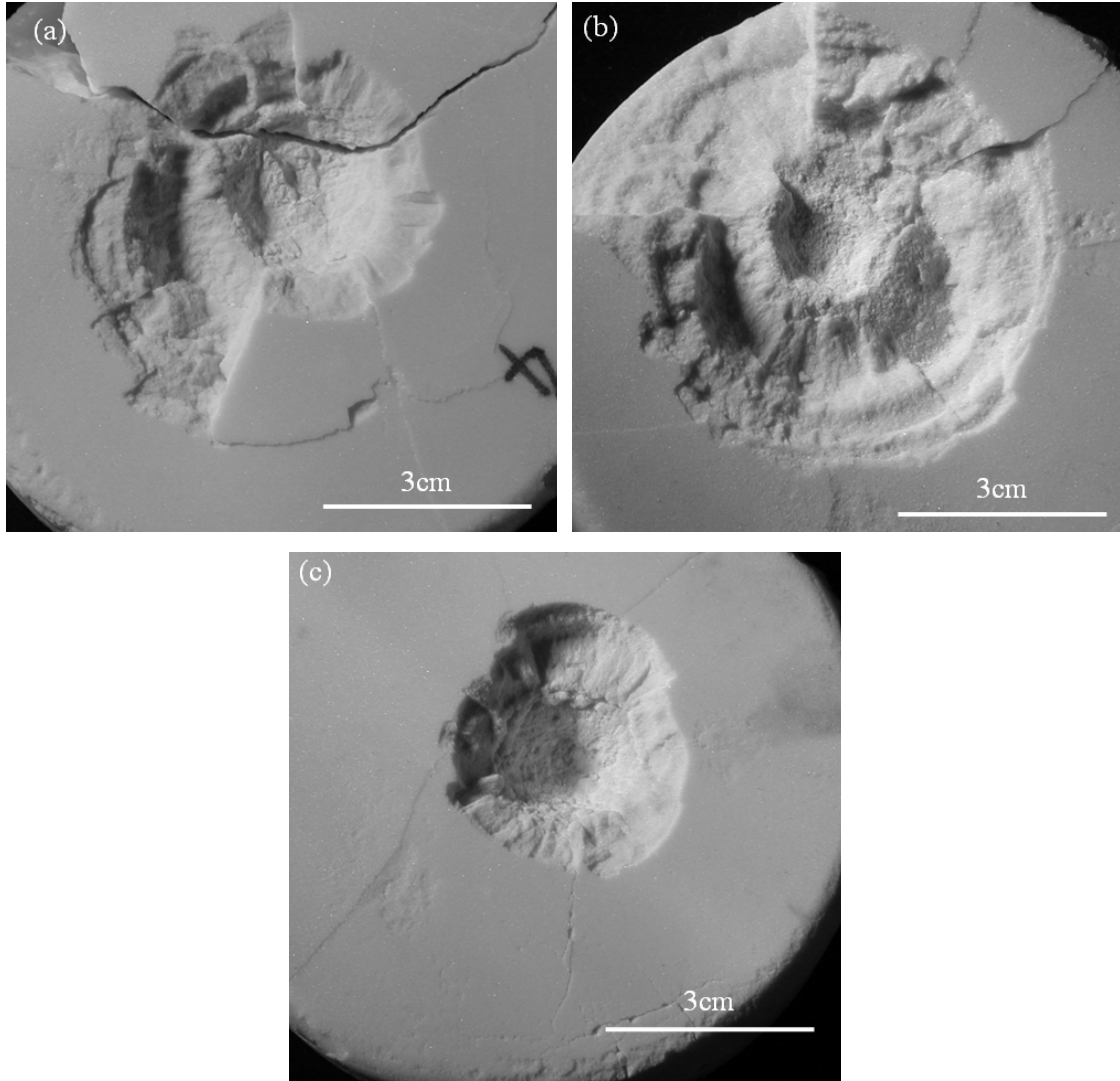


Fig. 3.6. The images of the crater on S-H2 targets from shots (a) 21n, (b) 22n and (c) 23n. The upper part of 21n is separated from the target. Other cracks on each image do not correspond to open surfaces. The light illuminated from the right side.

3.4.2. Shock attenuation rate and depth of the isobaric region

Fig. 3.7 shows the image of an antipodal ejection. Fig. 3.8 (a) and (b) show the relation between the target thickness normalized by the projectile radius and the antipodal shock pressure normalized by the initial peak pressure, and the antipodal shock pressure from the results of Setoh et al. (2007), Setoh et al. (private communication) and this study, respectively. The antipodal ejecta in the experiments performed with the two-stage light-gas gun were fine grains, which corresponds to the glass beads or silicate powders. Thus, the free-surface approximation at the antipodal surface is probably valid. However, the antipodal ejecta in the experiments made with the gas gun were fragments (Setoh et al., 2007). The shock attenuation rate at low impact velocity may thus be smaller than the one provided by this result. From the fitting curves in Fig. 3.8 (a), the shock attenuation rate and the depth of the isobaric

region for each experimental condition can be obtained. The shock attenuation rate and the depth of the isobaric region for each disc-shaped target are summarized in Table 3.3. The values of the shock attenuation rate and the depth of the isobaric region are almost the same in each target and for different impact velocities, as the longitudinal sound velocity in S-H2 target is much higher than that in other targets. The lowest antipodal ejection velocity in these experiments was 1.1 ± 0.2 m/s, which is the rightmost data of S-L experiments in Fig. 3.8 (a) and (b).

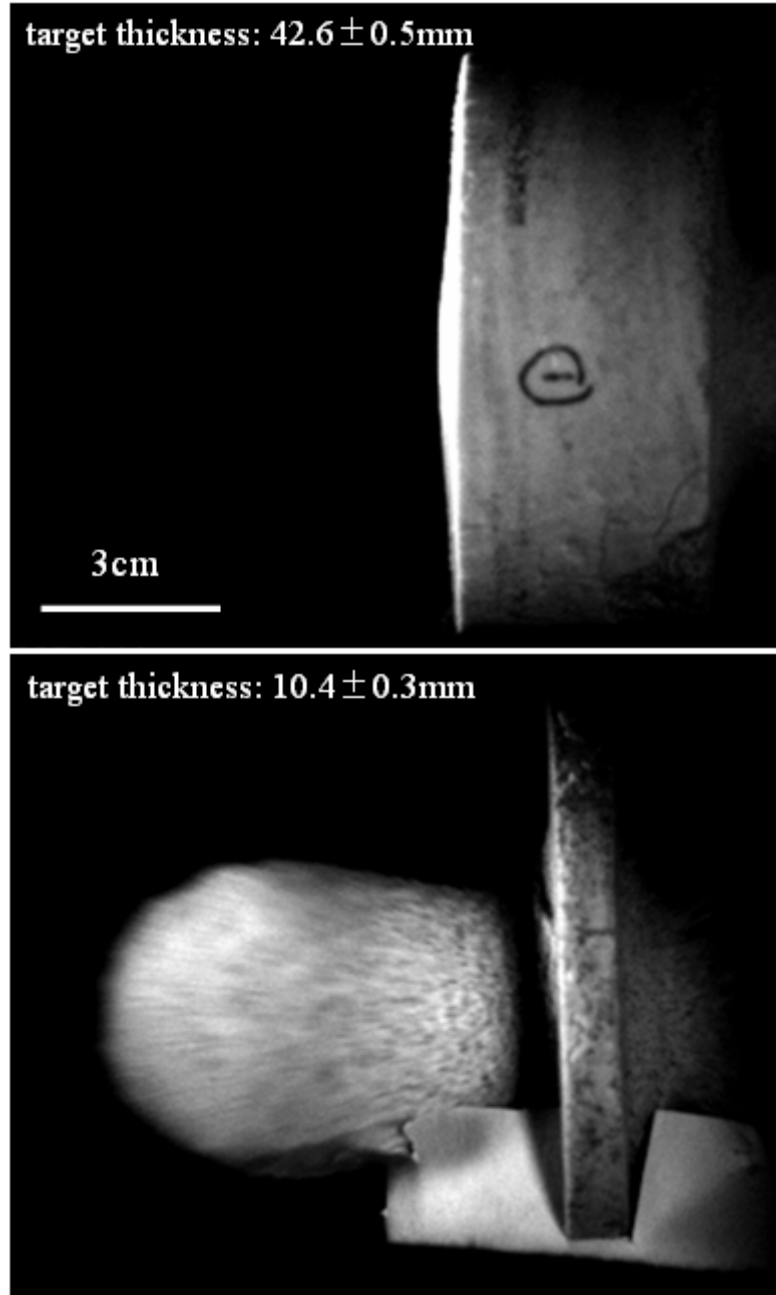


Fig. 3.7. The images of antipodal ejection, which correspond to the 7th frame after the impact. Frame rate was 31000 frames/s. The targets are P35-R25. The impact direction is from right to left.

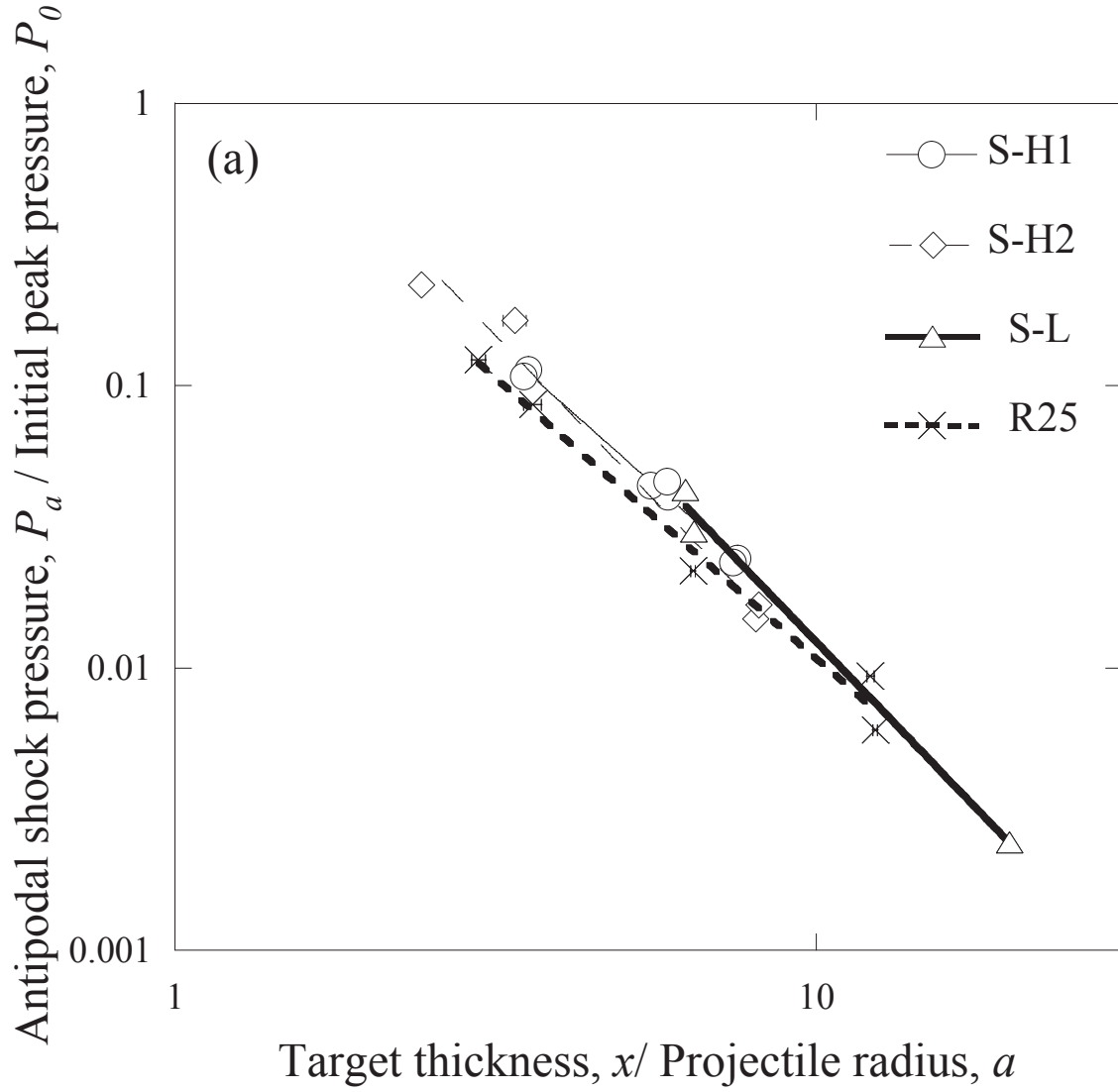


Fig. 3.8 (a). The relation between the target thickness normalized by the projectile radius and the antipodal shock pressure normalized by the initial peak pressure for the results of Setoh et al. (2007), Setoh et al. (private communication) and this study. The symbols represent the target type in Table 3.3. The initial peak pressure of S-L experiments was calculated by Eq. (3.4).

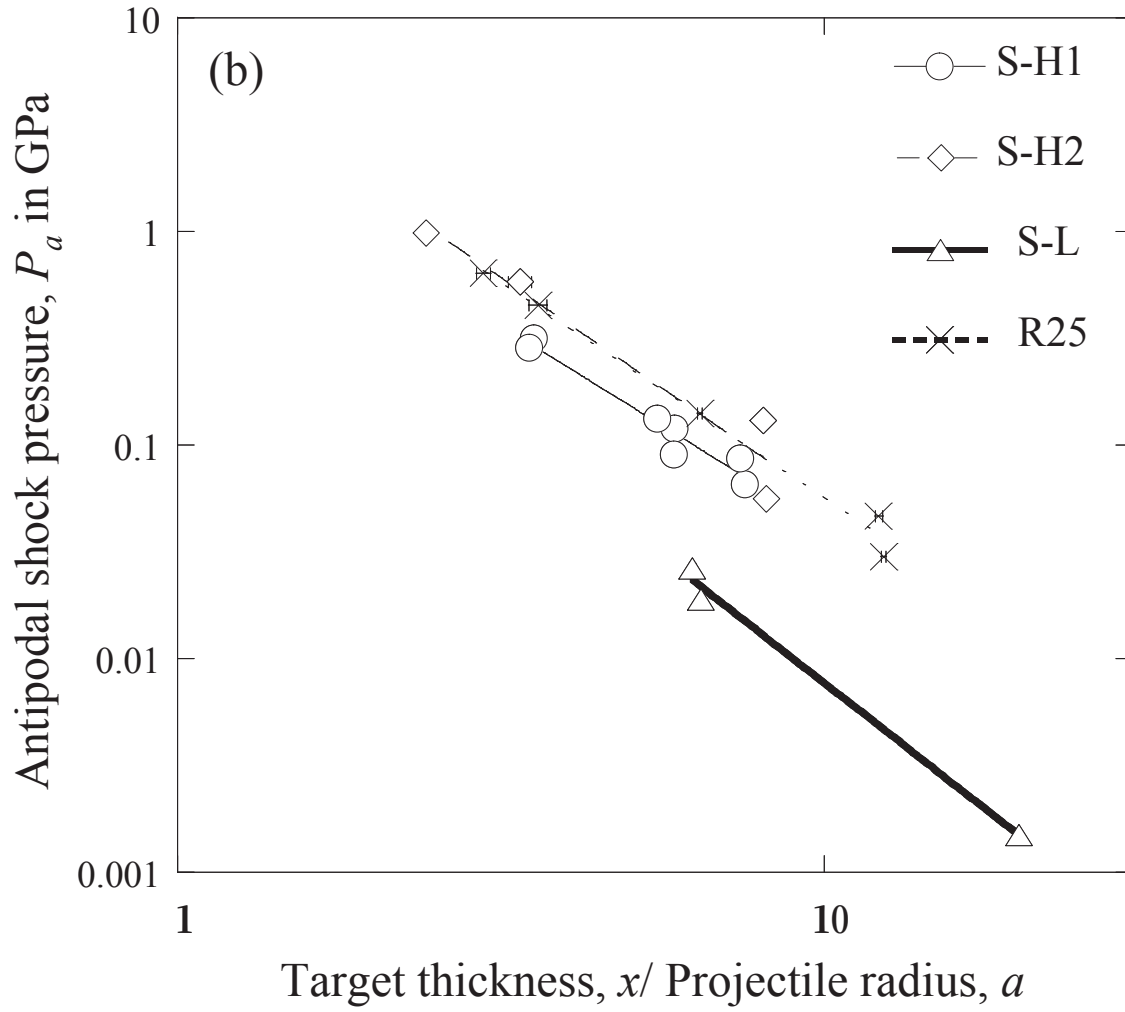


Fig. 3.8 (b). The same as Fig. 3.8 (a), but for the initial peak pressure.

Table 3.3.

Experimental conditions and results of measurements of antipodal ejection velocity

Target type	Silicate content in wt%	Porosity in %	Impact velocity in m/s	Shock attenuation rate, b	Depth of isobaric region, d_i in projectile radius	Longitudinal sound velocity in m/s
S-H1	0	40.7 $\pm 1.2^{(1)}$	1700-2100 ⁽¹⁾	2.01 $\pm 0.09^{(1)}$	1.2 $\pm 0.1^{(1)}$	1900 $\pm 160^{(2)}$
S-H2	0	$\sim 32^{(2)}$	1900-3390 ⁽²⁾	2.4 $\pm 0.2^{(2)}$	1.4 $\pm 0.4^{(2)}$	3150 $\pm 20^{(2)}$
S-L	0	40.7 $\pm 1.2^{(1)}$	260 ⁽¹⁾	2.4 $\pm 0.2^{(1)}$	1.6 $\pm 0.4^{(1)}$	1900 $\pm 160^{(2)}$
R25	25	32.2 ± 1.6	2250-2630	1.99 ± 0.14	1.0 ± 0.1	1958 ± 148

⁽¹⁾ Setoh et al. (2007)

⁽²⁾ Setoh et al. (private communication)

The uniaxial compressive strength of S-H2 target was estimated to be about 41MPa.

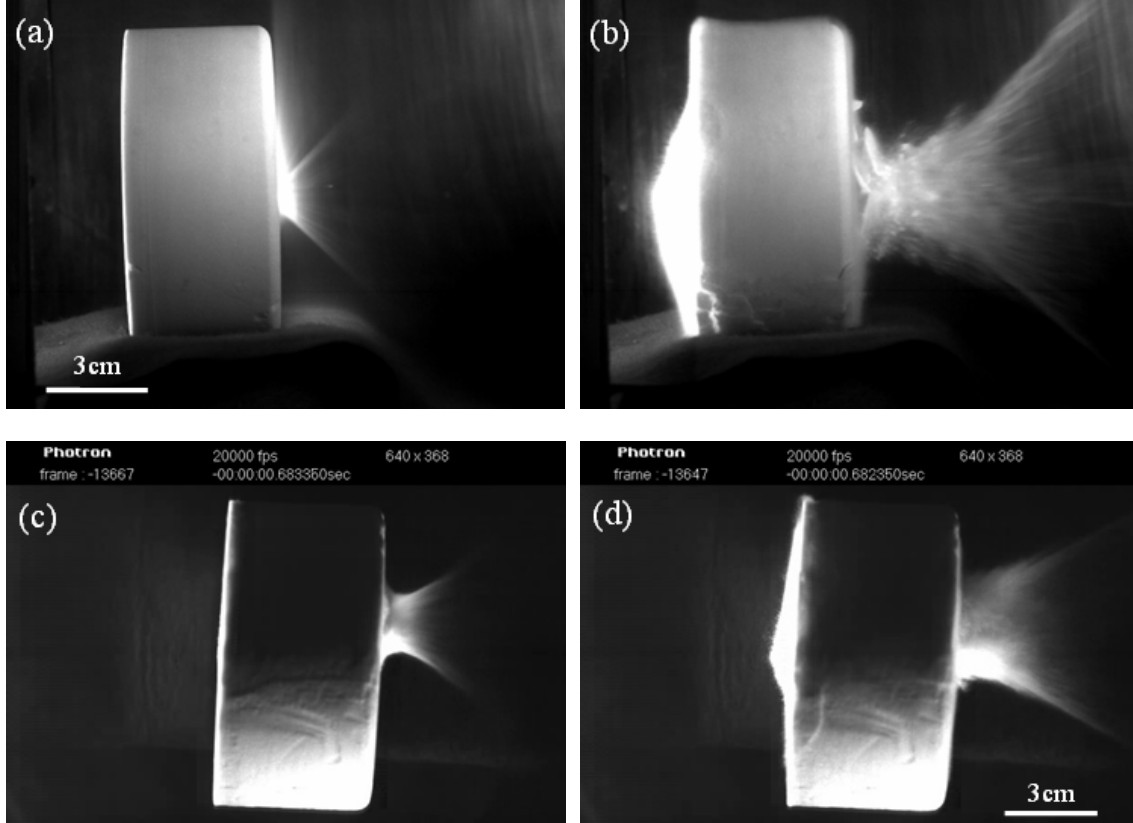


Fig. 3.9. The images of high-speed camera supported by Photron Co., Ltd. of shots 09g3.2 ((a) and (b)) and 19a ((c) and (d)). (a) and (b) were taken from side, and (c) and (d) were taken from upside. The impact direction was from right to left. The frame rate of (a) and (b) was 3000 frames/s and that of (c) and (d) was 20000 frames/s. (a) is the image of impact, and (b) is the image after 1 msec of (a). (c) is the image when the shock wave arrived at the antipodal surface, and (d) is the image after 1 msec of (c).

3.4.3. Estimation of the depth of the isobaric region

In our impact cratering experiments, different materials were used as projectiles. Thus, the depth of the isobaric region for each projectile material has been investigated. In this study, we estimate the depth of the isobaric region by using the antipodal ejection velocity that was measured in each impact cratering experiments. At first, we measure the antipodal ejection velocity in order to estimate the antipodal shock pressure. Assuming that the shock attenuation rate is constant, the depth of the isobaric region can be calculated using the following equation, which is derived from Eq. (3.1),

$$d_i = x \left(\frac{P_a}{P_0} \right)^{1/b}. \quad (3.7)$$

In this equation, the propagation distance, x is the target thickness in our impact cratering experiments, and for the shock attenuation rate, b , the values of Section 3.2.2 are used.

Fig. 3.9 shows the antipodal ejection in the impact cratering experiments corresponding to shot no. 09g3.2 and 19a. The measured antipodal ejection velocities are listed in Table 3.4. The relation between the ratio of projectile to target density, and the depth of the isobaric region is shown in Fig. 3.10.

Table 3.4.
Antipodal ejection velocity, estimated antipodal shock pressure and depth of the isobaric region

Shot no.	Target type	Target thickness in cm	Antipodal ejection velocity, V_a in m/s	Used shock attenuation rate, b	Antipodal shock pressure, P_a in MPa	Depth of isobaric region, d_i in projectile radius, a
01s	P35-R0	4.86 ±0.04	7.7 ±0.2	2.01 ±0.09	13.1 ±0.4	1.7 ±0.3
02s	P35-R0	4.98 ±0.04	7.7 ±0.2	2.01 ±0.09	13.2 ±0.4	1.8 ±0.3
03s	P35-R0	^a	^a	-	-	-
04s	P35-R12.5	4.59 ±0.04	6.6 ±0.3	1.99 ±0.14	10.7 ±0.7	1.5 ±0.4
05s	P35-R12.5	4.25 ±0.04	7.6 ±0.3	1.99 ±0.14	12.2 ±0.7	1.5 ±0.4
06s	P35-R25	4.25 ±0.04	7.0 ±0.3	1.99 ±0.14	12.5 ±1.1	1.6 ±0.4
07s	P35-R25	4.71 ±0.04	7.1 ±0.3	1.99 ±0.14	12.7 ±1.1	1.6 ±0.4
08g3.2	P35-R0	4.72 ±0.04	16.8 ±0.3	2.01 ±0.09	28.6 ±0.7	1.9 ±0.2
09g3.2	P35-R0	4.60 ±0.04	18.1 ±0.3	2.01 ±0.09	30.8 ±0.7	1.7 ±0.2
10g3.2lp	P35-R0	^a	^a	-	-	-
11g3.2lp	P35-R0	^a	^a	-	-	-
12g3.2	P35-R12.5	4.64 ±0.04	20.0 ±0.5	1.99 ±0.14	32.2 ±1.5	1.5 ±0.3
13g3.2	P35-R12.5	4.60 ±0.04	12.4 ±0.5	1.99 ±0.14	20.0 ±1.1	1.7 ±0.3
14g3.2	P35-R25	4.45 ±0.04	13.9 ±0.5	1.99 ±0.14	25 ±2	1.4 ±0.3
15gl	P35-R25	^a	^a	-	-	-
16gl	P40-R0	^a	^a	-	-	-
17gl	P40-R0	4.81 ±0.05	2.4 ±0.3	2.01 ±0.09	2.3 ±0.4	1.9 ±0.4
18a	P40-R0	^a	^a	-	-	-
19a	P40-R0	5.22 ±0.05	6.6 ±0.6	2.01 ±0.09	6.3 ±0.9	1.8 ±0.3
20a	P40-R0	3.91 ±0.05	8.1 ±0.4	2.01 ±0.09	7.7 ±0.9	1.5 ±0.3
21n	S-H2	^b	^b	-	-	-
22n	S-H2	^b	^b	-	-	-
23n	S-H2	2.85 ±0.01	21.2 ±0.2	2.4 ±0.2	56 ±2	-

Note. ^a and ^b mean that we could not measure the value because the antipodal surface was not observed by high-speed camera, and no antipodal ejection occurred, respectively.

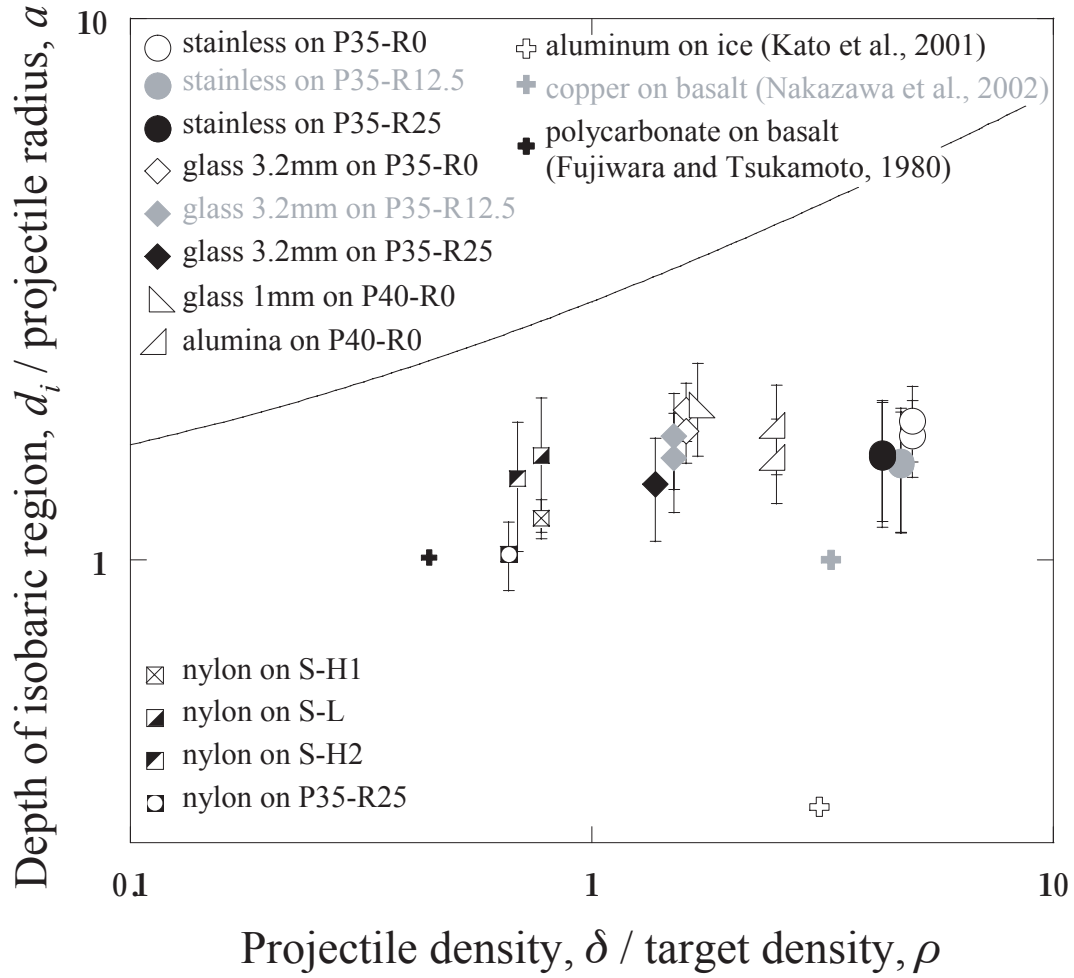


Fig. 3.10. The relation between the ratio of projectile to target density, and the depth of the isobaric region normalized by the projectile radius. The dashed-line is the value of Melosh (1984), which is Eq. (3.2) plus the projectile radius. The depth of the isobaric region of Fujiwara and Tsukamoto (1980) is assumed as a projectile radius.

The depth of the isobaric region seems to be independent on the density ratio of projectile to target. This tendency is also seen in the experiments in basalt targets. This result is consistent with the conclusion of Nakazawa et al. (2002); the depth of the isobaric region is controlled by the rarefaction wave. Thus, for sintered glass beads-silicate mixtures, the depth of the isobaric region is also controlled by the rarefaction wave. From the crush curve of glass beads, 40% porosity is almost closed packed structure, and the glass beads are only collapsed near the initial peak pressure because of the high strength of glass beads (see Appendix II).

3.4.4. Scaling of the crater depth

In this section, we scale the crater depth by using Eq. (3.3) and the values listed in Table 3.2 and 3.4. For the crater depth whose depth of isobaric region was not obtained in Table 3.4, the average value for the same type of target and projectile is adopted. Fig. 3.11 is the scaling result for our crater depth.

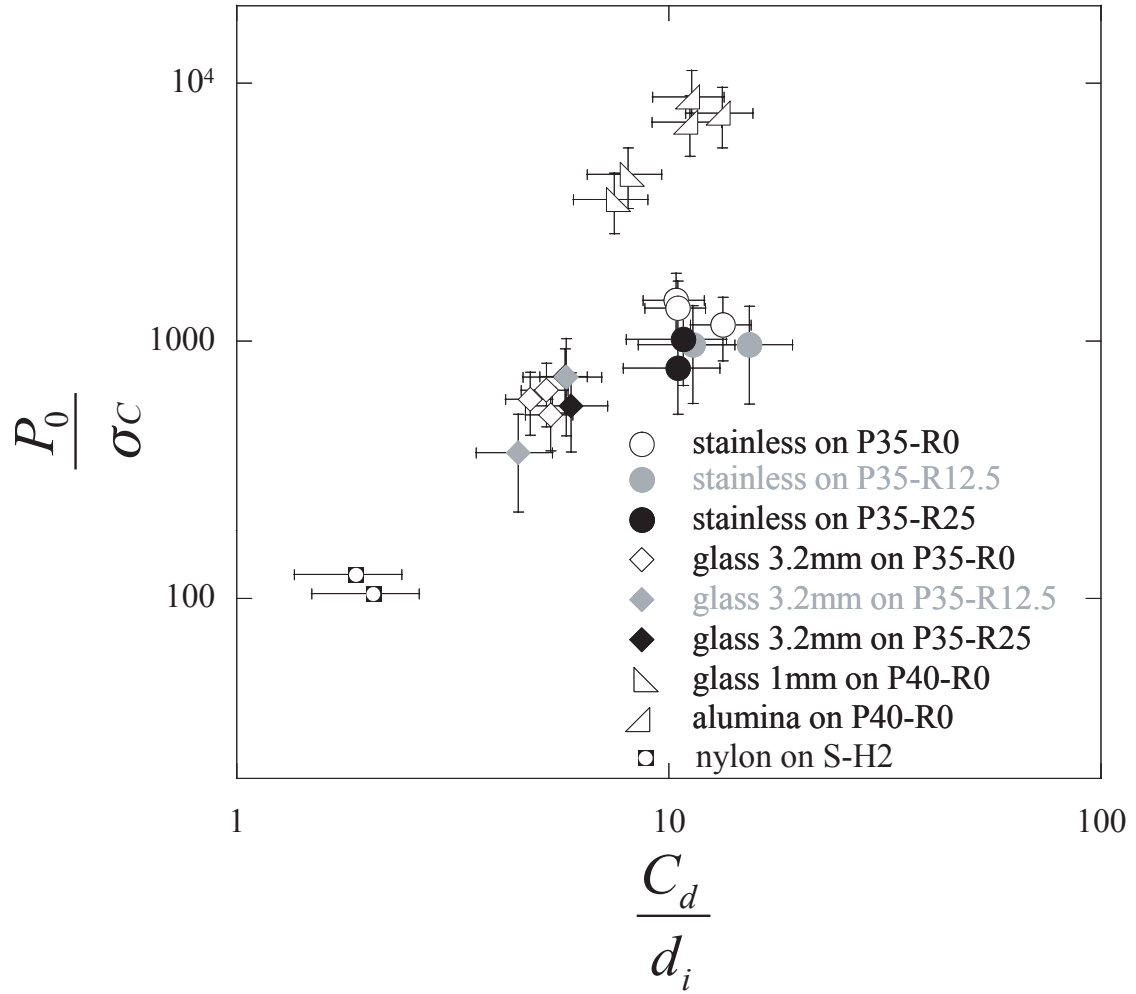


Fig. 3.11. The relation between the crater depth, C_d on ice normalized by the depth of the isobaric region, d_i and the initial peak pressure, P_0 normalized by the uniaxial compressive strength, σ_c . The result from shot 22n is not shown because the exact impact velocity was not measured.

Fig. 3.12 shows the scaling results with previous works. Previous impact cratering experiments on sintered glass bead targets were performed by 1.6mm glass projectiles (Love et al., 1993) and about 1mm alumina projectiles (Michikami et al., 2007). Thus, the values of the depth of the isobaric region for each projectile are $1.8 \pm 0.3 a$, where a is the projectile radius, which is the average for 3.2mm glass projectile on P35-R0 target and 1mm glass projectile on P40-R0 target, and are $1.7 \pm 0.3 a$, which is the average for the about 1mm alumina projectile on P40-R0 target. Since the lowest and highest porosities in both works, which are about 6% and 60%, respectively, differ greatly from our target porosity (32 to 40%), the scaling was not performed.

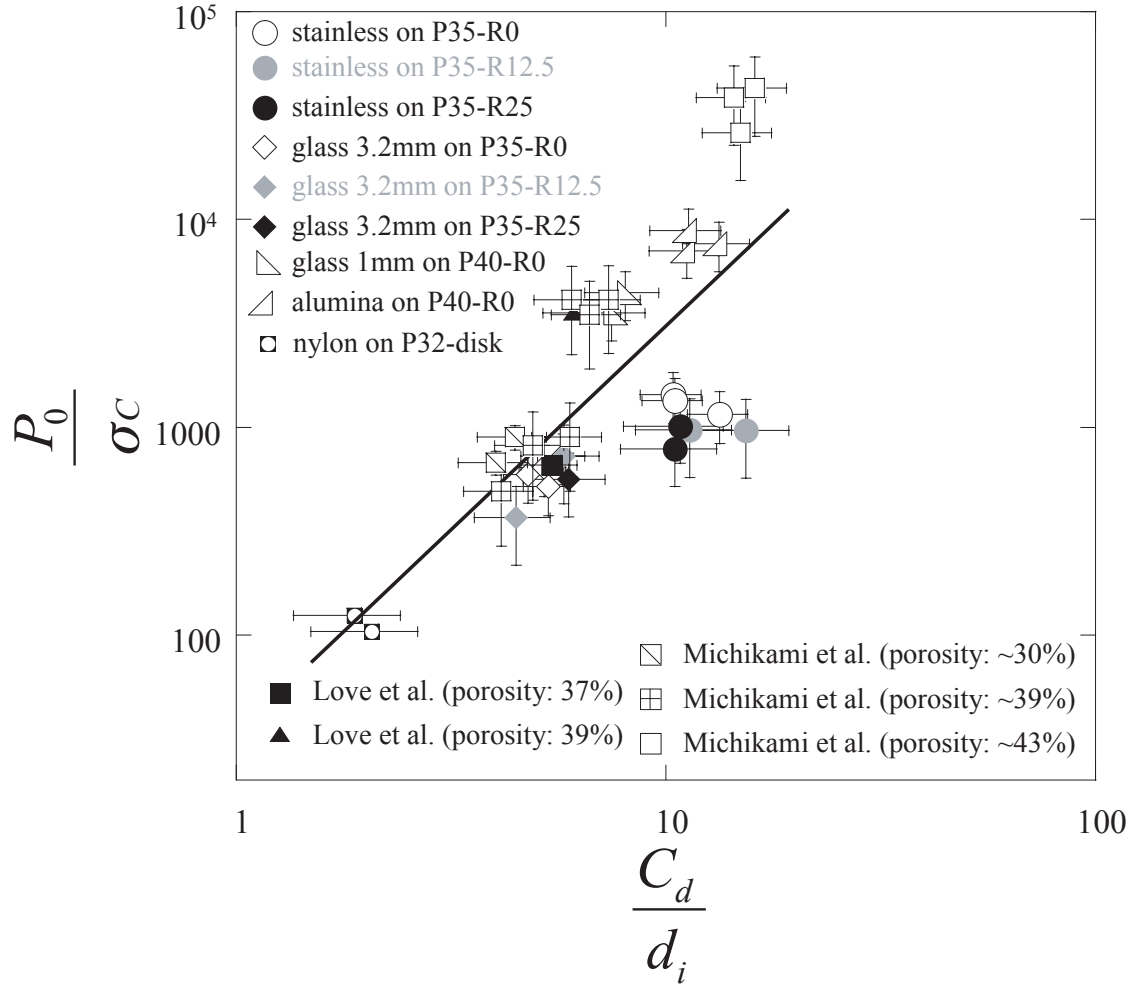


Fig. 3.12. The relation between the crater depth, C_d on ice normalized by the depth of the isobaric region, d_i and the initial peak pressure, P_0 normalized by the uniaxial compressive strength, σ_c , compared with previous impact cratering experiments on sintered glass bead targets. The target porosities of previous works are indicated.

The fitting curve for all plots in Fig. 3.12 is,

$$\frac{P_0}{\sigma_c} = 31 \pm 20 \left(\frac{C_d}{d_i} \right)^{2.0 \pm 0.3}. \quad (3.8)$$

Since the slope of Eq. (3.8) corresponds to the shock attenuation rate, this scaling is consistent with the measurements of shock attenuation rate and with the scaling for ice targets (Fig. 3.1). However, the fitting coefficient is 0.68. Therefore further investigations of shock propagation in porous targets are required to confirm these results.

3.4.5. Implication for the crater depth on small bodies and future work

In order to apply Eq. (3.8) to the crater depth on small bodies, further investigations of the dependence of the depth of the isobaric region and of the shock

attenuation rate on both target and projectile properties are required. Porous structure is common in the small bodies in the solar system, and the shock attenuation rate of porous and weak targets was reported as above 3 (Yanagisawa and Itoi, 1994). When a porous target consists of weak grains, the depth of the isobaric region and the shock attenuation rate are likely larger than those found in this study. If the depth of the isobaric region can be expressed as a function of the projectile radius, the relation between the projectile radius and the uniaxial compressive strength of the target is obtained from the crater depth on small bodies made in the strength regime by assuming the initial peak pressure and varying the shock attenuation rate. The initial peak pressure is estimated from surface materials and porosity, using some assumptions for the impact velocity and projectile material.

When experiments like Deep Impact mission are performed in the strength regime, the shock attenuation rate and the uniaxial compressive strength of the target surface can be estimated by measuring the crater depth because the projectile radius and impact velocity are known. Thus, it is necessary to measure the crater depth made by Deep Impact-like mission to estimate the surface properties by using Eq. (3.8).

In order to investigate the dependence of the depth of the isobaric region on both target and projectile properties, recovered projectiles are probably helpful. Figs.3.13 show the projectiles before impact and the recovered projectiles, and the cross-sectional view of the recovered projectile. The recovered projectile is attached to the target glass beads because of impact heating. The shapes of both the recovered glass and alumina projectiles are similar. On the other hand, that of stainless projectiles is more crushed than others. This may be caused by the difference in the kind of projectile material, brittle or ductile. The ratio of height to width of the recovered projectile is about 1.1 for the alumina projectile and 0.9 for the glass projectile. This difference perhaps corresponds to that of the depth of the isobaric region produced by these projectile materials. However, there is no striking difference in Fig. 3.10.

Since the antipodal ejection was affected by the impact angle in Fig. 3.2, the shock wave propagation in the radial direction from point source should be different from that in the direction normal to the impact direction. Thus, for the scaling of the crater diameter by using an equation similar to Eq. (3.8), the shock propagation to radial direction from the point source has to be studied.

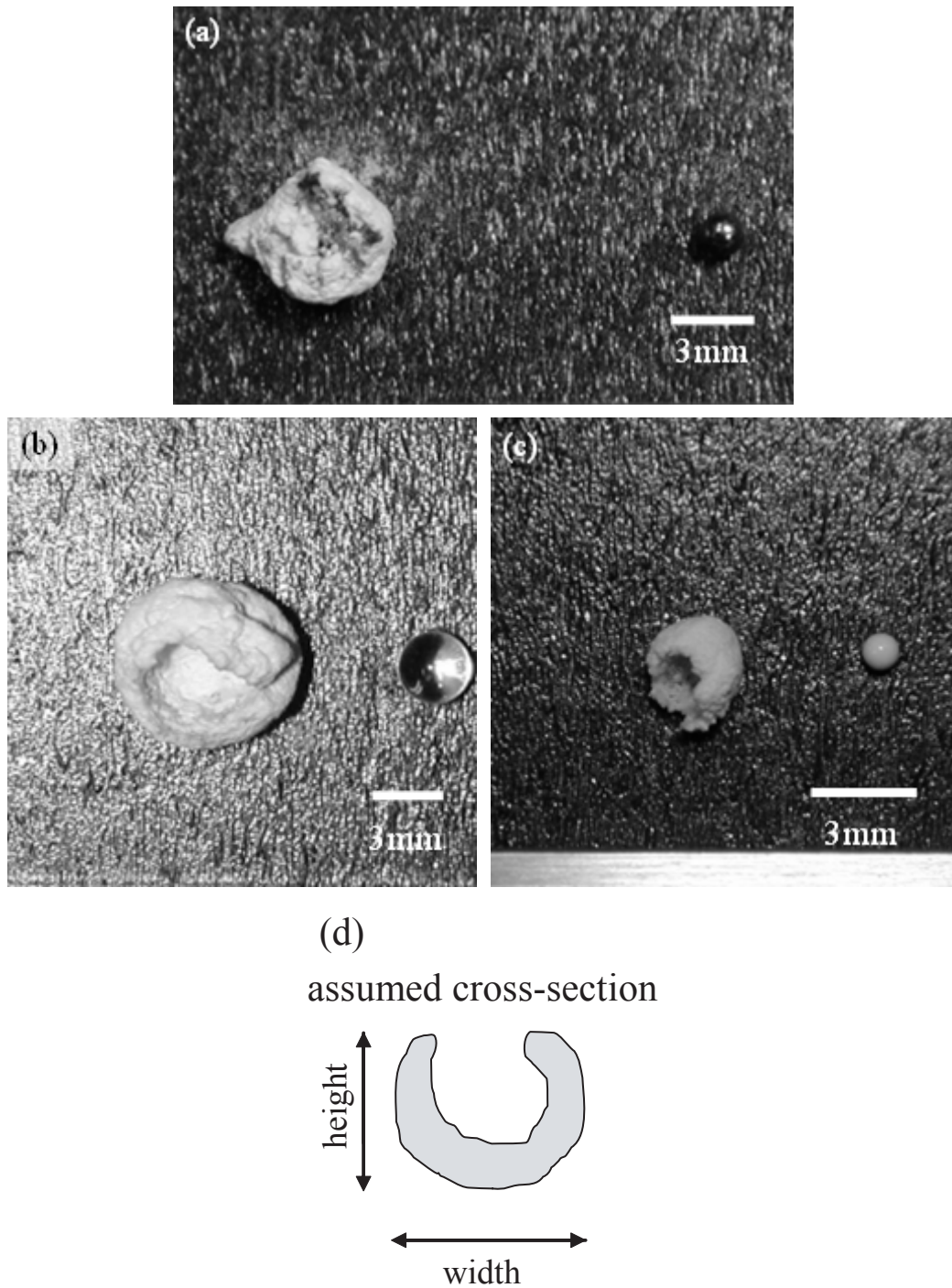


Fig. 3.13. A typical recovered projectile (left in each figure) and the same projectile before impact (right in each figure) in shots (a) 02s, (b) 11g3.2lp and (c) 19a, respectively. The glass beads of the target attach with the recovered projectiles. (d) A schematic view of the geometric of cross-section of the recovered projectile.

4. General Summary

Impact cratering experiments were performed on ice-silicate mixtures and sintered glass beads-silicate mixtures. In order to investigate the cratering process in the strength regime, target strengths and the shock attenuation rate in the targets were measured.

The uniaxial compressive and tensile strengths of ice-silicate mixtures were measured by uniaxial compressive and Brazilian tests, respectively, in a cold room (263K) at Hokkaido University. The shear strength was then estimated from these measurements. It was found that those strengths increase with silicate content. However, the gradient of increase of the uniaxial compressive strength is different from that of the tensile strength and eventually, the difference between both strengths decreases with the increase of silicate content up to 50wt%.

Impact cratering experiments on ice-silicate mixture targets were performed in the cold room at Hokkaido University. The decrease of crater volume with increasing silicate content in the target was visible in the results from the two-stage light gas gun experiments, as expected from the increase of the target strength with the silicate content. It was also found that the uniaxial compressive strength, and not the tensile and shear strengths, controls the crater depth. As for the crater diameter, it was found that the tensile strength has the major role in its determination. Indeed, the relation between the normalized crater diameter and the normalized tensile strength is not sensitive to the silicate content of the target.

The shock attenuation rate in sintered glass beads-silicate mixtures was estimated by the measurements of the antipodal ejection velocity and its variation with the target's thickness in a first set of experiments. Those experiments were performed on sintered glass beads-silicate mixtures using the two-stage light-gas gun installed at JAXA/ISAS and nylon sphere projectiles, and the gas gun installed at Kobe University and glass sphere projectiles. Another set of impact cratering experiments using the two-stage light-gas gun was then performed. Stainless, glass and alumina spheres were used as projectiles in order to change the shock pressure and compare with the previous works. The depth of the isobaric region, which depends on the projectile's material, was estimated by measuring the antipodal ejection velocity for each projectile material and by using the shock attenuation rate measured in the first set of experiments.

It was found that the shock attenuation rate was almost independent on the silicate content in the target. Although the depth of the isobaric region is predicted to correlate with the density ratio between the target and projectile materials, such correlation was not found in these experiments. The relation between the normalized crater depth and the normalized initial peak pressure is fitted by the same curve as that found in previous experiments on ice. However, the fitting coefficient is not particularly good. Thus, for the scaling of the crater depth, further investigations of the shock pressure propagation are required.

For the scaling of the crater diameter, the shock propagation to radial direction

from point source has to be studied. Since the antipodal ejection was affected by the impact angle, the shock wave propagation in the radial direction from the point source should be different from that in the direction normal to the impact direction.

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Appendix I

A.1. Estimation of initial peak pressure

The peak pressure (P) for each impact is estimated as done by Kani et al. (1991). We used the Hugoniot data of dunite, nylon, stainless and alumina in Marsh (1980), serpentine in Tybruczy et al. (1991), and ice in Stewart and Ahrens (2003). For soda lime glass, Hugoniot data of Kobayashi et al. (1997) was used. The data was listed in Table A1.1. When the data of exact material which was used in the experiments was not found in the references, the closest data in the references was used. For example, the data of steel 304 and corundum was used for the stainless and alumina, respectively. Thus, the bulk densities in Table A1.1 for each material do not correspond to that used in the experiments. The Hugoniot for mixture target is obtained from the following equation (Munson and Schuler, 1971);

$$\frac{1}{U_s} = \sum \frac{\alpha_n}{U_n}, \quad (\text{A1.1})$$

where α_n , U_s and U_n are the volume fraction of the n -th constituent, the shock wave velocity in the mixture target and in the n -th constituent, respectively. The correction for porosity is estimated by the following equation (McQueen et al., 1970),

$$P = P_H \frac{2 - \rho\gamma(V_0 - V)}{2 - \rho\gamma(V_0^* - V)}, \quad (\text{A1.2})$$

where P and V are respectively the pressure and the specific volume of the porous material; P_H is the pressure after the passage of the shock front; V_0 and V_0^* are the initial specific volume of the solid and the porous material respectively; ρ is the density of the solid material; γ is the Grüneisen parameter. This equation is derived from Mie-Grüneisen equation.

Fig. A1.1 shows a Hugoniot curve for a porous material (initial specific volume V_0^*) along with the Hugoniot curve for the same material without pores (initial specific volume V_0). At same specific volume, the pressure for the porous material is always higher than that of the dense material. We can calculate this pressure gap by Eq. (A1.2). Thus, the pressure in a porous material at a specific volume that is smaller than the initial specific volume of the dense material cannot be estimated by Eq. (A1.2).

Note that for highly porous materials this correction is valid only for higher pressures. For example, a pressure higher than about 2GPa can be estimated by Eq. (A1.2) for SiO_2 target whose porosity is 65% (Borg et al., 2005). The Grüneisen parameter of mixture targets is calculated from the following equation (McQueen et al., 1970),

$$\frac{1}{\rho\gamma} = \sum \frac{\alpha_n}{\rho_n\gamma_n}, \quad (\text{A1.3})$$

where ρ_n and γ_n are respectively the density and the Grüneisen parameter of the n-th component. We used the Grüneisen parameter of ice, serpentine and soda lime glass in Hobbs (1974), Tybruczy et al. (1991) and Padmaja (1996) respectively. The Grüneisen parameters for each material are summarized in Table A1.1. Since the value for dunite was assumed to be almost same with that for serpentine, the initial peak pressure is not sensitive to the value of Grüneisen parameter in our experimental conditions.

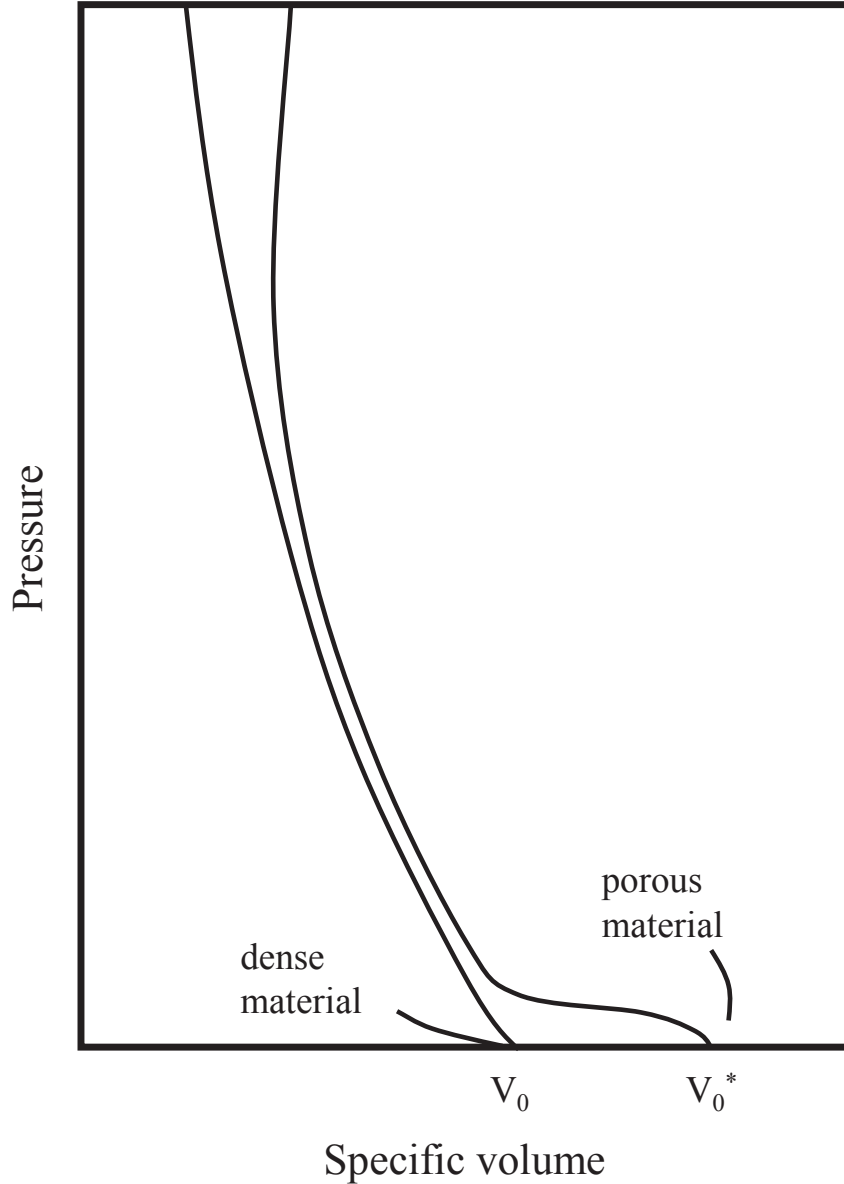


Fig. A1.1. Hugoniot curve for a porous material (initial specific volume V_0^*) along with the Hugoniot curve for the same material without pores (initial specific volume V_0).

Table A1.1.
Hugoniot data and Grüneisen parameter of each material

Material	Bulk density in kg/m ³	Bulk sound velocity, C in m/s	$s^{(1)}$	Particle velocity, u_p range in m/s	Grüneisen parameter, γ
Ice	910	3610 $\pm 61^{(2)}$	0.92 $\pm 0.63^{(2)}$	0 - 175 ⁽²⁾	$\sim 0.5^{(3)}$
		388 $\pm 78^{(2)}$	2.61 $\pm 0.14^{(2)}$	275 - 1025 ⁽²⁾	
		1200 $\pm 140^{(2)}$	1.46 $\pm 0.11^{(2)}$	775 - 1715 ⁽²⁾	
Serpentine	2500 ⁽⁴⁾	5290 $\pm 170^{(4)}$	0.78 $\pm 0.10^{(4)}$	400 - 3000 ⁽⁴⁾	0.63 ⁽⁴⁾
Nylon	1150 ⁽⁵⁾	3350 $\pm 90^{(5)}$	1.32 $\pm 0.03^{(5)}$	760 - 5100 ⁽⁵⁾	
Soda lime glass	2500	140 $\pm 21^{(6)}$	1.92 $\pm 0.05^{(6)}$	3200 - 4600 ⁽⁶⁾	$\sim 0.63^{(7)}$
Dunite	3320 ⁽⁵⁾	6600 $\pm 82^{(5)}$	0.76 $\pm 0.04^{(5)}$	720 - 3426 ⁽⁵⁾	0.6 ⁽⁸⁾
Steel 304	7890 ⁽⁵⁾	4580 $\pm 10^{(5)}$	1.49 $\pm 0.01^{(5)}$	230 - 2770 ⁽⁵⁾	
Corundum, Al ₂ O ₃	3740 ⁽⁵⁾	6610 $\pm 160^{(5)}$	1.35 $\pm 0.07^{(5)}$	1000 - 3300 ⁽⁵⁾	

⁽¹⁾ The shock wave velocity, U is expressed by $U = C + su_p$.

⁽²⁾ Stewart and Ahrens (2003)

⁽³⁾ Hobbs (1974)

⁽⁴⁾ Tybruczy et al. (1991)

⁽⁵⁾ Marsh (1980)

⁽⁶⁾ Kobayashi et al. (2007)

⁽⁷⁾ Padmaja (1996)

⁽⁸⁾ Grüneisen parameter of dunite was not found in the reference. Thus, it was assumed to be 0.6.

Appendix II

A.2. Measurements of the crush curve

In order to investigate the effect of the target porosity on the disruption, compression tests of porous material are studied. The crush curve is the stress-strain curve of porous material, which is obtained by a compression test when the specimen is confined. The crush curve is used as a fundamental data/input for numerical simulations of impact process on porous bodies.

The crush curves of sintered and non-sintered glass beads were obtained by the compression testing machine installed at Kobe University. The sample was put in a hollow circular cylinder made by stainless and whose inner diameter was 9.95mm. Then the sample was compressed by a stainless cylinder head of 9.95mm in diameter. The loading rate was changed to 0.06 and 6mm/min. The maximum loading pressure was about 125MPa. The porosity of sintered glass beads was $38\pm2\%$, and the uniaxial compressive strength was 13 ± 2 MPa.

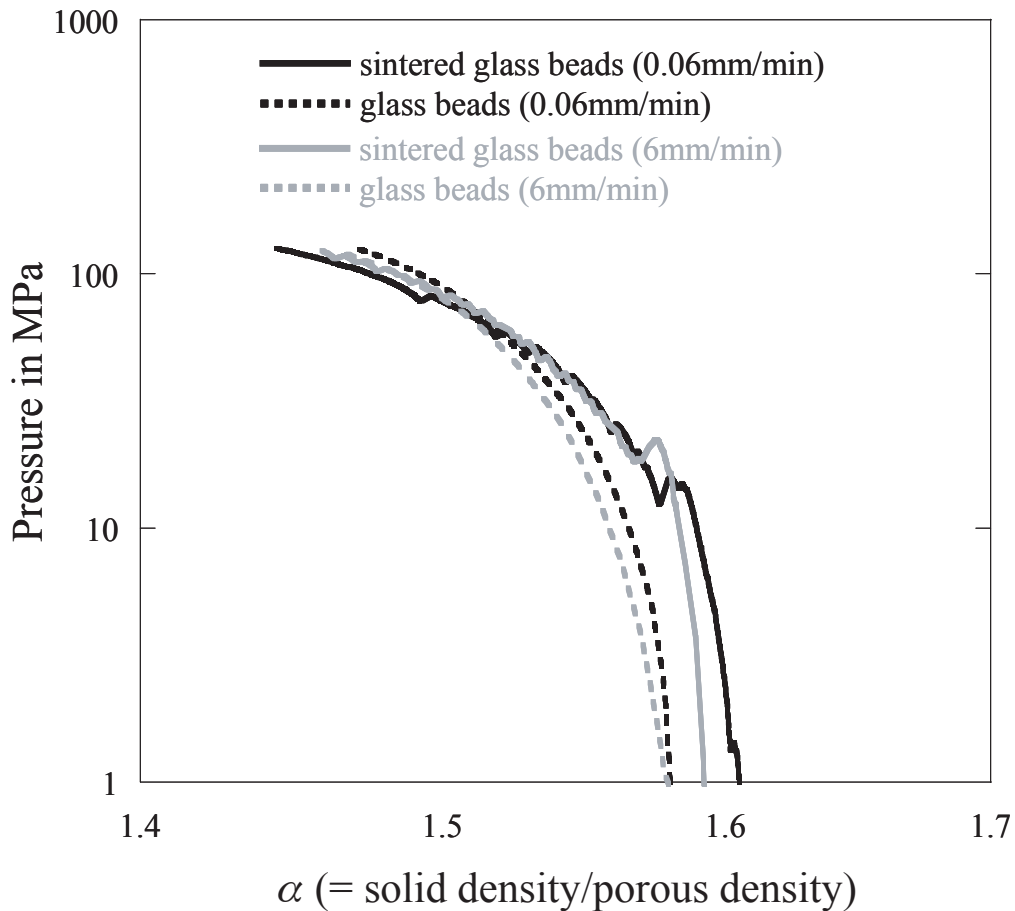


Fig. A2.1. The crush curves of sintered and non-sintered glass beads at loading rates of 0.06 and 6mm/min.

Fig. A2.1 shows the crush curves of sintered and non-sintered glass beads at different loading rates. The horizontal axis shows the ratio between the density of porous material, ρ and that of non-porous material, ρ_s ,

$$\alpha = \frac{\rho_s}{\rho} = \frac{1}{1-p}, \quad (\text{A2.1})$$

where p is the target porosity. The sintered glass-bead samples were compressed elastically at a pressure under the uniaxial compressive strength, and then disrupted at the pressure corresponding to the uniaxial compressive strength. After the disruption, the sintered glass beads were compressed plastically, and the crush curves of the sintered glass beads approach that of the glass beads. The crush curves of the glass beads and the plastic region of the sintered glass beads are independent on the loading rate. The strength of glass beads is about 800MPa, which is much smaller than the maximum pressure of these measurements. In fact, the disrupted glass bead was not confirmed in the sample after the compression test. Thus, the porosity was probably decreased by relocation of glass beads.

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