LABORATORY IMPACT CRATERING ON ICE-SILICATE MIXTURE TARGETS

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ABSTRACT

We performed impact experiments on ice-silicate mixture targets and measured target compressive and tensile strength at low strain rate (~$10^{-3}s^{-1}$) by uniaxial compression and Brazilian tests at 263K. The crater volume decreases with increasing silicate content. Both compressive and tensile strength increase with silicate content, however, tensile strength is more sensitive over wide range of silicate content. We found that the crater depth and the crater diameter are well scaled by the compressive and the tensile strength of the target, respectively. As crater size decreases, the fraction of material ejected by spallation increases. Thus increase of the tensile strength with silicate content is probably the main reason why the crater volume decreases with silicate content.

1. INTRODUCTION

There are many objects with surfaces consisting of water ice in the solar system such as icy satellites and comets. Water ice in the solar system is not pure ice, but mixed with other material (e.g., silicate, NH_3 and CO_2). This is why understanding the impact process of mixtures of ice and other materials is important. In this study, we focus on impact cratering on ice-silicate mixtures.

Previous studies suggest that a crater size decreases with increasing silicate content[1][2]. Reference [2] performed impact cratering experiments on ice-silicate mixture targets. They changed silicate content of target from 5 to 20wt% and impact velocity from about 1km/s to 10km/s. They found the crater volume decreased with increasing silicate content (see Fig. 9 in [2]). Because the data of crater volume of 5wt% silicate content was very scattered, they decided this tendency with the results of 0, 10 and 20wt%. The reason of this tendency is not understood. Reference [3] estimated the dynamic tensile strength of ice and ice-silicate mixture at high strain rates of about 10^4s^{-1}. They concluded that ice had a tensile strength of about 17MPa, and ice-silicate mixtures with 5 and 30wt% silicate content had strengths of about 20 and 22MPa, respectively. From this study we qualitatively expect that increase of target strength with silicate content explains why the crater volume decreases with silicate content. However, the strength of ice-silicate mixtures would depend on the particle size and the kind of silicate, and other experimental conditions. Thus it is necessary to measure the strength of the target used in impact cratering.

We performed impact experiments on ice-silicate mixtures and measured the target strength. Silicate content of the targets was varied from 0 to 50wt%.

2. EXPERIMENTS

2.1 Impact cratering on ice-silicate mixture targets

The experiments were performed in a cold room (263K) at Institute of Low-Temperature, Hokkaido University, Japan. Cylindrical projectiles (pure ice, 15mm in diameter, 10mm in height and 1.6g in weight) were used for gas gun and corn shaped projectiles (nylon, 1mm and 2mm in diameter, 2.5mm in height and 7mg in weight) for the two-stage light-gas gun. The range of impact velocity was from 299 to 657m/s and from 1,480 to 3,684 m/s, respectively. The silicate content was changed from 0 to 50wt%. The powder of serpentine was used. The porosity of our target was estimated to be about 10%. The diameter of serpentine was several μm in most of the experiments. In order to investigate the effect of the difference of size of silicate powder, we made three targets of 50wt% silicate content with powders of about 200-500μm in diameter. No difference due to the diameter of silicate grain was found for any results. Detail of our impact experiments is described in our previous paper[4].

2.1 Measurement of target strength

The cratering in the strength regime continues until the target strength becomes higher than stress caused by impact, which propagates from impact site with attenuation. A compressive wave caused by impact excavates the target, and this process makes a central pit. Thus, a crater depth would depend on compressive strength. The compressive wave reflects as a tensile wave at the target surface, which detaches the surface and it is called “spallation”. Spallation determines crater diameter. Thus, a crater volume probably depends on both compressive and tensile strength.

Accordingly, we measured the target compressive and tensile strength at low strain rate (~$10^{-3}s^{-1}$) by uniaxial compression and Brazilian test[5]. We performed the experiments in the cold room (263K) in the Institute of Low-Temperature, Hokkaido University. Ice-silicate mixture samples were prepared in cylindrical sample cases by following the same steps of the procedure in the impact experiments[4]. The porosity of samples was estimated to be about 10%. The silicate content of most of the samples was serpentine powders with typical diameter of several μm similar to the powder used in cratering experiments. We used two other kinds of powders for comparison that were coarse serpentine and dunite powders. These powders were about 200-500 μm in diameter. The test specimens were 32mm in diameter and 43-48mm in height for uniaxial compression test, and 20-35mm in height for Brazilian test, respectively. The silicate content of the samples using fine serpentine powder was changed from 0 to 50w% for both tests. For the coarse powder samples, only 50wt% silicate content specimens were prepared. Each strength test was repeated more than three times for the same type of specimens.

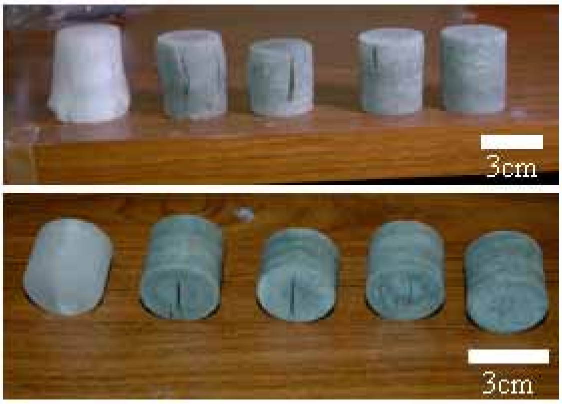

Fig. 1. Samples after uniaxial compression (upper) and Brazilian test (lower). From the left silicate content is 0, 12.5, 25, 37.5 and 50wt%, respectively.

3. RESULTS

3.1 Impact cratering

The crater volume was calculated by dividing the crater weight by the target density. The crater weight was determined by a subtraction of the weight of the post-impacted target from the weight of the pre-impacted target. The crater volume decreases with increasing silicate content. Especially, this tendency is clear for the results of two-stage light-gas gun (Fig. 2). In the range of this kinetic energy, the crater volume is more sensitive to the silicate content than the kinetic energy. The plots of 100wt% in Fig. 2 are the results of serpentine block. The crater volume of 50wt% target is especially smaller than those of the other silicate content. More detail results are described in our previous paper[4].

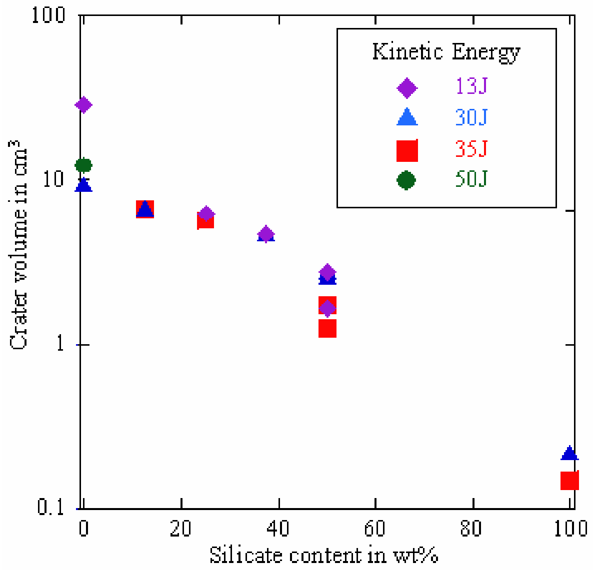

Fig. 2. The relation between the silicate content and the crater volume for the data of the shots by two-stage light-gas gun. The symbols show the kinetic energy of the projectiles.

3.2 Target strength

The results of uniaxial compression and Brazilian test were shown in Fig.3. Both strengths increase with silicate content, although the gradient of increase was steeper for the tensile strength. The compressive strength did not differ among the samples of fine, coarse serpentine, and dunite particles. It drastically increased when a small amount of silicate (less than 12.5wt%) was included and, then, it gradually increased for the wide range of silicate content from 12.5 to 50wt% except for 37.5wt%. The compressive strength of the 37.5wt% silicate content was lower than expected. An irregular deformation was observed for the other silicate content samples and probably related to the scatter in the measured values. The compressive strength of pure ice at 263K[6] was 6.6MPa at lower strain rate ($10^{-4}s^{-1}$). This pure ice sample was made by bubble free, which would explain why its compressive strength was higher than those of our samples.

The tensile strength increased differently with silicate content from the compressive strength. In Brazilian test, the amount of plastic deformation of ice-silicate mixture samples increases with increasing silicate content. Accordingly, the tensile strength of the specimens with higher silicate content might not be measured precisely. Tensile strength of dunite coarse 50wt% samples was smaller than the serpentine fine 50wt%, while the 50wt% coarse serpentine samples continued plastic deformation without fracture. The

present results are lower than the tensile strength of ice at higher strain rate ($1s^{-1}$), which was found 1.6MPa[3], and those of ice-silicate mixtures at much higher strain rate (~$10^4 s^{-1}$), which were 17, 20 and 22 MPa for 0, 5 and 30wt% silicate[3], respectively. This discrepancy is probably due to the higher strain rate.
In general, the ratio of compressive to tensile strength for a brittle material is from about 8 to 20. Thus the present values of the tensile strength were not strange. However, because flat plates were used as loading plates, accurate tensile strength might not be measured[5].

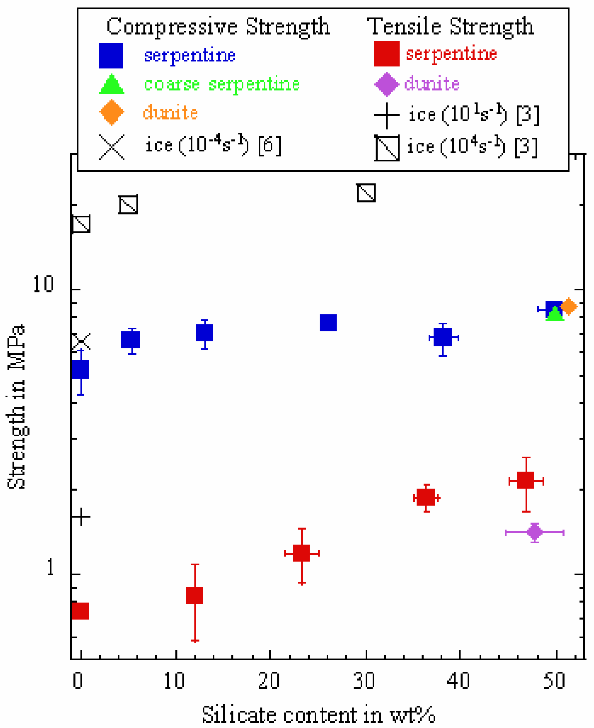

Fig. 3. The relation between the silicate content and the compressive and tensile strength.

4. DISCUSSION
4.1 Crater depth

The initial peak pressure for the mixture targets was calculated[7] using Hugoniot data of ice[8] and serpentine[9]. A value of 6.6MPa[11] is adopted as the compressive strength of the ice specimens.
The crater depth is better scaled by initial peak pressure normalized by the compressive strength than by the tensile strength. However the slope in log-log plot (Fig. 4) becomes shallower at higher peak pressure. This is probably due to higher shock attenuation rate at higher peak pressure[10]. The crater depth found in impact experiments with projectiles of aluminium and polycarbonate[11] are larger than our results and the results of ice-on-ice impact. This is probably caused by the difference of projectile materials.

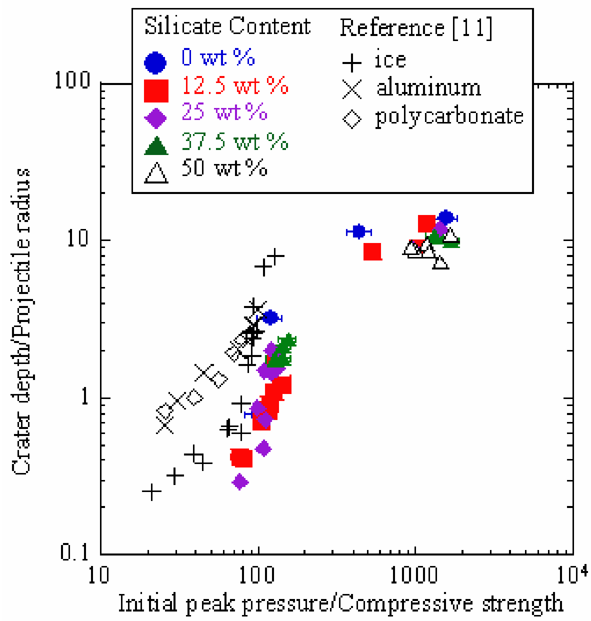

Fig. 4. The relation between normalized initial peak pressure and normalized crater depth. The projectile material of the previous study[11] is shown by different symbols.

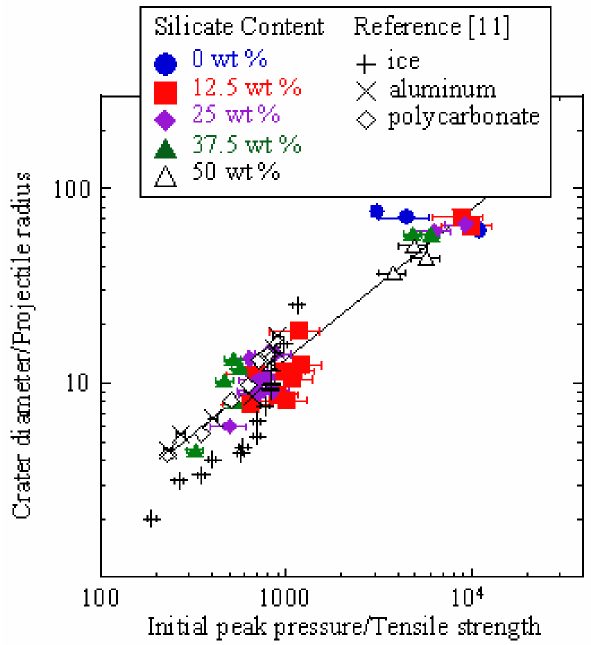

Fig. 5. The relation between normalized initial peak pressure and normalized crater diameter. The projectile material of the previous study[11] is shown by different symbols.

4.2 Crater diameter

The crater diameter is well scaled by initial peak pressure normalized by tensile strength. A least squares fit in Fig. 5 gives

$$\frac{D_c}{a_p} = 0.063 \pm 0.003 \left(\frac{P_i}{Y_T} \right)^{0.78\pm0.04} \qquad (1)$$

where D_c is the crater diameter, a_p is the projectile radius, P_i is the initial peak pressure and Y_T is the tensile strength.
Although the slope in log-log plot of the crater depth becomes shallower at higher peak pressure, the slope of the crater diameter seems almost constant. This probably indicates that the shock attenuation rate in horizontal direction is not sensitive to the initial peak pressure.

4.3 Crater volume

The crater volume is well scaled by initial peak pressure normalized by tensile strength. A least squares fit in Fig. 6 gives,

$$\frac{C_V}{a_p^3} = (1.5 \pm 0.9) \times 10^{-5} \left(\frac{P_i}{Y_T} \right)^{2.3\pm0.1} \qquad (2)$$

where C_V is the crater volume. As crater size decreases, the fraction of material ejected by spallation increases. Thus the crater volume depends on the crater diameter and is controlled by the tensile strength. It is consistent that the slope in Fig. 6 seems constant like the plot of the crater diameter. Increase of the tensile strength with silicate content is probably the main reason why the crater volume decreases with silicate content.

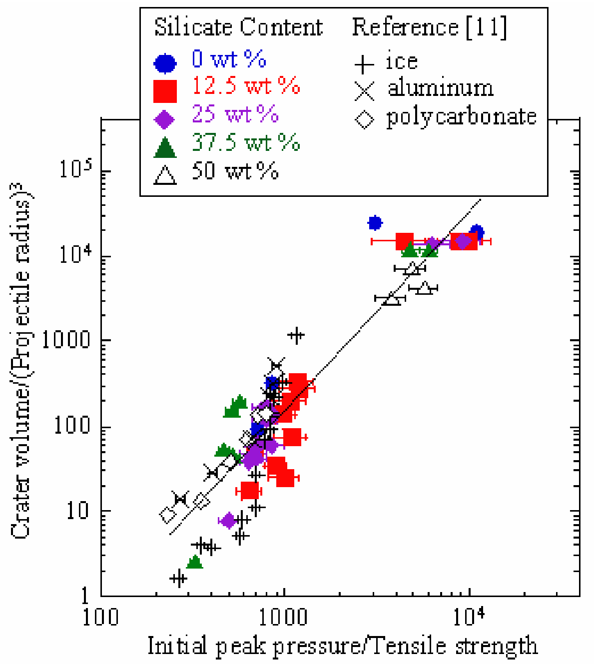

Fig. 6. The relation between normalized initial peak pressure and normalized crater volume. The projectile material of the previous study[11] is shown by different symbols.

5. SUMMARY

We performed impact experiments on ice-silicate mixtures and measured compressive and tensile strength of the targets at low strain rate (~$10^{-3}s^{-1}$). The crater volume decreases with increasing silicate content. We confirm that the tendency, which was also suggested by previous work, continues until 50wt% of silicate content. The compressive and tensile strengths increase with silicate content, although the gradient of increase was different. The compressive strength drastically increased when a small amount of silicate was included and, then, it gradually increased for the wide range of silicate content from 12.5 to 50wt%. The tensile strength increased with almost constant gradient. When we apply these strengths to the results of impact cratering, the crater depth and the crater diameter are well scaled by the compressive and the tensile strength of the target, respectively. The crater volume is well scaled by the target tensile strength. Increase of the tensile strength with silicate content is probably the main reason why the crater volume decreases with silicate content.

6. REFERENCES

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