EFFECTS OF MINOR COMPONENTS ON THE CONSOLIDATION OF PLANETESIMALS AND CHONDRITES

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Abstract: Effects of minor components (ice, serpentine and glass) on the strength of consolidated aggregates (peridotite powder, <500 microns) are investigated by low-velocity impact experiments. The strength is represented by the critical impact velocity at which the largest fragment becomes a half of the original mass. Aggregates without minor components have the critical impact velocity of about 2 m/s. Addition of less than a few weight percent of minor components is insignificant. When aggregates are added with more than 5 wt% ice (at $-22°C$), or with more than about 10 wt% soda glass powder (≤ 74 microns) and heated at 700°C for 15 hours, the critical impact velocity increases to about 9 m/s, which is similar to that of pure ice. Addition of several weight percents of minor components significantly enhances consolidation, when mixtures are heated up to the glass transition temperature of amorphous minor components or the melting temperature of crystalline ones. Dehydration of hydrous minerals is not effective.

1. Introduction

Planetesimals with radii of about several kilometers ($10^{18} \sim 10^{19}$ g) are considered to be formed by gravitational collapse of the dust layer which had been sedimented from the primordial solar nebula (GOLDREICH and WARD, 1973). Chondrite parent bodies, satellites and planets evolved from these planetesimals by mutual collision (SAFRONOV, 1969; HARTMANN, 1978). In the early stage of the primordial solar nebula, collisions of kilometer-size planetesimals occurred probably at speeds less than a few tens of meters per second. HARTMANN (1978) suggested the importance of such low-velocity impacts and carried out experiments to quantify the modes of collision, rebound and fragmentation at low impact velocities (1–50 m/s). The growth process by collisions strongly depends on both impact velocities and mechanical properties of colliding bodies, *i.e.* whether they are rocky, loosely consolidated, or sticky (MARCUS, 1969;

MATSUI and MIZUTANI, 1977; HARTMANN, 1978; GREENBERG et al., 1978). Consolidation degree and fracture strength of colliding planetesimals affect energy balance of the impact process and the internal structure of growing planetoids. Since pressure by their own gravitational potential is very low (about $0.1 \sim 1$ bar) even at the center of planetesimals, these planetesimals are supposed to consist of loosely consolidated aggregates of silicates and other minor components.

Chondrites are obviously lithified to some extent (FUJII et al., 1980, 1981a, b). No significant decrease of porosity is found for oxide and silicate powders by the low-temperature sintering processes, i.e. temperatures lower than $0.8 \ T_m$, where T_m is the melting temperature of silicates (FUJII et al., 1978; HONDA et al., 1979; YOMOGIDA et al., 1980; MATSUI et al., 1980). Loosely consolidated aggregates of silicates need to experience high temperatures near the melting point in order that they become rocky (i.e. melting compaction; FUJII et al., 1978). Otherwise, the size of chondrite parent bodies should be so large that chondrites were compacted by pressures or stresses alone (pressure compaction). However, chondritic meteorites have not experienced widely remelting process nor high static pressure compaction (WASSON, 1974).

The strength of chondrites varies widely from that similar to basalt to that crushable between thumb and fingers (WOOD, 1963). Differences of strength among chondrites as measured by the vibrational fracturing rate indicate that the matrix of Allende (C3) and LL chondrites have strength one order of magnitude lower than that of calcite single crystal. Whereas H and L chondrites except L6 are as strong as basalt which is about one order of magnitude stronger than calcite (FUJII et al., 1980, 1981a, b).

Although the origin and mechanisms of the variation of strength among chondrites remain unsolved yet, several processes are likely to produce such variation under relatively low temperature and pressure conditions. Such processes are grain-to-grain adhesion with sticking materials at grain boundaries (FUJII et al., 1979, 1981b, c, MIYAMOTO et al., 1980b), compaction and loosening by thermal stress within chondrite parent bodies (Y. HAMANO, private communication, 1981; FUJII et al., 1981b, d), and consolidation by impact pounding or implantation of small particles on the surface of parent bodies. Shock and fragmentation histories would also affect the variation of strength among chondrites and planetesimals.

One of the purposes of this study is to evaluate the effects of minor components with some sticking properties such as low melting-temperature material (i.e. ice), volatile-containing material (i.e. hydrous mineral) and amorphous material (i.e. glass) on the consolidation of loosely compacted aggregates. In this study, the strength of aggregates is measured by the degree of fragmentation of projectiles, in low-velocity impact experiments, which is used by HARTMANN (1978).

2. Experimental Procedures

The procedures of low-velocity impact experiment are similar to that reported

by Hartmann (1978). Spherical projectiles of about 1.5 cm in diameter are made from sample powders added with an appropriate amount of water and are left for more than half a day under various temperature conditions. Samples are made of mixtures of peridotite powder (Horoman, Hokkaido) added with various amounts of minor components. Peridotite powder is composed of grains with 23 wt% of 500–250 microns, 44 wt% of 250–74 microns and 33 wt% of less than 74 microns. Four different minor components are chosen, i.e. H_2O (ice), serpentinite powder (Ohtoyo, Kochi Pref.) of less than 250 microns, albite composition glass powder of less than 250 microns, and soda glass powder of less than 74 microns. These samples will be abbreviated in the present paper to $Ol+H_2O$, $Ol+serp$, $Ol+Ab$ and $Ol+soda$, respectively.

$Ol+H_2O$ projectiles with 1, 2, 5 and 10 wt% H_2O are frozen at $-22°C$ and used within a few seconds after taken out of a freezer. $Ol+serp$ projectiles with 0, 2, 5 and 10 wt% serpentinite are heated at 200°C and 700°C for 12 to 15 hours in atmospheric condition. $Ol+Ab$ projectiles with 2, 5 and 10 wt% albite glass are heated at 700°C. $Ol+soda$ projectiles with 5, 10 and 20 wt% soda glass are heated at 550°C and with 20 wt% soda glass are heated 500, 550, 600 and 700°C for 15 hours in atmospheric condition. Then the projectiles dropped in air onto a smooth, flat surface of a large steel block at room temperature.

Weights of the original spherical projectile and of the largest fragment after low-velocity impact experiment are measured. In the case of $Ol+H_2O$ projectiles, each measurement is made within ten seconds in order not to be disturbed by room temperature condition. Estimated porosity of projectiles ranges from about 20% to 35% depending on the grain size distribution, the amount of minor components and the conditions to make spherical projectiles by addition of water.

3. Results and Interpretations

Figures 1a–d show ratios of the weight of the largest fragment after impact experiment to that of the original as a function of impact velocity for $Ol+H_2O$, $Ol+serp$, $Ol+Ab$ and $Ol+soda$ projectiles, respectively. The variation of projectile mass has no significant effect on this diagram. Dotted lines show the results of dirt clods and pure ice reported by Hartmann (1978). The mass ratios of the largest fragment to the original projectiles decrease with increasing impact velocity more abruptly in the present experiments than in Hartmann's (Fig. 1, 1978). This is probably due to geometrical difference of sphericity of the projectiles used in the two experiments.

$Ol+H_2O$ projectiles with 5 wt% H_2O are as hard as pure ice (dotted line), whereas the projectiles with less than 2 wt% H_2O are much weaker (Fig. 1a). $Ol+serp$ projectiles for less than 10 wt% heated at 200°C indicate little consolidation and are as weak as dirt clods (Fig. 1b). Slightly higher degree of consolidation is obtained for $Ol+serp$ projectiles heated at 700°C in air, when compared to those heated at 200°C.

It may be the effect of dehydration reaction of serpentine. Ol+Ab projectiles heated at 700°C show no effect of the additives, as the mass ratio versus the impact velocity curve shown in Fig. 1c is similar to the curve for projectiles without additives (0% in Fig. 1b). In contrast, Ol+soda projectiles heated at 550°C show some increases of the consolidation degree which are similar to those of Ol+serp projectiles heated at 700°C (Fig. 1d).

Effects of the amount of minor components on the consolidation of mixtures are apparent for Ol+H₂O projectiles in Fig. 2. The ordinate indicates the critical impact velocity at which the largest fragment equals a half of the original mass. The critical impact velocity may correspond to the impact energy per projectile mass or the impact velocity when the catastrophic disruption of a spherical projectile occurs.
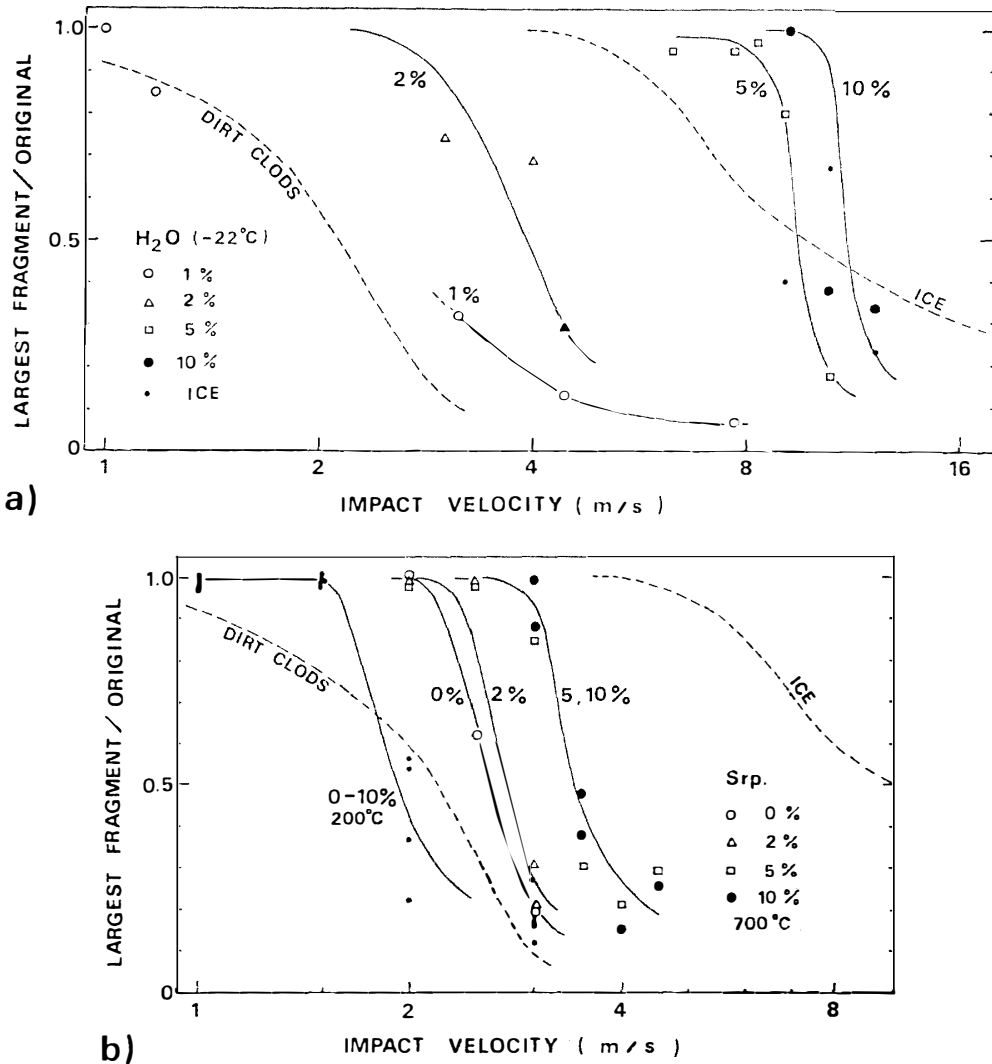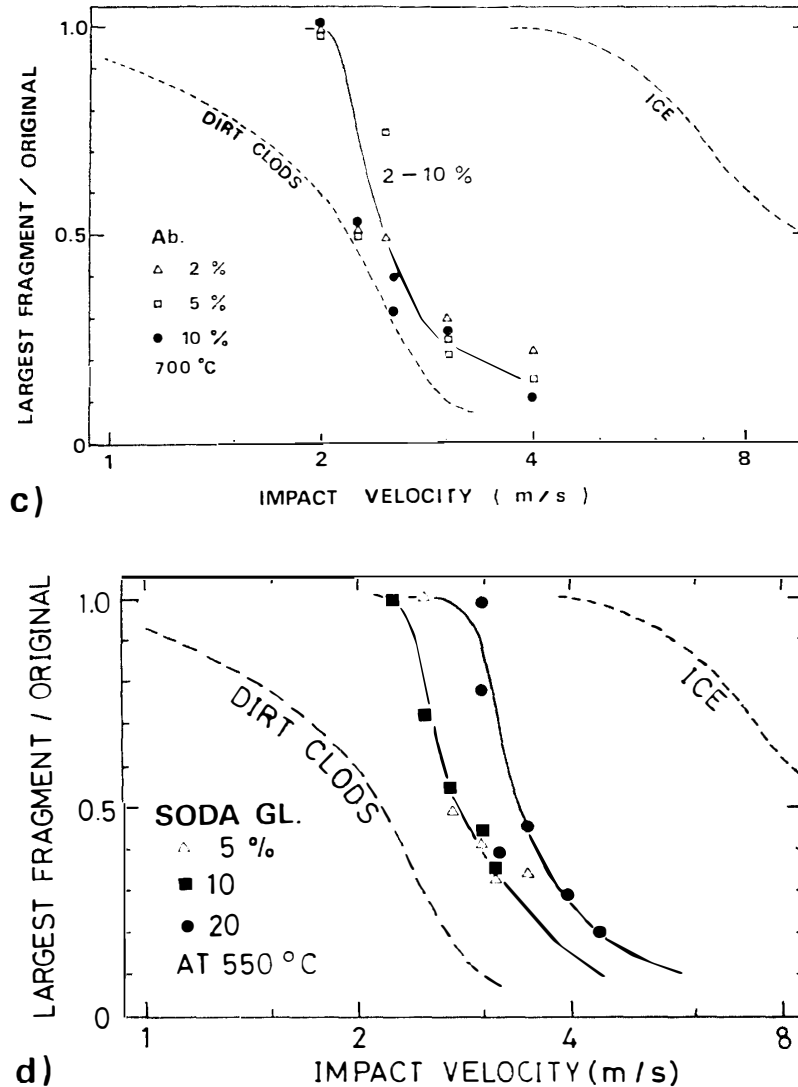

a)

b)

Fig. 1.

Fig. 1. Ratios of the weight of the largest fragment after impact experiment to that of the original spherical projectile are shown as a function of impact velocity. The spherical projectiles are made of peridotite powder with various amounts of minor components which are a) H_2O, frozen at $-22°C$, b) serpentinite powder heated at $200°C$ and $700°C$, c) albite composition glass powder heated at $700°C$, and d) soda glass powder heated at $550°C$, respectively. Amounts of minor components are indicated by different symbols as shown in the insert in each diagram. Dotted lines are from HARTMANN (1978).

$Ol + H_2O$ projectiles show a gradual increase in the critical impact velocity as the water content is increased up to about 5 weight percent, at which they have the same critical impact velocity as that of pure ice. As porosities of these projectiles are about 30%, pores are not fully saturated with ice even for the aggregates with 5 and 10 wt% water content.
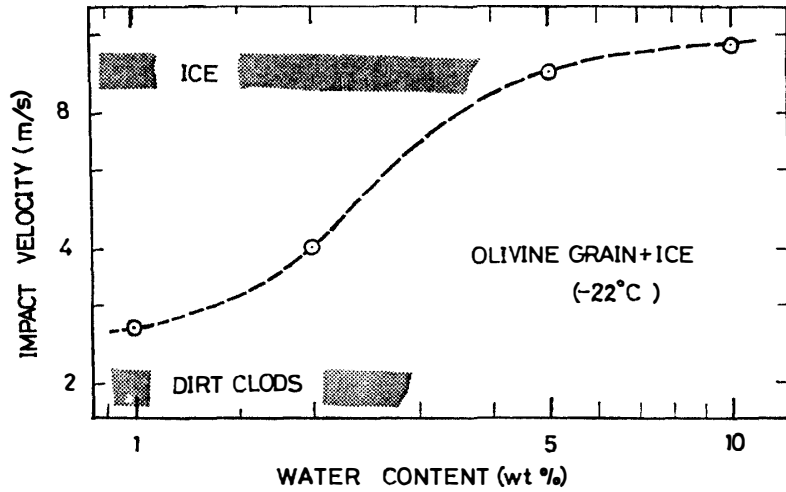
Fig. 2. The critical impact velocity versus the water content of frozen projectiles of $Ol + H_2O$. For pure ice and dirt clods, the critical impact velocities are indicated by shaded bars from HARTMANN (1978).
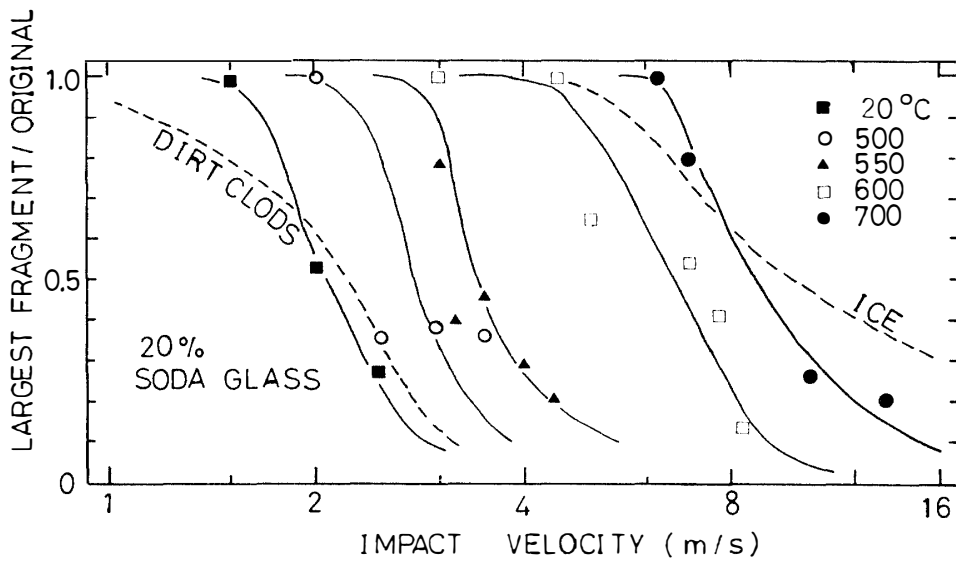

Fig. 3. Ratios of the weight of the largest fragment to that of the original as a function of impact velocity for peridotite powder projectiles with 20 wt % soda glass powder heated at various temperatures for 15 hours.

In Fig. 3, mass ratios of the largest fragment to that of the original are shown as a function of impact velocity for the spherical aggregates with 20 wt% soda glass powder heated at various temperatures for 15 hours. A large increase of consolidation is observed for Ol+soda projectiles heated at higher than 600°C, whereas the projectiles dried at room temperatures show almost the same strength as dirt clods

as shown by the dotted line in Fig. 3.   The difference of consolidation between albite composition glass powder and soda glass powder can be attributed to the difference of the glass-transition temperature of these two glasses.

The critical impact velocities of the aggregates with 20 wt% soda glass powder are shown as a function of heating temperatures (bottom of Fig. 4), together with a nominal viscosity variation with temperature for soda glass (top of Fig. 4). The temperature of about 580°C where the increase of the critical impact velocity is the most abrupt corresponds to the glass-transition temperature of soda glass with the viscosity of about 10^{13} poises (Hayden et al., 1965).   It is likely that the glass-transition process of amorphous materials at grain boundaries would effectively contribute to the increase of grain-to-grain adhesion of loosely consolidated aggregates.
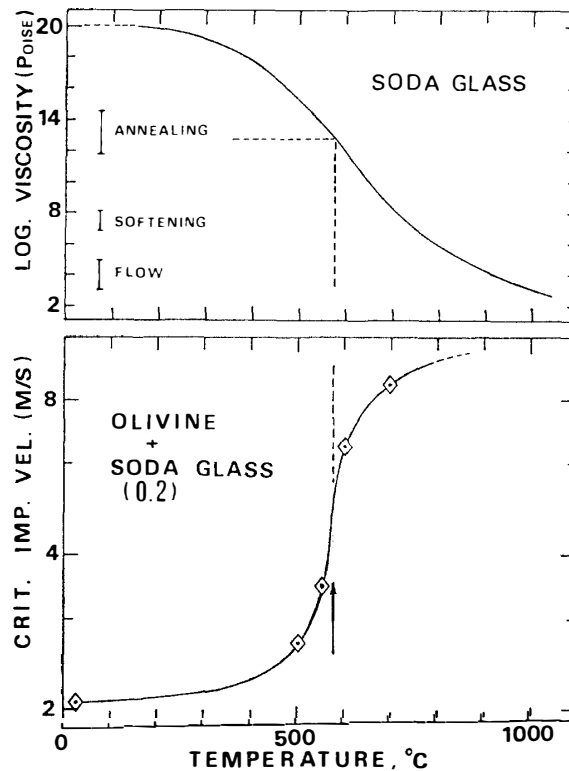

Fig. 4.   The critical impact velocity versus temperatures (bottom) and the viscosity of soda glass
versus temperatures (top).

Results of projectiles with 5 wt% of ice (−22°C), serpentine powder (700°C) and albite composition glass powder (700°C) and 20 wt% of soda glass powder (700°C) are shown for comparison in Fig. 5.   As wt% is large enough to see the effect of additives and further addition increases the strength of projectiles only a little, these curves can be considered to represent the effects of the respective minor components on consolidation.
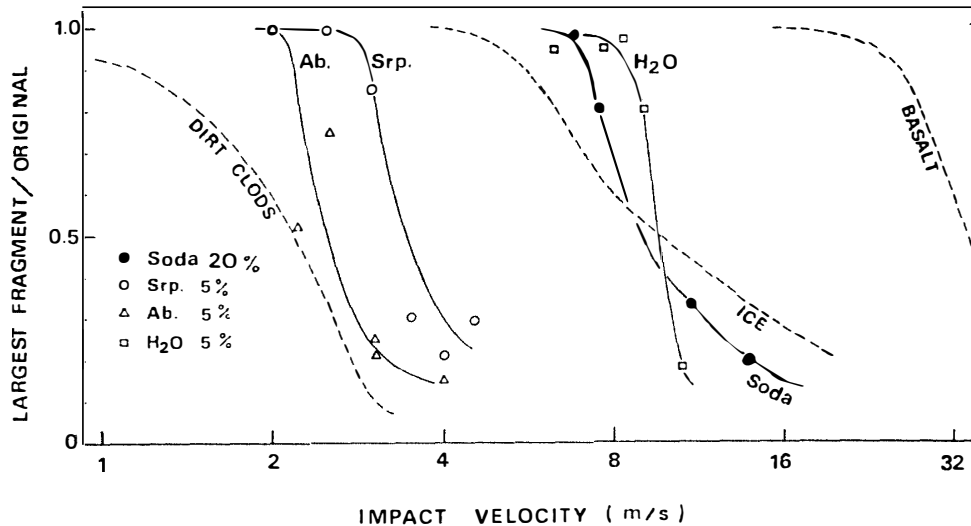
Fig. 5. Ratios of the weight of the largest fragment to that of the original as a function of impact velocity for peridotite powder projectiles with ice (5 wt %, −22°C), serpentinite powder (5 wt %, 700°C), albite composition glass powder (5 wt %, 700°C) and soda glass powder (20 wt %, 700°C), respectively.

4. Discussions

In low-velocity impact experiments on projectiles of loosely consolidated aggregates with semi-infinite hard target, a small portion of total energy is delivered to the kinetic energy of fragments after the impact. The mass ratio of the largest fragment to the original projectile is only a crude indication of the energy per unit volume used for fracturing the projectile. There is, however, a sharp transition over a narrow range of impact velocity (i.e. total kinetic energy per projectile mass) from minute local damage to massive fracture of the projectile, as illustrated in Fig. 1. The critical impact velocity defined in the previous section corresponds to the impact strength and is independent of projectile mass as pointed out by GREENBERG et al. (1978). Thus the consolidation degree of loosely consolidated aggregates can be represented by the critical impact velocity.

The consolidation degree of planetesimals influences the modes of their mutual collision and the cratering processes at the surface of chondrite parent bodies. Various effects of minor components at grain boundaries on the consolidation degree of planetesimals are as follows:

4.1. Effects of remelting and successive freezing of low melting-temperature materials

If some portion of impact energy is delivered to the melting of low melting-temperature material of the planetesimals, a considerable increase of consolidation would

result as demonstrated in Figs. 1a and 2. Ice is one of the major components among solid particles composing planetesimals in the Kepler orbits further than those of asteroids. In the early stage of planetesimal growth, ice would be an important constituent even in the terrestrial planet region because of low temperature in the primordial solar nebula (SAFRONOV, 1969; KUSAKA et al., 1970; LEWIS, 1974). Rebound coefficients between ice spheres or mixtures of ice and clay materials are very small for low impact velocity and grain-to-grain adhesion by the melting and successive freezing of ice may occur in the impact process (FUJII et al., 1979). As shown in Figs. 1a and 2, the consolidation of loosely compacted aggregates certainly increases to some degree if aggregates would contain more than several weight-percents of low melting-temperature materials such as ice. It is noted that the mixture of silicate grains and icy material would have the strength at most as high as that of pure ice. Similar process would occur for other lower melting-temperature materials such as FeS, etc. than silicates if the temperature condition at the impact process was convenient.

4.2. Effects of evaporation of volatiles from fine-grained hydrous materials

Hydrous minerals and amorphous materials are commonly observed in the matrix and at grain boundaries of chondrites. The petrologic types of chondrites are probably produced by thermal metamorphism within chondrite parent bodies (e.g. MIYAMOTO et al., 1980a). Effects of dehydration of hydrous minerals such as clay and serpentine on the consolidation of silicate aggregates remain unknown. The observation of grain boundaries for L chondrites by the scanning electron microscope suggests that needle- or plate-like fine materials between large grains would contribute to the grain-to-grain adhesion in L3 chondrite (Y-74191), whereas rounded fine materials in L6 chondrite (ALH-77231) would not (FUJII et al., 1980, 1981b). Although the consolidation mechanism to make L3 chondrite as hard as basalt remains unsolved, the release of volatiles could loose the grain-to-grain adhesion in L6 (N. ONUMA, private communication, 1981). Although dehydration reaction could slightly increase the consolidation degree as shown in Figs. 1b and 5, and heating of planetesimals by the impact process or the radioactive elements could cause dehydration reaction and release of water vapor, consolidation of the aggregates by these processes might be less significant than that by the following effects of amorphous materials.

4.3. Effects of viscous deformation of amorphous materials

Amorphous materials commonly found in the matrices and at grain boundaries of unequilibrium ordinary chondrites are mixtures of albite- and olivine-composition glasses (IKEDA et al., 1981). The glass-transition temperature (or annealing temperature) of albite glass is not certain. Considering that the temperature where viscosity of albite glass shows about 10^6 poises is $1300°C$ while it is $800°C$ for soda glass (CLARK, 1966), the galss-transition temperature of albite composition glass might be 1000

$\sim 1100°C$. If this is reasonable, the temperature needs to be as high as 1000°C for Ol+Ab projectiles so that they may show a similar increase of consolidation degree to that of Ol+soda projectiles heated at 700°C for 15 hours. Grain-to-grain adhesion could be caused by the deformation of amorphous material between grains or by wetting and bridging grains. If the mechanism to increase the consolidation degree of aggregates depends only on the viscous deformation of amorphous materials, the similar degree of consolidation could be achieved even at low temperatures after a longer time under higher stresses than those in this experiment. The consolidation of planetesimals to the strength similar to that of pure ice or even higher could be possibly by this mechanism.

In conclusion, effects of minor components on the consolidation of planetesimals (simulated by aggregates of peridotite powder with minor components) are as follows: a) Viscous deformation of amorphous materials significantly increases the grain-to-grain adhesion. b) Dehydration or release of water vapor would slightly increase the consolidation degree of aggregates. c) Once melted and successively frozen H_2O largely contributes to the consolidation. d) More than 5 wt% of minor components would be enough for the consolidation. e) Pore spaces need not be fully saturated by minor components.

It is also noted that the strength of planetesimals would not become so high as that of igneous rocks such as basalt. However, other processes such as compaction by shocks or thermal stresses (Y. HAMANO, private communication, 1981; FUJII *et al.*, 1981b, d) and consolidation by implantation of small particles could be effective after the sizes of planetoids become larger than hundred kilometers, as well as cementing by sticking materials between grains.

Further investigation is needed on the grain size distribution and texture of fine materials existent at grain boundaries for simulated materials as well as chondrites. It is also desirable to make experiments under various temperatures and pressures, and stresses corresponding to those within and at the surface of chondrite parent bodies.

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