A NEW STRENGTH MEASURE FOR ORDINARY CHONDRITES

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Abstract: A new strength measure is proposed which is siutable for small rocks with high scarcity values such as extraterrestrial samples. It is defined as the rate of excavation on a sample surface by a 2 mm-diameter steel rod attached to an ultrasonic machine. The measure is named vibrational fracturing rate that correlates well with the relative hardness of common minerals (quartz, olivine, anorthite, calcite and talc).

Values of the vibrational fracturing rate for three ordinary chondrites, Yamato-74191 (L3), ALHA77231 (L6), and Yamato-75258 (LL6) are 0.02, 0.12 and 0.23 mm/min, respectively. Samples studied are classified on the basis of the present strength measure as follows: 1) Yamato-74191 (L3), olivine, anorthite, and basalt, 2) ALHA77231 (L6), calcite and serpentinite, and 3) Yamato-75258 (LL6) and talc.

The strength of ordinary chondrites represented by the vibrational fracturing rate seems to be controlled mainly by fine particles embedded between large grains. No lithification by high temperature sintering of large grains is observed under the scanning electron microscope.

1. Introduction

Collision is one of the most dominant processes in the evolution of chondrite parent bodies and planets. Mode of collision depends obviously on sizes, impact velocities and strength of mutually impacting bodies. In most of studies of impact experiments and model calculations for planetesimal growth, high impact velocity (>a few km/s) and high strength material such as basalts and irons have been considered (*e.g.*, Hartmann, 1969; Stöffler *et al.*, 1975; Fujiwara *et al.*, 1977; Matsui and Mizutani, 1977, 1978; Greenberg *et al.*, 1978). Hartmann (1978) pointed out, however, that collision processes with low impact velocity and of low strength material are also important in the evolution process of planetesimals. Fujii *et al.* (1978, 1979a) suggested that mechanical properties of less than hundred-kilometer size planetesimals grown from Goldreich and Ward's (1973) size ($\sim 10^{18}$g) must be weak and similar to those of dirty clods and loose mixtures of sand and ice. Lithification of material composing small planetesimals would not occur unless

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pressure compaction by their own gravitational field or melting compaction by internal heat sources took place. Sizes of parent bodies of ordinary chondrites are estimated to be relatively small in either internal heating model (MINSTER and ALLÉGRE, 1979; MIYAMOTO *et al.*, 1980a) or external heating model (WASSON, 1972, 1974; FUJII *et al.*, 1979b; MIYAMOTO and FUJII, 1980). Temperatures could not reach the melting point unless unplausibly intense internal heat source is assumed. Thus the fracture strength of ordinary chondrites and their parent bodies would be somewhat lower than that of igneous rock once melted.

Because of high scarcity values of extraterrestrial samples, experimental studies on the fracture strength (or impact strength) by usual methods in rock mechanics have been very few. One of the purposes of this study is to establish a new strength measure suitable for very small samples.

Formation processes of petrologic types from 3 to 6 in chondrite parent bodies remain unsolved. In contrast to many investigations of chemical, petrological and mineralogical properties, data of mechanical properties of extraterrestrial material are very scarce. Another purpose of this study is to clarify differences in mechanical properties among the petrologic types.

In this paper, a new strength measure named "vibrational fracturing rate" is proposed. The method is suitable for extraterrestrial samples because it does not require large samples and the strength can be measured without breaking samples. The strength of three ordinary chondrites, Yamato-74191 (L3), ALHA77231 (L6) and Yamato-75258 (LL6) is compared with that of terrestrial rocks (basalt, serpentinite, pyrophyllite and talc) and single crystals (quartz, olivine, anorthite, and calcite). To see differences between petrologic types 3 and 6, compressional wave velocities are measured and textures are observed under the electron microscope on the same specimen.

2. Experimental Procedures

2.1. Vibrational fracturing method

The vibrational fracturing rate was measured by using an ultrasonic machine (UM-150K, Nippon Electronics Ltd.). Fig. 1 shows a schematic diagram of the equipment. A steel rod tip with 2 mm-diameter vibrates vertically at 19.5 kHz and excavates the sample surface. The excavation rate is measured by a differential transformer. The amplitude and stability of vibration were measured by a moving-magnet type pick-up (DENON DL-108D, Nippon Columbia Ltd.) touched to the vibrating tip, as shown in Fig. 1. Frequency range of this pick-up was about 10 Hz–40 kHz. Output signal of the pick-up was shed to a 47 kilo-ohm registance and monitored by osciloscope. A peak-to-peak velocity amplitude thus monitored was about 5 cm/s at 19.5 kHz and corresponding peak-to-peak displacement amplitude was about 8 μm. The variations of vibration amplitude were less than 5% through-

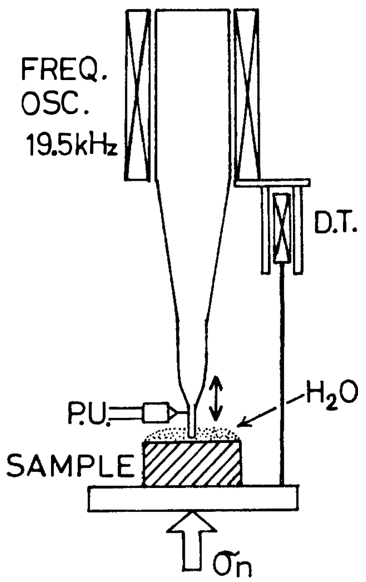

Fig. 1. Schematic diagram of the vibrational fracturing measurement. D. T. is a differential transformer and P. U. is a pick-up.

out the measurements.

The differential transformer is calibrated by a standard micrometer and has sensitivity of 0.99 V/mm within the range of ± 2.5 mm. Normal stress (σ_n) is supplied by a spring and is kept constant at (0.6 ± 0.1) MPa ($\sim$6 bars). Water is supplied to the sample surface so as to get good matching of mechanical impedance.

Samples of ordinary chondrites were embedded in resin, cut parallel and used for measurements of both vibrational fracturing rate and compressional wave velocity. For vibrational fracturing rate measurements specimens were mounted on a glass plate and their surfaces were ground flat. Single crystals of quartz, olivine and calcite were of gem quality and flawless, but cleavages with a few milimeters interval were observed in anorthite crystal. Thicknesses of single crystal samples were about 6 mm and flat surface areas ranged from 0.5 cm $\times$ 0.5 cm (anorthite) to 0.7 cm $\times$ 1.0 cm (calcite). Sizes of rocks studied (basalt, serpentinite, pyrophyllite and talc) were 1.0 cm $\times$ 1.5 cm $\times$ 2 cm or larger.

2.2. Compressional wave velocity measurements

Compressional wave velocity of the ordinary chondrites was measured by usual pulse transmission technique with 5 MHz PZT transducers under the room temperature and atmospheric pressure condition. Samples embedded in resin were ground flat to make parallel surfaces. All samples were about 5 mm long and the accuracy of velocity measurements was within about a few percent.

2.3. Scanning electron microscope (SEM) observations

Fresh surfaces of broken fragments were selected from the same pieces of ordinary chondrites, coated with gold, and observed by a SEM (JEOL, JSM-U3). Size of each specimen was about 2 mm.

3. Results

Vibrational fracturing rates were measured at several parts of each sample surface and the results were averaged. Fig. 2 shows typical examples of excavated

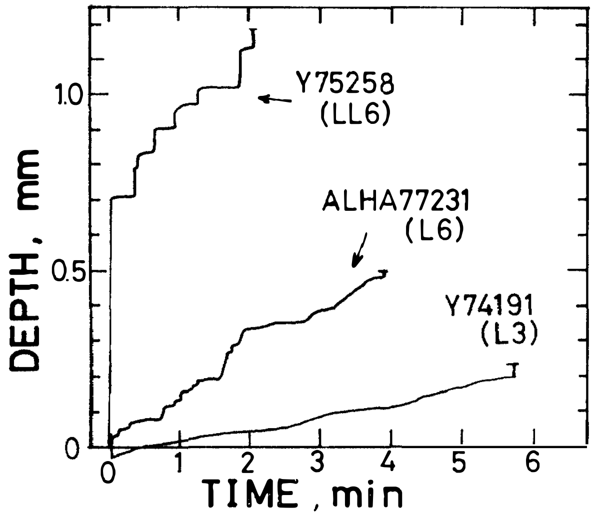

Fig. 2. Examples of excavation depth versus time curves for the ordinary chondrites studied. Vibrational fracturing rate is an average of gradients for each sample.

Table 1. Vibrational fracturing rate and relative hardness.

Samples	Relative hardness	Vibrational fracturing rate (mm/min)	Remarks
Single crystals			
Quartz	7	.009	Lar to c{001}, Minas Gerais, Brasil
Olivine	6.5	.020	Arizona
Anorthite	6	.025	Lar to b{010}, Yoichi, Hokkido, Japan
Calcite	3	.140	Lar to r{10$\bar{1}$1}
Rocks			
Basalt		.022	Nijyo-zan, Nara Pref., Japan
Serpentinite	2.5~6	.110[1)]	Ohtoyo, Kochi Pref., Japan
Pyrophyllite	1 ~1.5	.048	India
Talc	1	.220	Southern Manchuria, China
Ordinary chondrites			
Yamato-74191		.020	L3
ALHA77231		.120	L6
Yamato-75258		.230	LL6

[1)] Direction of excavation is nearly perpendicular to schistosity.

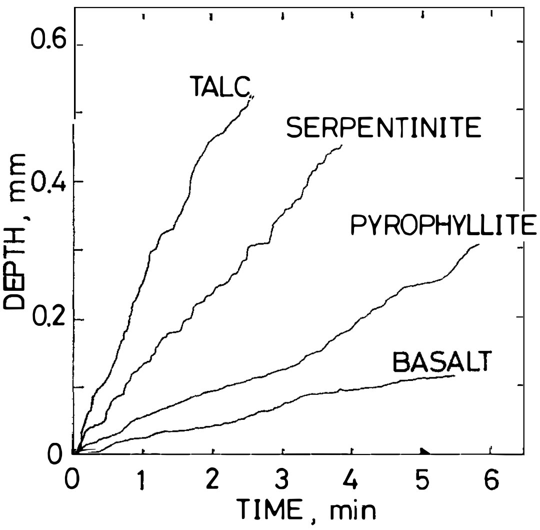

Fig. 3. Examples of excavation depth versus time curves for rocks studied.

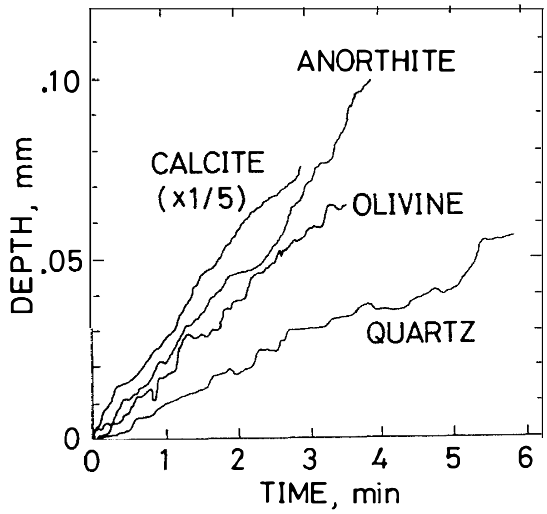

Fig. 4. Examples of excavation depth versus time curves for single crystals studied. Vertical scale for calcite curve is changed to one-fifth.

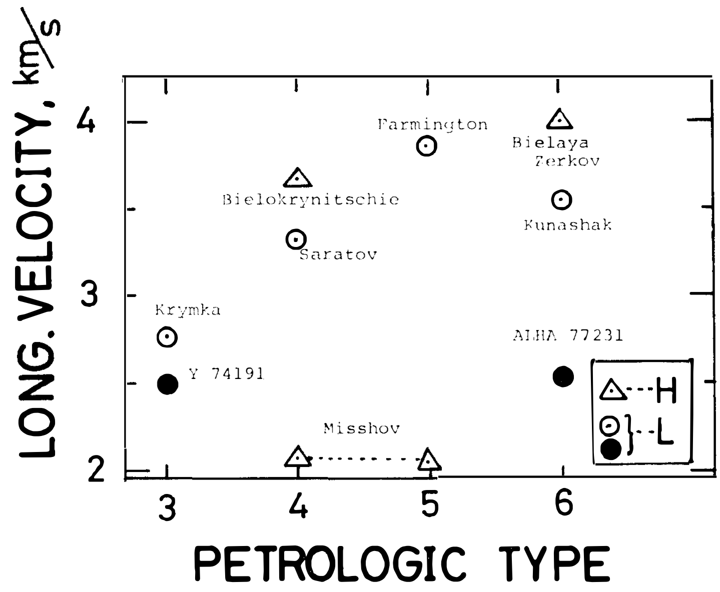

Fig. 5. Longitudinal (compressional) wave velocities for ordinary chondrites of different petrologic types under room temperature and atmospheric pressure. Thermal metamorphism advances from petrologic type 3 to type 6. H represents the high-iron group and L is the low-iron group. Closed circles are data in this study and open symbols are from Alexeyeva *(1960).*

depth versus time curves for ordinary chondrites. Relatively large steps shown in the curve for Yamato-75258 (LL6) indicate that this sample is highly heterogeneous. In contrast, Yamato-74191 (L3) shows a smooth and low rate of excavation. A negative step at the start of excavation of Yamato-74191 may be due to temporary accumulation of fractured powder between the tool tip and the sample surface. We take an average gradient for each curve as the vibrational fracturing rate of the sample (Table 1).

To compare the new strength measure obtained by the vibrational fracturing rate method with existing hardness measures, we measured vibrational fracturing rates of common single crystals and rocks. In Figs. 3 and 4, examples of excavated depth versus time curves for rocks (basalt, serpentinite, pyrophyllite, and talc) and single crystals (quartz, olivine, anorthite, and calcite) are shown. The highest rate of vibrational fracturing is observed in talc and the lowest in quartz.

From the results shown in Figs. 2, 3 and 4 and summarized in Table 1 we point out the following:

a) Yamato-75258 (LL6) has a similar rate of vibrational fracturing to that of talc. However, larger steps shown in the excavation curve indicate that Yamato-75258 (LL6) is much more heterogeneous.

b) The vibrational fracturing rate of ALHA77231 (L6) is about half of that of LL6 and is similar to those of calcite and serpentinite.

c) The vibrational fracturing rate of Yamato-74191 (L3) is comparable with those of olivine, anorthite and basalt, and is about one-sixth of that of calcite.

Fig. 5 shows the results of compressional wave velocity measurements together with the data of other ordinary chondrites by ALEXEYEVA (1960). Compressional wave velocities of Yamato-74191 (L3) and ALHA77231 (L6) were about 2.50 km/s and 2.52 km/s, respectively. For Yamato-77258 (LL6), signals of compressional wave were too weak to measure the velocity.

Fig. 6 shows scanning electron microscope photographs for three different petrologic types of ordinary chondrites studied. In Yamato-74191 (L3), fine angular grains of about 1 μm or less are embedded between larger grains (Fig. 6a), and platy or needle-like fine grains make bridges between larger grains (Fig. 6b). It is noticed that the peculiar texture shown in Fig. 6b is very similar to that of a unique lunar sample of "rusty" rock 66095 (TAYLOR, 1975, p. 229). This kind of texture is frequently observed in Yamato-74191 of type 3 but is less frequent in ALHA77231 (L6) and Yamato-77258 (LL6) as shown in Fig. 6c and 6d. This may be relevant to the fracturing strength of Yamato-74191 higher than those of the other two samples of type 6. Surfaces of large grains in type 6 samples are rounded and relatively smooth in contrast to those of Yamato-74191 (L3). Open cracks separate large grains and would contribute to high aspect ratios of cracks in average that make effects of cracks significant (O'CONNEL and BUDIANSKY, 1974). No appreciable difference between LL6 (Yamato-75258, Fig. 6c) and L6 (ALHA77231, Fig. 6d) is so far

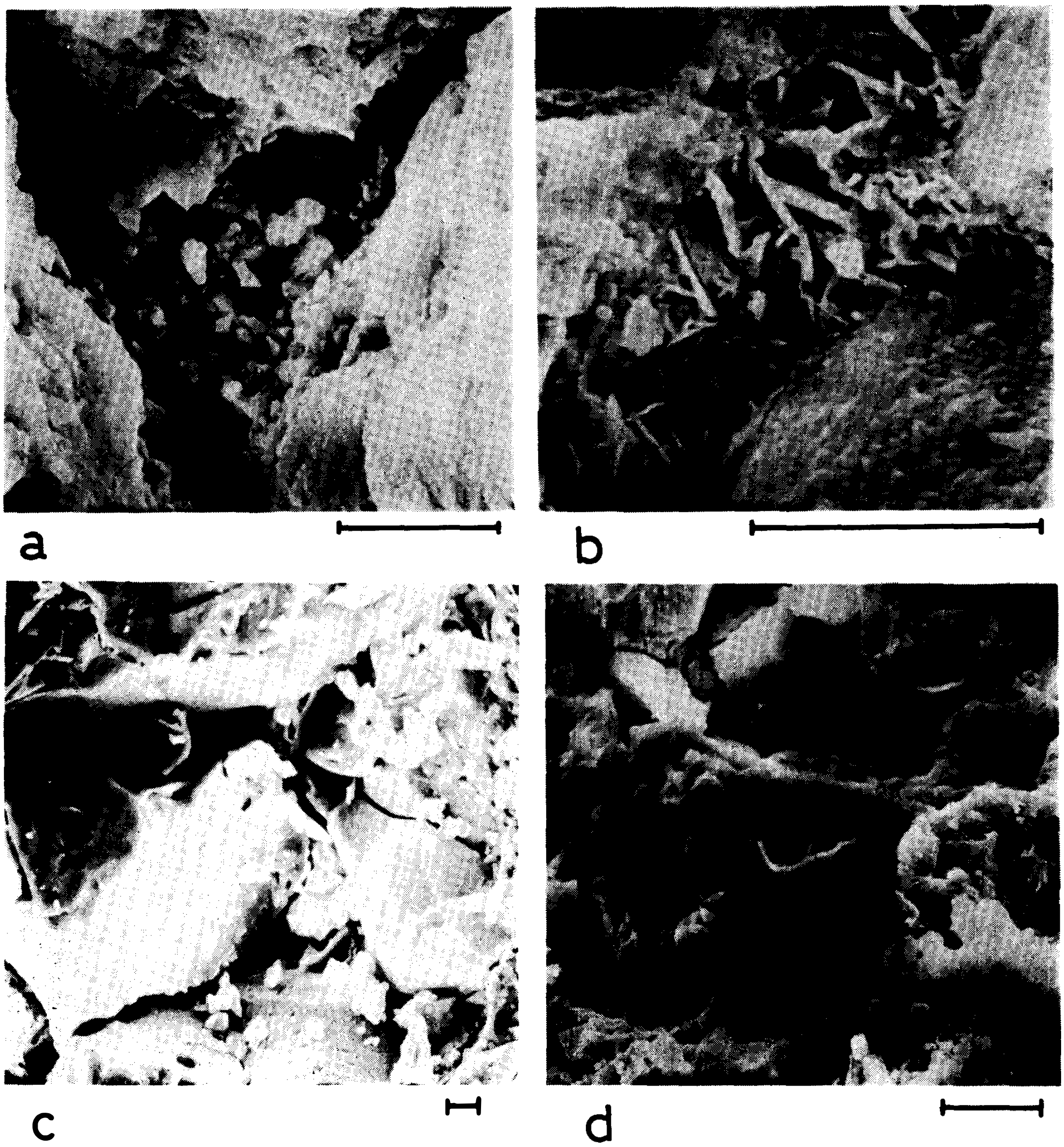

Fig. 6. Typical photographs for three different types of ordinary chondrites are shown. a) and b) are Yamato-74191 (L3), c) is Yamato-75258 (LL6), and d) is ALHA77231 (L6). A horizontal bar at lower right corner for each photograph indicates 10 μm long.

seen under the scanning electron microscope.

4. Discussion

4.1. Comparison of vibrational fracturing rate with relative hardness of minerals

In Table 1, relative hardness of minerals is also listed. The vibrational fracturing rate corresponds well with the relative hardness except pyrophyllite. In vibrational fracturing process, fragments of sample itself act as grinding powder hitting vertically the sample surface. Vibrational fracturing rate would be controlled by the rate of supply of fragments at resonant conditions of vibration. Cleavages, cracks and adhesion between grains at the sample surface which is covered by water are important factors. Exceptionally low vibrational fracturing rate of pyrophyllite may be understood since the pyrophyllite studied has no cleavages nor microcracks but is quite homogeneous consisting of fine grains.

Throughout this study normal stress σ_n, size of tool tip, and amplitude of vibration are kept fixed. These factors would certainly affect the absolute value of vibrational fracturing rate, but may not change the relative order.

Pouring water on sample surface may affect mechanical properties. Though effects are unknown and may be large for certain minerals like clay and water-soluble minerals, we choose pouring water for impedance matching because water is the most easily-obtainable, standard liquid. Besides, clay and water-soluble minerals are uncommon in ordinary chondrites.

4.2. Differences of vibrational fracturing rate among ordinary chondrites L3, L6 and LL6

Though sample numbers are limited, we may temporarily assume that Yamato-74191, ALHA77231 and Yamato-75258 represent petrologic type L3, L6 and LL6, respectively. SEM observations (Fig. 6) indicate that large grains are rounded and smoothly fitted each other in L6 and LL6 whereas in L3 pores between large grains are embedded with fine angular grains or they are bridged by platy or needle-like fine grains. It is likely that the vibrational fracturing rate of ordinary chondrites depends largely on grain-to-grain adhesion and cementing condition between grains. Although we could not distinguish difference between ALHA77231 (L6) and Yamato-74191 (LL6) by SEM observations (Figs. 6c and d), the difference of intergrain structure between Yamato-74191 (L3) and ALHA77231 (L6) or Yamato-75258 (LL6) is obvious. Relatively low vibrational fracturing rate of L3 in comparison with L6 and LL6 is likely due to adhesion effect of fine particles embedded between large grains. Further investigations for different petrologic types of ordinary chondrites are obviously needed.

As platy or needle-like grains in Fig. 6b are similar to those of the lunar "rusty" rock 66095, there is a possibility that these grains are hydrous minerals (TAYLOR, 1975; CIRLIN and HOUSLEY, 1980). It is also possible that these grains are rust caused by terrestrial water because the sample (Yamato-74191) was found in Antarctica. Anyhow, it is highly desirable to identify mineralogical composition of fine grains between large grains in Figs. 6a and b.

The presence of small fraction of hydrous minerals or ice at grain boundaries causes significant change in adhesive strength. Preliminary experiments on adhesive strength of olivine powder (<500 μm) indicate that adhesive strength is increased by the addition of 2–5 wt% of serpentinite powder (<250 μm) (MIYAMOTO *et al.*, 1980b).

Unlike the data by ALEXEYEVA (1960), no difference in compressional wave velocity is observed between L3 and LL6. It is well known that the values of compressional wave velocities of rocks under atmospheric pressure depend largely on cracks and porosity of samples (*e.g.*, BIRCH, 1961; O'CONNELL and BUDIANSKY, 1974). Elastic properties which are closely related to petrologic types of ordinary chondrites could be also affected sensitively by closure processes of pores and changes in configuration of cracks.

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