Static and Impact Strength of Chondrules: Comparison with Rock Samples

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Introduction:

Chondrules are thought to be captured into chondrites after their formation, then underwent collisional and thermal evolution. It was shown that the maximum pressure chondrite parent bodies experienced would be estimated from the tensile strength of chondrules and the fraction of intact chondrules [1]. However, the tensile strength of chondrules has not been measured. In this study, we conducted static and impact tests of chondrules and rock samples in order to estimate the strength of chondrules and the impact process they underwent.

Experiments:

Samples were chondrules from Allende (CV3) and Saratov (L4) specimens, 1 and 3 mm glass beads, and spherical and disc specimens of dunite (Horoman, Japan), basalt (Yakuno, Japan), Berea sandstone, and tuffaceous sandstone (Kimachi, Japan).

Chondrules of Allende were removed using tweezers and files, while those of Saratov were separated by means of Freeze-thaw method. Crushing strength was determined from compression test of spherical specimens and tensile strength was determined from compression test of disc specimens (Brazilian disc test). The loading rate was 1 μm s^{-1}.

Impact disruption experiments of chondrules, glass beads and spherical rock specimens were conducted using a small gas-gun with 3 mm bore diameter at Kobe University [2]. Targets were nylon, aluminum, and stainless-steel cylinders. The impact velocity ranged from 11 to 241 m s^{-1}. Specimens smaller than 2 mm in diameter were accelerated using polycarbonate sabot of 3 mm in diameter and 6 mm in height.

Results:

Fracture pattern varied depending on materials. As for impact disruption, specimens of two sandstones were more finely fragmented and numerous sand grains were generated. Especially, fragments of tuffaceous sandstone were too fine. The mass of the maximum fragment was less than 2.5×10^{-3} g and comparable to the minimum mass measurable in this study.

Crushing strength Y_c is determined as follows:

$$Y_c=2.8F/\pi d^2, \qquad (1)$$

where F is the peak value of force applied to the specimen and d is the diameter of the specimen [3]. Tensile strength Y_t is represented by following equation:

$$Y_t=2F/\pi lh, \qquad (2)$$

where l and h represent the diameter and the height of the disc, respectively.

Using the measurement data of the tensile strength, we determined the Weibull modulus m [4] in the same way as the previous study [5]. The Weibull modulus represents the distribution of intrinsic cracks in the sample. The higher value of m corresponds to more homogeneous distribution of cracks in rock samples.

The results of impact experiments are shown in Fig. 1. We define the impact strength as the impact pressure at which the maximum fragment mass fraction to the initial mass of the specimen, i.e., the vertical axis in Fig. 1 becomes 0.5.

The measurement results of three types of strength and the values of m are presented in Table 1. The values of tensile strength are slightly higher than the values of crushing strength, although they are almost equivalent. Impact strength is considerably higher than crushing (or tensile) strength.

Discussion:

Taking account of the slightly higher values of tensile strength than crushing strength for rock samples, the tensile strength of chondrules would be estimated to be about 10 MPa.

The present results show that the impact strength, i.e., dynamic strength is higher than the static strength for all materials, and that the ratio of impact to crushing (or tensile) strength ranges from about 10 to 45. Generally, the dynamic strength becomes higher with strain rate [6]. The dependence of strength on strain rate was modeled using Weibull modulus m [7]. In Fig. 2, the ratio of dynamic to tensile strength versus the value of m is shown for each rock sample. The ratio increases as the value of m becomes smaller, thus the strength would tend to become higher in relation with strain rate as the crack distribution becomes more inhomogeneous. The horizontal line shows the value for chondrules. Based on the line, the value of m of chondrules is estimated to be comparatively as large as that of tuffaceous sandstones.

The strain-rate dependence is also found in Fig. 1 in which the maximum fragment mass ratio versus the impact pressure for each sample is shown. The slope of this graph varies by samples. For example, the slope of tuffaceous sandstone is considerably steep, while that of Berea sandstone is rather more gradual. In Fig. 3, the value of slope is plotted against the value of m for each sample. The slope tends to being steep as the value of m becomes higher, except for the dunite. With the lower value of m, i.e., inhomogeneous distribution of crack, samples tend to be stronger and more difficult to be disrupted as the impact pressure and strain rate increase, resulting in the gradual slope of Fig. 1. On the other hand, for samples with higher value of m, the increase of strength due to higher strain-rate is not significant enough and samples would be disrupted immediately when the pressure exceeds the threshold strength, resulting in the steeper slope. This tendency of strengthening with increase of strain rate depending on the value of m is conformable to the result shown in Fig. 2. The slope of chondrules in Fig. 1 is much steeper than that of tuffaceous sandstone. Therefore, chondrules might have very high value of m.

These two results (the ratio of the impact dynamic strength to the static strength and the slope in Fig. 1) correctively may imply that chondrules have large m. The reason of the possible large m should be understood in relation with the impact and other process experienced by the chondrules.

References:
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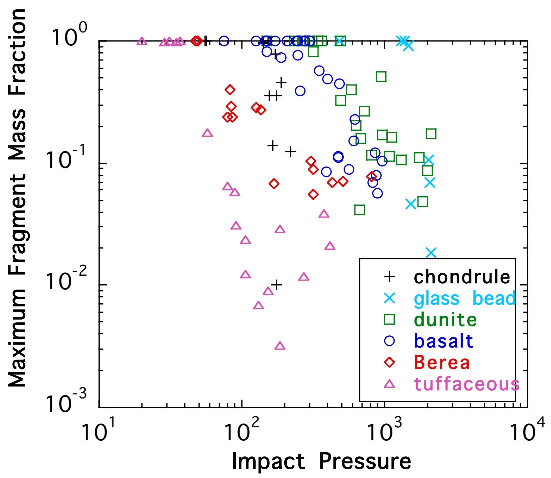

Fig. 1. Results of impact disruption experiments.

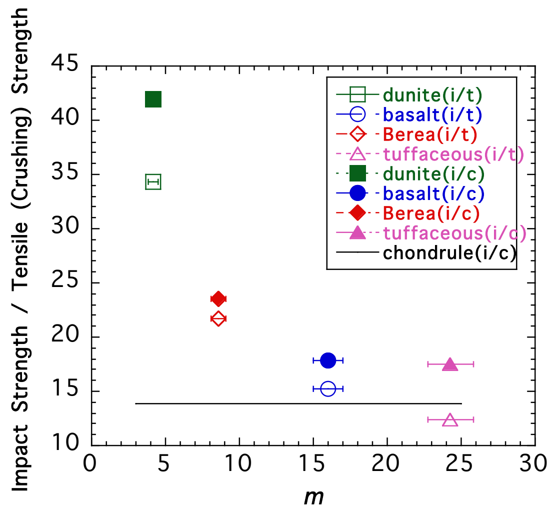

Fig. 2. Dynamic strength normalized by static strength versus the value of m for each sample. The horizontal line shows the value for chondrules.

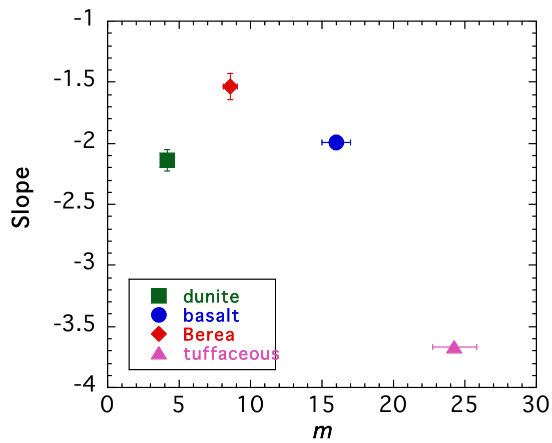

Fig. 3. The slope of the fitting line to the data shown in Fig. 1 for each rock sample.

Table 1. Strength and Weibull modulus m.

	crushing strength [MPa]	tensile strength [MPa]	impact strength [MPa]	Weibull modulus m
chondrule (Allende, CV3)	8.0±5.0	no data	no data	no data
chondrule (Saratov, L4)	11.8±12.2	no data	1.6×10^2	no data
dunite	13.1±2.6	15.9±3.4	5.5×10^2	4.17±0.33
basalt	16.5±2.1	19.3±0.05	2.9×10^2	16.0-17.0 [5]
Berea sandstone	3.4±0.7	3.7±0.5	8.0x10	8.57±0.49
tuffaceous sandstone	3.4±1.1	4.8±0.2	5.0x10	24.3±1.58
glass bead	217±29	no data	1.5×10^3	no data