POROSITY AND COMPRESSIONAL-WAVE VELOCITY MEASUREMENT OF ANTARCTIC METEORITES

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***Abstract*:** The intrinsic and bulk densities, porosities and compressional ultrasonic-wave velocities (V_p) in three mutually perpendicular directions have been measured in antarctic meteorites Allan Hills-769 and ALHA77231. V_p measurements were made at the room temperature and under one atmosphere pressure. The intrinsic and bulk densities and porosities are 2.89 g/cm^3, 3.59 g/cm^3 and 19.4% for the Allan Hills-769 and 3.07 g/cm^3, 3.58 g/cm^3 and 14.3% for the ALHA77231. The measured velocities were relatively low (the mean values of the three directions were 2.37 km/s for the Allan Hills-769 and 3.52 km/s for the ALHA77231) and showed up to 4% for the Allan Hills-769 and 10% for the ALHA77231 departures from the mean value of the three directions. The low values of velocity are attributed mainly to the high porosity of the sample. The velocity anisotropy might be due to a difference in crack shape between wave-transmitting directions. The porosity versus petrologic type diagram does not indicate a systematic variation of the porosity with the petrologic type.

1. Introduction

The view that meteorites are fragments of several hundred km size bodies is widely held. The central pressure of the parent bodies ($P_c = 2/3\,\pi G \rho^2 R^2$, ρ: mean density, R: radius, and G: gravity constant) is thus estimated to be several hundred bars at most. It is also clear that the chondritic meteorites such as carbonaceous and ordinary chondrites have never experienced complete melting. MIYAMOTO (1979) has compiled the data concerning the metamorphic temperatures of chondrites and derived the following critical temperature, T, which characterizes the respective petrologic type: 6 ($T > 1150°\text{K}$), 5 ($1150°\text{K} > T > 800 \sim 850°\text{K}$), 4 ($800 \sim 850°\text{K} > T > 500°\text{K}$) and 3 ($T < 500°\text{K}$). It is noted that the chondritic meteorites, those with the petrologic classification number smaller than 3, might have never been heated up to temperatures higher than 200°C. Irrespective of such considerably low temperature* and pressure, almost all chondrites appear to be tightly consolidated. Therefore, it is considered very interesting for understanding the origin of meteorites to reveal the nature of consolidation state of meteorites, because the consolidation

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* Here, the description "considerably low. . . ." is used because the above conditions are very low compared to the usual sintering experimental conditions ($T > 1000°\text{K}$ and $P > 1$ kbar).

state may retain some physical information on the formation conditions of meteorites. We do not have, however, any measure suitable for representing a degree of such consolidation state of materials so far. Elastic properties may be one of the physical quantities which characterize such a state, although only a few measurements on the physical properties of meteorites have been reported (ALEXEYEVA, 1958, 1960; MATSUI and OSAKO, 1979).

Recent progress in planetary formation theory has also revealed that mechanical properties of planetesimals may control the subsequent collisional evolution of planetesimal swarm (MATSUI and MIZUTANI, 1977; MATSUI, 1978, 1979). One of the certain ways to infer the mechanical properties of planetesimals might be given by measuring the mechanical properties of meteorites. Therefore, extensive measurements on elastic properties of meteorites are desirable. The physical properties of meteorites are, however, known to be much scattered and so more systematic studies are required for reaching any definite view on the physical properties of meteorites. Findings of a large amount of antarctic meteorites (*e.g.*, YANAI, 1978) are fortunately presenting to us a good opportunity for conducting such a systematic study. In this study, we will give a preliminary result of elastic property maesurements of the Allan Hills-769 and ALHA77231 as a first report of such a project.

The Allan Hills-769 and ALHA77231 were classified as the L6 chondrite by OLSEN *et al.* (1978) and MASON (1979): the Allan Hills-769 was described as Allan Hills #9 in OLSEN *et al.* In our Allan Hills-769 sample, however, we can see many chondrules with clear outlines irrespective of such a high thermal metamorphic grade as 6: according to MASON's description, "chondrules are present, but their outlines are blurred and merge with granular material". In addition, a large chondrule (~4 mm in diameter) was taken out from the Allan Hills-769 during the course of cutting and grinding of the sample. Therefore, chondrules are expected to be loosely contacted with surrounding matrix material. The reported petrologic grade of the Allan Hills-769 might be thus a matter of question.

2. Elastic Property Measurement

The intrinsic density, ρ_0, is measured by using the helium pycnometer (the model 1302 Helium-Air Pycnometer, Shimadzu Seisakusho Ltd.), which is operated on the principle that the change in the pressure of a nonadsorbing pure gas within an enclosed vessel accompanying a discrete change in the volume of the vessel is

Table 1. Intrinsic and bulk densities and porosity.

Sample	Volume (cm^3)	Mass (g)	Density (g/cm^3) Bulk	Density (g/cm^3) Intrinsic	Porosity (%)
Allan Hills-769	8.30	24.01	2.89	3.59	19.4
ALHA 77231	6.30	19.33	3.07	3.58	14.3

a function of the intrinsic volume of any solid object also in the vessel. The intrinsic volume of the object can be derived from the functional relationship, and then the intrinsic density of the object is obtained directly. Reproducibility of the data by this instrument is within 0.06%. The bulk (apparent) density of the sample, ρ_{bulk}, is measured by the modified Archimedes method*. Using the measured values of ρ_0 and ρ_{bulk}, the porosity, Φ, is estimated by the following relation, $\Phi = 1 - \rho_{\mathrm{bulk}}/\rho_0$. The results are listed in Table 1.

Compressional ultrasonic-wave velocity was measured under no axial stresses and in one atmosphere and the room temperature conditions by using the pulse transmission method. The two pulses, one through two buffer rods plus sample and the other through a calibrated variable mercury line, are displayed on a dual-trace osciloscope. Onsets of both signals are adjusted so as to coincide with each other. Since the velocity of mercury is known, we can determine very precisely the time required for wave transmission in the sample by this mercury delay line. A 1 MHz ceramic transducer was used. Measurements were conducted for three mutually perpendicular directions. Because of the very high porosity of the sample (see Table 1) the wave transmission efficiency is considerably poor, so that the onset of the signals is very blunt. The accuracy of the velocity determination is thus probably not better than a few percent. The results are summarized in Table 2. The ultrasonic-wave velocities differ up to ~10% among transmitting directions specifically for the ALHA77231 (anisotropy is greater than ~10%). Differences in velocity between the Allan Hills-769 and ALHA77231 might be mainly due to a difference in porosity between them. Shear ultrasonic-wave velocity of these samples could not be measured successfully so far because of their considerably high attenuative nature.

Table 2. Elastic wave velocity.

Sample	Direction	Length (mm)	Velocity V_p(km/s)
Allan Hills-769	L1	11.45	2.31
	L2	14.15	2.46
	L3	15.05	2.34
ALHA77231	L1	9.35	3.87
	L2	11.45	3.53
	L3	12.10	3.16

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* First, the sample is wrapped by the saran-wrap in order to avoid the water to sink into the sample. Then, the sample and saran-wrap are wrapped once again by clay. Changing the amount of the clay, we can obtain the linear relation between the weight and the volume of the sample plus saran-wrap plus clay. Extrapolation of this line to no clay limit gives an estimate of the bulk volume of the sample.

3. Sintering Process of Meteorites

The porosity may be one of the most simple measures of the consolidation state. Because, the secondary effect such as due to the impact process was shown to be negligible: according to ANDERS (1964), there are no distinct difference in the porosity between shocked and unshocked meteorites. All the porosity data of chondrites reported to date (ALEXEYEVA, 1958; STACEY *et al.*, 1961), including this study, are plotted against their respective petrologic types in Fig. 1 (see also Table 3). The porosity of the Allende meteorite (about 26.5%) measured by us is also plotted in this figure. However, we cannot find from this figure such a clear correlation that the porosity of meteorites varies with the petrologic type, although sintering degree of materials is expected to be controled by the maximum metamorphic temperature which materials have experienced, that is, the petrologic type. We need more measurements to obtain any rigid conclusion on this matter since only a few data with reliable quality are available at present.

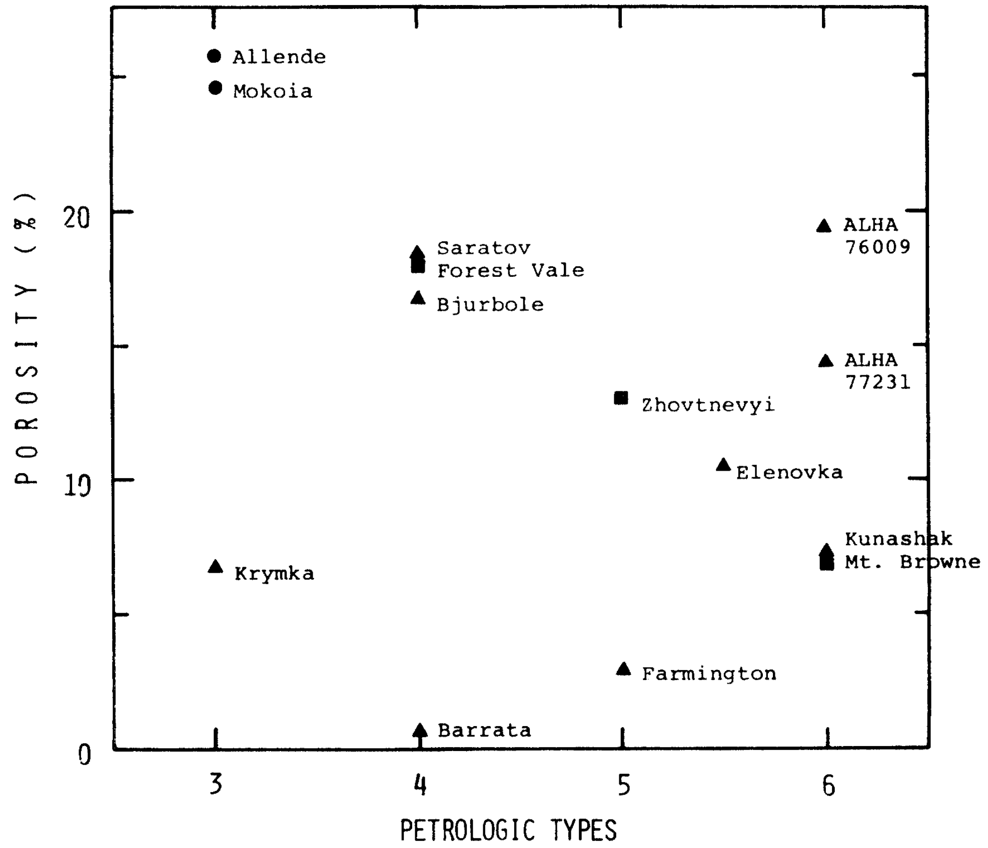

Fig. 1. Porosity-petrologic type systematics of some chondritic meteorites. ●, ▲ and ■ represent carbonaceous, L and H type chondrites, respectively.

Table 3. Elastic properties of stony meteorites.

Sample	Type	ρ_{bulk}* (g/cm^3)	ρ_0* (g/cm^3)	Φ (%)	V_p (km/s)	V_s (km/s)	λ* (kbar)	μ* (kbar)	K* (kbar)	E* (kbar)	ν*
Krymka	L3	3.35	3.59	6.7	2.76	0.83	209	23.1	224	67	0.45
Saratov	L4	3.64	4.45	18.2	3.30	1.13	303	46.5	334	133	0.43
Farmington	L5	-	-	-	3.85	1.00	-	-	-	-	0.46
Elenovka	L5 or 6	3.5	3.91	10.5	-	-	-	-	-	-	-
Kunashak	L6	3.54	3.81	7.08	3.57	-	-	-	-	-	-
Sevrukovo	L?	-	-	-	4.2	0.60	-	-	-	-	0.49
Bielokrynitschie	H4	-	-	-	3.66	1.22	-	-	-	-	0.44
Misshov	H4 or 5	-	-	-	2.05	0.90	-	-	-	-	0.38
Zhovtnevyi	H5	3.27	3.76	13.08	-	-	-	-	-	-	-
Bielaya Zerkov	-	-	-	-	3.99	-	-	-	-	-	-
Pesyanoe	Enstatite Achondrite	3.02	3.56	15.1	-	-	-	-	-	-	-

* Estimated by the author using the original data by ALEXEYEVA (1958, 1960).

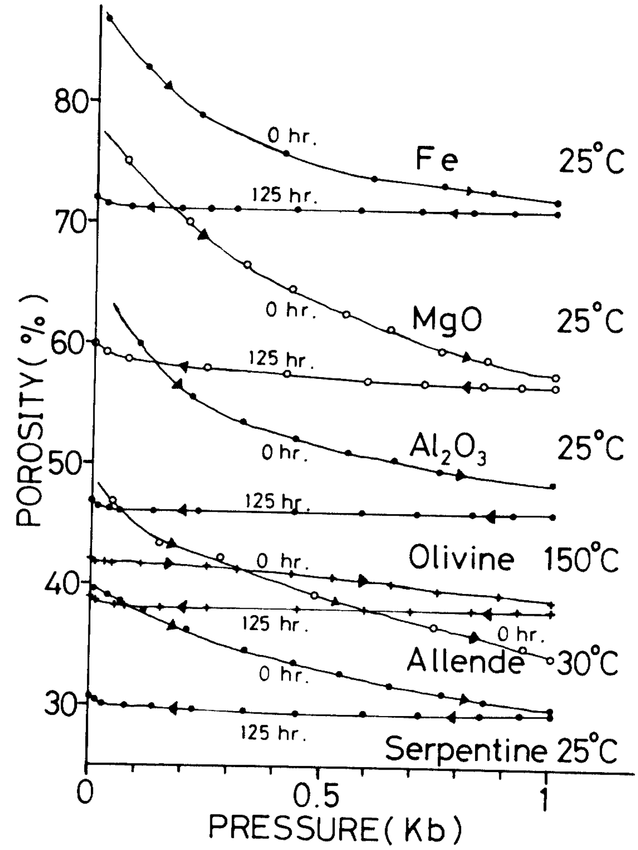

Fig. 2. Porosity variation with applied pressure. Experiments were conducted under 1 atm. N_2 gas except for the Allende (after HONDA *et al., 1979 and* YOMOGIDA *et al., 1980).*

Using the powdered samples (Allende meteorite, olivine (Hawaiian Dunite), serpentinite, Fe, MgO and Al_2O_3), we are conducting a sintering experiment under low temperature (up to 300°C) and vacuum conditions (up to 10^{-7} mmHg). In Fig. 2 are shown the variation of the porosity with applied pressure of these samples (HONDA *et al.*, 1979; YOMOGIDA *et al.*, 1980). As easily seen from this figure, the crushed rock and meteorite samples suffer significant compaction compared to other samples. It is tentatively suggested from this experiment that size distribution of grains may play a key role in the sintering process under low temperature and pressure conditions. Because, one big difference between the rock and meteorite samples and the other is their size distributions. Specifically, adhesive agents such as, for example, metal embedded within silicate grains in the meteorite sample may play an important role in the sintering process of meteorites. The porosity of the Allende metorite is, however, still lower than that of the most-sintered Allende sample at 2 kb (about 30%). Such discrepancy may be solved by the time effect since, in fact, a very long time is available for the sintering of meteorites.

4. Discussion

The ultrasonic-wave velocities of some stony meteorites have been measured by ALEXEYEVA (1960). Her data are summarized in Table 3. Although ρ_{bulk} and ρ_0 have not appeared in her paper, we can estimate these values from the porosity data. Elastic constants can also be calculated. Extremely high Poisson's ratio is noticed. However, such high Poisson's ratio is questionable since it is derived from the dynamical experiment such as velocity data. Poisson's ratio of porous materials differs significantly between dynamical and static conditions: for example, Poisson's ratio of tuff calculated from the velocity is about 0.4, whereas the value obtained from the static experiment is about 0.1 (BIRCH, 1966; PRESS, 1966). Therefore, we need a static experiment of meteorites in the future.

Our results seem to demonstrate the presence of velocity anisotropy (>4%). We should notice, however, that for the ALHA77231 the velocity decreases with the sample length. Such tendency might be also explained by the scattering effect due to existence of many pores. However, anisotropy as much as 10% is considered to be difficult to explain by the scattering effect only. Therefore, careful treatments are necessary when we discuss the systematics such as velocity-petrologic type systematics of meteorites. In addition, elastic properties of the whole meteorite sample are probably different from those of the sample measured in laboratory if the size of the sample is small, since meteorites are usually not homogeneous in both texture and composition to some extent. In this study, we used the relatively large sample (larger than 1 cm^3) to avoid such ambiguity: the size of the sample measured in the present study is considered to be large enough to characterize the elastic properties of the whole meteorite sample judging from the observed grain sizes of the sample.

In summary, the following measurements are proposed for the future studies based on the present preliminary study. (1) Both static (either compression or tension) and dynamic experiments are necessary for estimating the elastic constants of meteorites. (2) We need to measure both compressional and shear wave velocities in more detail by changing applied stresses, frequency of transducers, and so on. (3) Extensive and systematic measurements are indispensable for revealing the nature of consolidation process of meteorites and their origin.

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