

CMWG Report Material Density and Porosity

Physical Properties of CI and CM Carbonaceous Chondrites
CMWG Report – Lindsay Keller, Lead Scientist
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Introduction

Analysis of meteorite analogues have concluded that the most likely meteorite analogs for Bennu are the CI and CM meteorites. This report is a compilation of available data on the physical properties of these carbonaceous chondrite types and focuses on density, porosity, strengths, thermal conductivity and electrical conductivity (Table 1 and 2). These data should allow constraints to be placed on the likely parameter space to be expected at the surface of Bennu. Sections I and II are taken from a report compiled by P. Michel for the RDWG earlier this year.

I. Solid material density and microporosity

The possible microporosity and density of the solid material composing Bennu may be estimated on the basis of density and porosity measurements of its most likely meteorite analogs: CM and CI. However, note that meteorites may have been subjected to compaction processes, possibly during the extraction of their parent bodies (numerical simulations of impact on porous materials tend to show that the ejected material is generally more compact than its original state within the parent body), and also believe that our meteorite collection is biased towards the stronger component of materials in space that can survive atmospheric entry. So, the values provided by those meteorites may be considered as possible upper limit in terms of the bulk density, compared to the actual density of the solid material composing Bennu. Macke et al. (2011) published a paper in December 2011 in which they describe the first detailed measurements of density and porosity of various types of Carbonaceous Chondrites, including CM and CI. Without going into the details of the measurements, the following subsections summarize for these two groups the relevant information for the RDWG.

CM Chondrites

Bulk densities are rather low, although not as low as Orgueil (see below for CI). They average 2.20 g/cc, with a range from 1.88 to 2.47 g/cc. Grain densities average 2.92 g/cc, with a low of 2.74 g/cc and a maximum value of 3.26 g/cc. CMs are quite porous, averaging 24.7% and ranging from 15.0% to 36.7%.

CI Chondrites

CI meteorites are highly porous, extremely friable, and quite rare, with only nine meteorites of the type known. Because of their extreme friability, Curators and collections managers have been reluctant to grant access for whole-rock study even using the relatively benign methods employed in this study, and no new report is provided for CIs by Macke et al. (2011). However,

Consolmagno and Britt (1998) report physical properties of Orgueil from the Vatican collection. Its grain density (2.43 g/cc) and bulk density (1.58 g/cc) place it among the least dense of chondrites, and give it a very high porosity of 35%. It should be noted that porosity of the extremely primitive and friable ungrouped CC Tagish Lake, determined by methods comparable to Macke et al.'s one, was comparably high at an average of 40% over multiple stones (Hildebrand et al., 2006). Such high porosities are therefore not unreasonable nor unheard of.

Summary: If we assume CM-like material for the solid material of Bennu, the bulk density may be about 2.2 g/cc (and porosity about 25%); if we assume CI-material, then the bulk density may be lower (1.6 g/cc for Orgueil) and microporosity higher (35%). So, if one wants to stick to the range of measured values for CI and CM, we may consider the measured range accounting for both types, i.e. within 1.6 – 2.5 g/cc. However, because meteorites are likely to be more compacted or less fragile than pristine material, we may consider a range of bulk densities including lower values, e.g. within 1.0 – 2.0 g/cc. The microporosity of this material would then be from 20 to 40%, maybe higher if pristine material is not as compacted (microporous materials on Earth can have a much greater fraction of microporosity: for instance, without claiming this is a good analog, a bloc of solid pumice can have a microporosity as high as 80-90%).

II. Macro-porosity

The question of macro-porosity is even more difficult. What we may say is that if the bulk density of Bennu is 0.98 g/cc, and if we assume that the bulk density of its solid component is 2 g/cc (upper range above, already including micro-porosity), its macro-porosity is 51%; say 50%. Note that usually the exercise is done using the grain density of meteorites instead of their bulk density, and the derived porosity for the whole asteroid is higher as it includes both micro and macro-porosity. Here I only consider macro-porosity, having already addressed the micro-porosity in the previous section.

However, what does 50% macro-porosity mean? No one knows and we speculate: It can correspond to 50% of void space distributed uniformly in large voids separating a large number of small monolithic (micro-porous) blocs. It can also correspond to <50% of void space distributed in small voids separating a small number of big monolithic (micro-porous) blocs, added with a thick layer of loose regolith, to reach the 50% level. This regolith may still be composed of the same kind of solid material, but instead of being cohesive, as large monolithic blocks, it may be composed of structurally loose smaller components (cohesionless, but possibly with a Mohr-Coulomb/Drucker-Prager shear strength behavior), maybe down to grain size. Its level of compaction (or how much packed it is) depends on its dynamical history (and various processes such as thermal cycling) and on how much we leave for large voids in the macro-porosity fraction, which unfortunately cannot be constrained at this stage except on a purely arbitrary basis. In other words, there are different combinations of large void fraction and regolith (and its packing) fraction that can lead to the same whole macro-porosity. Unfortunately at this stage, we don't see any rationale that can allow us to give plausible estimate of the level of compaction we might or can expect for the regolith material on Bennu. This goes back to a more general discussion about the regolith properties we can expect on Bennu, which is not the scope of this report.

Note that in the close future, we plan to look at the possible regolith formation and evolution on Benu, based on its possible dynamical history, the history of Earth approach distances (to check whether they may have helped freshening the surface) etc. But this is an ambitious project, requiring simulations of regolith evolution under various effects and the investigation of a large parameter space that cannot be done on a time short enough to provide information at the current stage.

Electrical conductivity in meteorites and terrestrial rocks

Sample	Type	$\sigma(300\text{K})$ (ohm-cm) ⁻¹	Low-temperature σ_0 (ohm-cm) ⁻¹
<i>Carbonaceous chondrites</i>			
Orgueil	C-1	$3-8 \times 10^{-11}$	—
Cold Bokkeveld	C-2	$4-7.5 \times 10^{-11}$	—
Mighei	C-2	$0.4-4 \times 10^{-9}$	—
		3×10^{-9}	—
		2×10^{-8}	2.8×10^{-8}
Murchison	C-2	5×10^{-9}	3.8×10^{-9}
Lancè	C-30	$0.2-2 \times 10^{-5}$	—
		$1.4-3.5 \times 10^{-5}$	—
		2×10^{-3}	—
		1.2×10^{-5}	2.2×10^{-5}
Allende	C-3V	$0.2-5 \times 10^{-6}$	—
		$4-5.5 \times 10^{-7}$	—
		2.7×10^{-7}	4.8×10^{-7}
		2.7×10^{-7}	—
Ornans	C-4,50	$1-4 \times 10^{-11}$	—
<i>Other meteorites</i>			
Kelly	LL-4	2×10^{-9}	—
Arriba	L-5	$1-8 \times 10^{-6}$	—
Leedey	L-6	4×10^{-7}	—
Plainview	H-5	$1.6-11 \times 10^{-4}$	—
Richardson	H-5	$1.8-6 \times 10^{-7}$	—
Rose City	H-6	$7-15 \times 10^{-2}$	—
Pinto Mts.	(L)	7×10^{-9}	—
Elenovka	(L)	8×10^{-6}	—
Norton Cty.	Ach.	1.2×10^{-8}	—
Goalpara	Ach.	$1-4 \times 10^{-3}$	—
		8.5×10^{-4}	—
<i>Terrestrial rocks</i>			
Serpentine	—	$1-10 \times 10^{-10}$	—
		4×10^{-9}	3×10^{-9}
Serpentine marble	—	$1-20 \times 10^{-11}$	—
		5×10^{-10}	1.2×10^{-10}
Olivine	—	1×10^{-12}	—

Table 1. Physical properties of carbonaceous chondrites taken directly from Macke et al. (2011).
III. Strength of Materials

Limited laboratory data are available on the compressive and tensile strengths of meteoritic materials. Tsuchiyama and colleagues (Tsuchiyama et al. 2008; 2009) have obtained tensile strengths of CM, CI and Tagish Lake (TL) chondrites. The tensile strengths range from ~0.3 to 30 MPa with a general trend of lower strength from CM>CI>TL. Higher petrographic (i.e., metamorphic) grade ordinary chondrites have typical tensile strengths of ~30-40 MPa and

compressive strengths ranging from ~60 to 450 MPa (Popova et al. 2011). The “average” tensile strength of Murchison is ~2 MPa, and the averages for CIs and TL are slightly lower. The compressive strength of Murchison is reported to be ~50 MPa (Tsuchiyama et al., 2008).

Material strengths have also been inferred from the break-up of bolides with well-constrained trajectories (Popova et al. 2011). Popova et al. estimate the strength of Tagish Lake between 0.3 and 1.3 MPa based on the height of earliest fragmentation and major fragmentation, respectively. More importantly, they note that the bulk strengths at atmospheric entry are low and describe the bolides as “weak and crumbly” objects compared to the measured tensile strengths of recovered fragments.

IV Thermal Properties

Thermal conductivities of chondritic meteorites range from ~0.5 to 4.5 W/m/K and are nearly constant with temperatures >100K as shown in the figure 1 below (Szurgot 2011; Opeil et al. 2012). Opeil et al. (2012) note that the thermal conductivity of meteorites are, in general, lower by up to a factor of 3-10 than that of a collection of the pure minerals from which they are made. They also note that a linear relationship exists between thermal conductivity and the inverse of porosity and suggest that micro-cracks and porosity provide a barrier to the transmission of thermal energy in these objects.

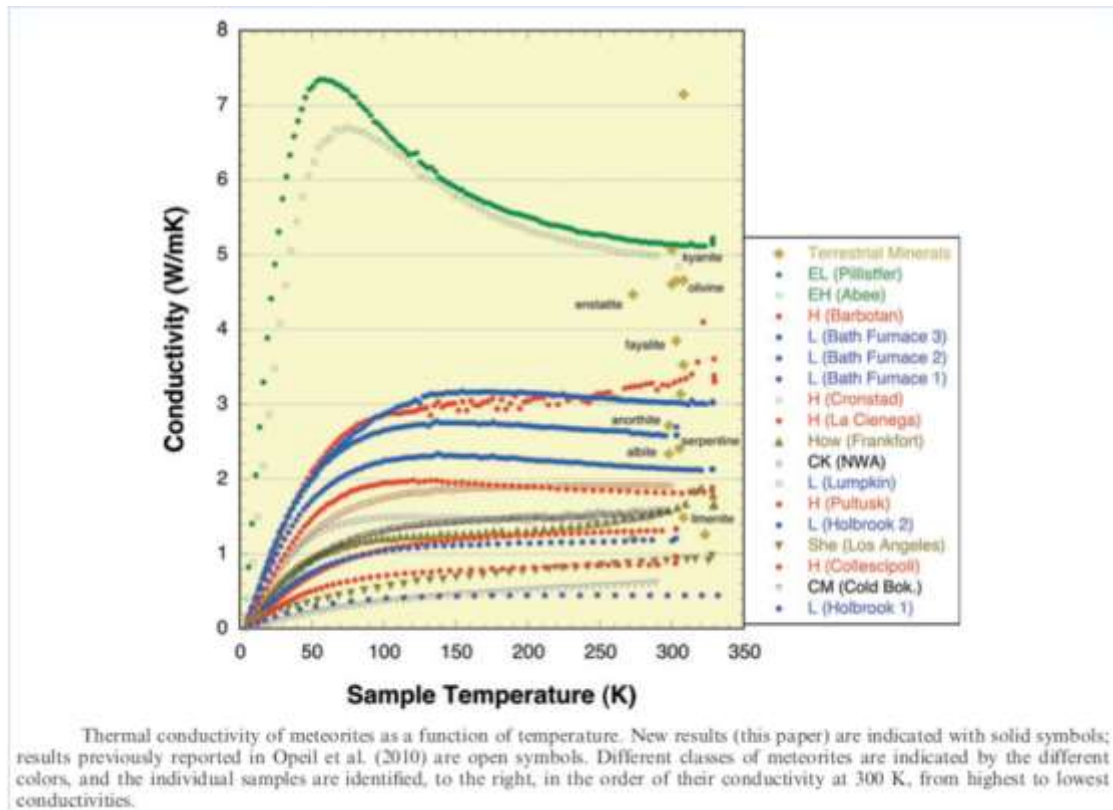


Figure 1. Conductivity vs. sample temperature for chondrites and terrestrial minerals. From Opeil et al. (2012).

V. Electrical Properties

The electrical conductivities (ECs) of carbonaceous chondrites are not well known (Table 2). Brecher et al. (1975) measured conductivities of a number of carbonaceous chondrites (Lance, Murchison, Meighe, and Allende) at low temperatures (90-300K; Fig. 2); Duba and Boland (1984) measured Murchison and Allende at temperatures up to >700C (973K; Fig. 3). The results of both studies show that carbonaceous meteorites are substantially more conductive at low temperatures than terrestrial olivine and terrestrial rocks, even when dried prior to measurement. From the data in Brecher et al. (1975), the anhydrous, high petrographic grade chondrites typically show the highest electrical conductivities, the CMs are intermediate, and the one CI chondrite measured show an EC similar to terrestrial serpentinites. For all the meteoritic samples examined in these two studies, EC is dependent both on temperature and the meteorite's thermal history. Possible explanations for this behavior are a) temperature-dependent variation in the abundance of free carriers corresponding to variations in metal content (Brecher et al., 1975); or b) thermally controlled variations in carbon-rich grain-coating residues that moderate conductivity (Duba and Boland 1984). To our knowledge, to date, no systematic studies of the effects of variations in metal content (e.g., free native iron) or other species (organic or otherwise) on electrical conductivity or dielectric constant have been performed, either on meteorite material or on manufactured samples of simpler composition.

Table 1. Physical property averages for carbonaceous chondrite falls by petrographic type.

Petrographic type	No. meteorites	Bulk density (g cm ⁻³)		Grain density (g cm ⁻³)		Porosity (%)		Magnetic susceptibility (log γ)	
		Average	Max. Min.	Average	Max. Min.	Average	Max. Min.	Average	Max. Min.
1	1	1.57	1.57	2.42	2.42	34.9	34.9	4.49	4.49
2	13	2.26 ± 0.09	3.05 1.88	2.93 ± 0.05	3.37 2.74	23.1 ± 2.2	36.7 9.5	4.03 ± 0.16	5.11 3.30
3	10	2.90 ± 0.08	3.22 2.42	3.63 ± 0.03	3.74 3.50	21.0 ± 2.7	34.2 8.3	4.39 ± 0.12	4.81 3.65
4	4	3.04 ± 0.19	3.23 2.85	3.58 ± 0.02	3.60 3.56	15.0 ± 5.8	20.8 9.2	4.55 ± 0.12	4.67 4.43

Note: "±" denotes 1 SD among the meteorites represented.

Table 2. Adapted from Brecher et al. (1975).

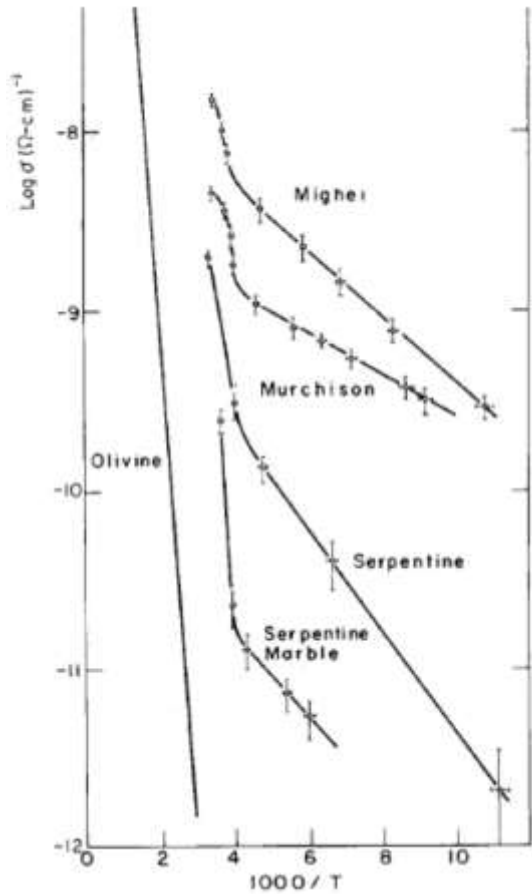


Figure 2. Figure adapted from Figure 2 of Brecher et al. (1975) showing the electrical conductivities of two CM chondrites and two terrestrial serpentinites as a function of temperature.

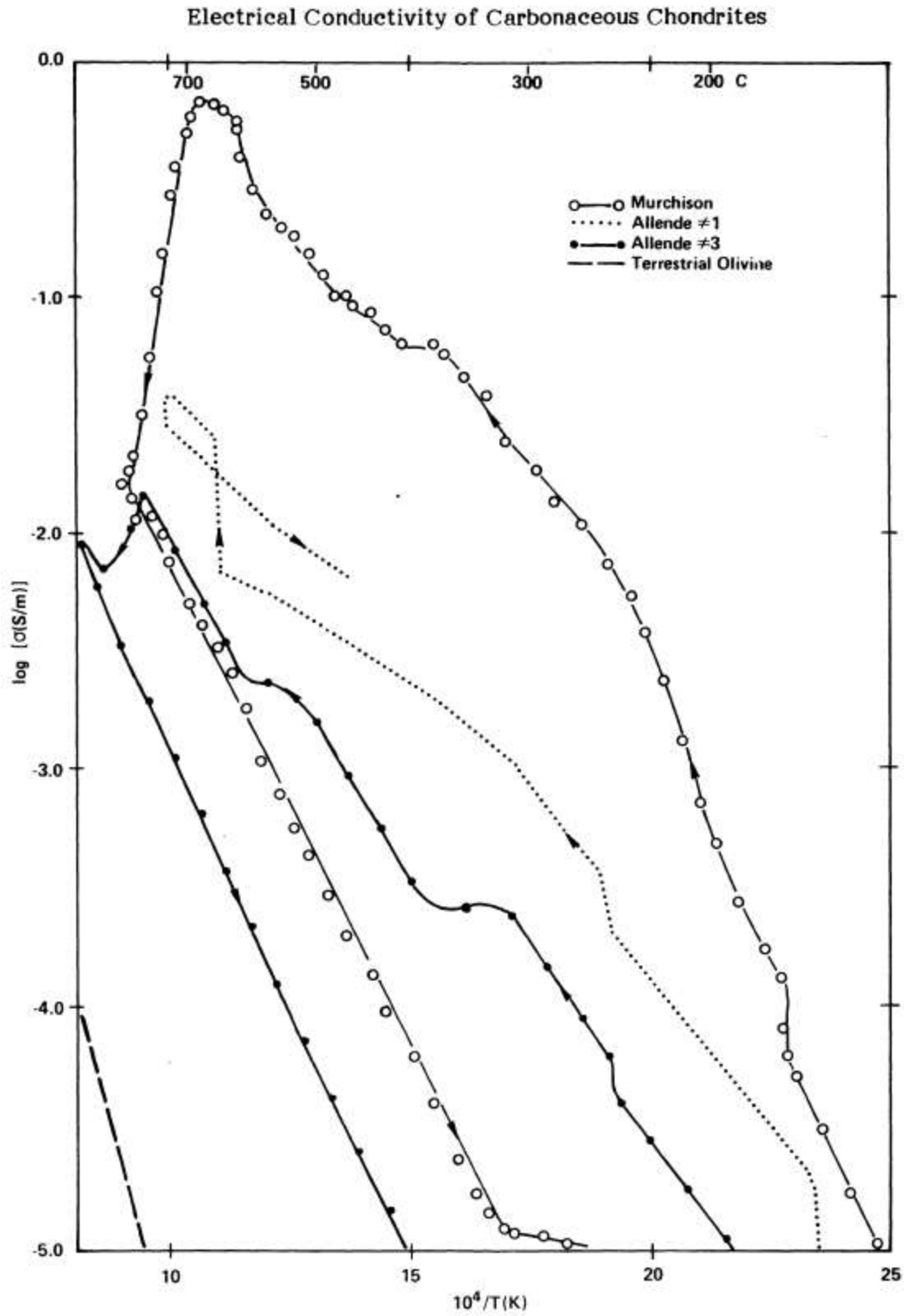


Figure 3. Electric properties vs. temperature for two carbonaceous chondrites and two terrestrial

samples. Taken directly from Duba and Boland (1984).

References:

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Revised 1 October 2013: Changes made via Becky Ghents by adding references to Duba and Boland (1984) and added some text to section V. Connolly also updated various aspects of the text and organized the tables and figures.