ON THE MEAN GRAIN DENSITY OF PULTUSK, CHELYABINSK, MURRAY AND MURCHISON CHONDRITES, AND MEAN DENSITY OF THEIR PORES. M. A. Szurgot, Lodz University of Technology, Center of Mathematics and Physics, Al. Politechniki 11, 90 924 Lodz, Poland (mszurgot@p.lodz.pl).

Introduction: Knowledge of bulk density *(db)*, grain density *(dgr)* and porosity *(P)* is important to characterize minerals and rocks, planets, moons, and asteroids. The aim of the paper was to confirm and apply the relationship between bulk density and porosity for ordinary chondrites, to verify grain densities of Pultusk, Chelyabinsk, Murray, and Murchison chondrites, and to estimate density of matter filling their pores. Literature data on bulk densities and poros-ities of individual chondrites and chondrite groups have been used [1-3].

Results and discussion:

There exists relationship between bulk density $db(g/cm^3)$ and porosity $P(\%)$ for ordinary chondrites which is expressed by the equation:

$$db(P) = - a\cdot P + b, \quad (1)$$

where constants *a* and *b* are different for H, L, and LL chondrites, and different for falls and finds [1-2]. *db(P)* dependence was also discovered for various types of terrestrial rocks [4], and was shown that *a* and *b* constants depend on the rock type (sandstone, limestone, dolomite), and on material occupied their pores: air, water, gas, oil or their mixture [4].

If porosity is determined by the equation:

$$P = (1 - db/dgr), \quad (2)$$

then eq. (1) takes the form:

$$db(P) = (-dgr)\cdot P + dgr, \quad (3a)$$

or the form:

$$db(P) = (-dgr/100)\cdot P(\%) + dgr, \quad (3b)$$

for *P* given in percents. This means that values of constants *a* and *b* in eq. (1) should be equal to: *b* = *dgr*, and *a* = *dgr*, or *a* **=** *dgr/100* (eqs. (3a), (3b)).

An analysis of literature data for terrestrial rocks and ordinary chondrites indicates that expected relation $a = b$ is rarely realized, usually we have $a \le b$ (eqs.(7)-(13), and table 1 for OCs and CMs).

To describe physical properties of porous rocks we can separate constituent matter into two parts: rock skeleton/matrix, and matter of pores **[**4]. For a two component rock the following relation can be applied:

$$db(P) = (1- P)\cdot dgr + P\cdot dpores, \quad (4)$$

where *dpores* is the mean density of fluid present in pores and fractures, and *dgr* is the mean density of solid sceleton material. Coefficient *(1–P)* represents a volume part occupied by the minerals forming meteorite, and *P* represents a volume part of the rock occupied by the pores [4]. Equation (4) can been rewritten as follows:

$$db(P) = -(dgr-dpores)\cdot P + dgr, \quad (5a)$$

or

$$db(P) = - (dgr – dpores)/100)\cdot P + dgr, \quad (5b)$$

if *P* is given in percents. This means that values of constants *a* and *b* present in equation (1) are equal to: *a = dgr-dpores* (for eq. (5a)), or *a* **= (***dgr-dpores)/100* (for eq. (5b)), and *b = dgr.*

Equations (5a) and (5b) enable one to determine/verify mean grain density of an individual chondrite or a group of chondrites:

$$dgr = b, \quad (6a)$$

and to determine/predict mean density of pores:

$$dpores = b – a = dgr – a, \quad (6b)$$

or:

$$dpores = b – 100\cdot a = dgr – 100\cdot a, \quad (6c)$$

in the case when *P* is expressed in percents.

Literature data on experimental values of bulk densities, porosities and grain densities of two ordinary chondrites: Pultusk (H5) [1], and Chelyabinsk (LL5) [3], and two carbonaceous (CM2) chondrites: Murray and Murchison [1], were used to verify *db(P)* relation-ship.

For Pultusk meteorite the following relation has been obtained:

$$db(P) = - (0.0333\pm0.0053)\cdot P + (3.71\pm0.04), \quad (7)$$

for which R^2 = - 0.80, and RMSE = 0.08.

The mean grain density of Pultusk H5 chondrite established by *db(P)* relationship is equal to *dgr* = 3.71 ±0.04 g/cm^3, and predicted mean density of pores: *dpores* = 0.38±0.09 g/cm^3. These are reasonable values. Mean grain density established by Macke [1] for many Pultusk meteorite samples equals 3.72 g/cm^3, and range of values of Pultusk individual meteorites *dgr*: 3.54-3.89 g/cm^3 [1]. The value of density of Pultusk pores indicates that certain heavy matter rather than exclusively air fills the pores.

For light and dark lithologies of Chelyabinsk LL5 meteorite, the following relation has been obtained:

$$db(P) = - (0.0315\pm0.0045)\cdot P + (3.48\pm0.03), \quad (8)$$

for which R^2 = - 0.87, and RMSE = 0.05.

The mean grain density of Chelyabinsk LL5 chondrite established by *db(P)* relationship is equal to *dgr* = 3.48±0.03 g/cm^3, and mean density of pores: *dpores* = 0.33±0.03 g/cm^3. These are also reasonable values. Mean grain density established by Kohout and coworkers [3] equals 3.42±0.10 g/cm^3 for dark lithology of Chelyabinsk chondrite, and 3.51±0.07 g/cm^3 for the light lithology. The mean density of Chelyabinsk mete-orite pores is comparable to the value of *dpores* of Pultusk chondrites.

For Murray (CM2) meteorite, the following relation has been obtained:

$db(P) = - 0.0273 \cdot P + (2.87 \pm 0.03)$, (9)

for which R^2 = - 0.95, and RMSE = 0.02.

The mean grain density of Murray established by *db(P)* relationship is equal to: 2.87±0.03 g/cm^3, quite close to the mean value: 2.91 g/cm^3 measured by Macke [1], and the mean density of Murray pores is equal to: 0.14±0.06 g/cm^3.

For Murchison (CM2) meteorite, the following relation has been obtained:

$db(P) = - 0.0281 \cdot P + (2.93 \pm 0.10)$, (10)

for which R^2 = - 0.86, and RMSE = 0.04.

The mean grain density of Murchison established by *db(P)* relationship is equal to: 2.93±0.10 g/cm^3, quite close to the mean value: 2.96 g/cm^3 measured by Macke [1], and the mean density of Murchison pores is equal to: 0.12±0.10 g/cm^3.

Li et al. [2] established *P(db)* dependences for ordinary chondrites falls, which after rearrangement into *db(P)* relation take the forms:

$db(P) = -0.0364 \cdot P + 3.78$, (11)

for H falls,

$db(P) = -0.0352 \cdot P + 3.58$, (12)

for L falls, and

$db(P) = -0.0342 \cdot P + 3.51$, (13)

for LL falls.

According to the data, values of coefficients *a* in eqs. (11)-(13) are nearly the same, and of coefficients *b* are different for H, L and LL falls.

Table 1. Values of coefficients: *b* = *dgr*, *a* = *dgr* – *dpores*, and *dpores* = *b* - *a* for Murray (CM2), Murchison (CM2), Pultusk (H5), and Chelyabinsk (LL5) chondrites, as indicated by values of *db* and *P* measured by Macke [1], and Kohout et al. [3], and for H, L, and LL falls, as well as Antarctic H finds resulted from experimental data reported by Li et al. [2].

Chondrite / Group	***dgr = b*** *(g/cm^3)*	***a*** *(x0.01 g/cm^3)*	***dpores*** *(g/cm^3)*
Murray	*2.87±0.03*	*2.73*	*0.14*
Murchison	*2.93±0.10*	*2.81*	*0.12*
Pultusk	*3.71±0.04*	*3.33*	*0.38*
Chelyabinsk	*3.48±0.03*	*3.15*	*0.33*
H falls	3.78	3.64	0.14
L falls	3.58	3.52	0.06
LL falls	3.51	3.42	0.09
H finds	3.65	7.52	-3.87

Table 1 presents data on values of coefficients *a*, and *b* of equation (5a), and *dpores* (eq.(6b) for falls of various groups: H, L and LL of ordinary chondrites, and for Antarctic H finds, resulting from values of *db* and *P* of individual meteorites measured by Li and coworkers [2], and for Murray (CM2), Murchison (CM2), Pultusk (H5) and Chelyabinsk (LL5) chondrites as established in this report using Macke [1] and Kohout et al. [3] experimental data.

The data collected in Table 1 and presented by eqs. (7)-(13) confirm that Pultusk, Chelyabinsk, Murray and Murchison chondrites, and H, L and LL groups of ordinary chondrites falls follow the equation (5) and values of *dgr* and *dpores* are reliable.

Combined data (eqs. (7), (8), (11)-(13) and Table 1) indicate values of mean grain densities: 3.78 g/cm^3 for H falls; 3.58 g/cm^3 for L falls; and 3.51 g/cm^3 for LL falls. These values are comparable with the mean grain densities established by Macke: 3.71 g/cm^3 for H falls, 3.58 g/cm^3 for L falls, and 3.52 g/cm^3 for LL falls [1], and are comparable to mean grain densities established by Li et al.: 3.78±0.06 g/cm^3 for H falls, 3.58±0.07 g/cm^3 for L falls, and 3.51±0.02 g/cm^3 for LL falls [2].

Preliminary data for mean density of matter of pores indicate the values: 0.14-0.48 g/cm^3 for H falls, 0.06 g/cm^3 for L falls, and 0.09-0.33 g/cm^3 for LL falls. Positive values of *dpores* indicate that *dpores* < *dgr.*

Negative value of *dpores* for Antarctic H finds (Table 1) indicates that *dpores* > *dgr*. This means that weathering processes lead to decrease in mean grain density: from 3.78 g/cm^3 for H falls to 3.67 g/cm^3 for H finds, and to increase in density of matter of pores. Matter filling the pores consists likely of weathering products of meteorite minerals, mainly weathering products of metallic phases.

Conclusions: Relationship between bulk density and porosity for ordinary and carbonaceous chondrites has been confirmed. New form of *db(P)* dependence has been derived (eq. (5)), explained, and applied. It was shown that reliable values for grain density of Pultusk, Chelyabinsk, Murray, and Murchison chondrites, and for H, L, LL chondrite group have been obtained using *db(P)* dependence. Preliminary data on values of mean density of pores has been predicted for ordinary chondrites. The values of *dpores* indicate that weathering of Pultusk, Chelyabinsk, Murray, and Murchison meteorites takes place.

References: [1] Macke R. J. (2010) *PhD Thesis*, Univ. Central Florida, Orlando. [2] Li S. J. et al. (2019) *J. Geophys. Res., Planets 124*, 2945-2969. [3] Kohout T. et al. (2014) *Icarus 228*, 78-85. [4] Schön J.H. (2011) *Physical Properties of Rocks A Workbook*, Elsevier, Amsterdam.