

RELATIONSHIP BETWEEN GRAIN DENSITY AND MEAN ATOMIC WEIGHT FOR LUNAR MATERIALS. PREDICTING GRAIN DENSITY OF LUNAR METEORITES. M. Szurgot, Lodz University of Technology, Center of Mathematics and Physics, Al. Politechniki 11, 90 924 Lodz, Poland (mszurgot@p.lodz.pl).

Introduction: Knowledge of densities, iron to silicon ratios, and mean atomic weights is important to characterize minerals and rocks, planets, moons, and asteroids. Lunar matter is interesting and important subject of investigations [1-6]. There exists relationship between density $d(g/cm^3)$ and mean atomic weight (A_{mean} , A) which enables one to determine uncompressed density of planets, moon, and asteroids, and grain density of ordinary and enstatite chondrites. $d(A_{mean})$ dependence is expressed by the equation:

$$d(A_{mean}) = 0.133 \cdot A_{mean} + 0.37, \quad (1)$$

for which RMSE = 0.07 [7].

Equation (1) predicts reliable values for uncompressed density of the Moon: 3.27 g/cm³ ($A_{mean} = 21.8$) [8], and for lunar core: 7.06 g/cm³ ($A_{mean} = 50.3$) [8], but leads to too high grain densities for lunar rocks and regolith. The aim of the paper was to discover new empirical relationship between grain density d and mean atomic weight A_{mean} of Moon's crustal materials, and to predict grain density of lunar meteorites, lunar rocks, and global lunar crust.

Literature data on chemical composition [5,9-14] and experimental values of grain densities for lunar meteorites and Apollo samples [15,16] have been used to establish new $d(A_{mean})$ relationship. Various lunar meteorites and Apollo samples representing various groups of lunar crust materials were analyzed.

Mean atomic weights A_{mean} were calculated using the following formula:

$$A_{mean} = \sum w_i / \sum (w_i / A_i), \quad (2)$$

where w_i (wt%) is the mass fraction of i th element, and i th oxide, and A_i is atomic weight of i th element and i th oxide.

Results and discussion: Collected data indicate that $d(A_{mean})$ dependence describing lunar surface materials can be expressed by the equation:

$$d(g/cm^3) = 0.296 \cdot A_{mean} - 3.52, \quad (3)$$

for which R² = 0.97, and RMSE = 0.06.

We can predict A_{mean} value by grain density d using $A_{mean}(d)$ relation:

$$A_{mean} = (d + 3.52) / 0.296 \quad (4)$$

for which RMSE = 0.21, and values of d specified in this equation are given in g/cm³.

Our data indicate that there exists also second dependence: $d(Fe/Si)$ relationship for lunar crust materials, which enables us to predict or verify grain density by Fe/Si atomic ratio:

$$d(g/cm^3) = 1.60 \cdot Fe/Si + 2.73, \quad (5)$$

for which R² = 0.97, and RMSE = 0.06.

Tables 1, 2 and 3 compile data on A_{mean} , experimental $dexp$, and predicted by eqs. (3) and (5) values of grain densities $d(g/cm^3)$ of lunar meteorites and Apollo returned samples.

Table 1. Mean atomic weights A , predicted grain densities $d(A)$, $d(Fe/Si)$ and experimental values of grain densities $dexp(g/cm^3)$ of first group of lunar meteorites, and Apollo samples.

Meteorite/Rock	A	$d(A)$	$d(Fe/Si)$	$dexp$ [15]
60025	21.41	2.82	2.74	>2.71
Dho 733	21.46	2.83	2.82	-
Dho 302	21.50	2.84	2.83	-
Dho 081	21.57	2.86	2.83	
Y 82192	21.58	2.87	2.86	-
DaG 400	21.63	2.88	2.84	-
QUE 93069	21.63	2.88	2.86	-
MAC 88104	21.63	2.88	2.86	-
Dho 026	21.63	2.88	2.85	-
DaG 262	21.64	2.89	2.86	-
NWA 482	21.64	2.89	2.85	2.84, 2.87
ALHA 81005	21.65	2.89	2.89	-
Dho 025	21.67	2.89	2.88	-
Y 791197	21.74	2.92	2.92	-
15418	21.77	2.92	2.92	2.92
NWA 4932	21.83	2.94	2.98	2.91
PCA 02007	21.84	2.94	2.94	-
NWA 5000 cl	21.92	2.97	2.95	2.87
Highland crust	21.62*	2.88*	2.85*	-

*Mean values for Demidova et al. [9] bulk composition, cl=Clast.

Comparison of grain densities predicted by eq. (3) and by eq. (5) and those measured in the laboratory reveals satisfactory agreement. Mean value of grain density of anorthosite, highland rocks predicted by $d(A)$ dependence is equal to 2.88 g/cm³ ($A = 21.62$), mixed basaltic-anorthositic rocks: 3.03 g/cm³ ($A = 22.13$), and basaltic, mare rocks: 3.33 g/cm³ ($A = 23.15$). They are close to the values determined by $d(Fe/Si)$ relationship: 2.85, 3.05, and 3.34 g/cm³, respectively (Tables 1-4).

Mean grain density of lunar crust predicted by equation (3) is equal to: 2.90 g/cm³ ($A_{mean} = 21.7$ [7]), and by eq. (5): 2.92 g/cm³ (Table 4).

Table 2. Values of A , $d(A)$, $d(Fe/Si)$, and $dexp(g/cm^3)$ of second group of lunar meteorites and Apollo samples.

Meteorite/Rock	A	$d(A)$	$d(Fe/Si)$	$dexp$ [15]
77035 m	21.81	2.94	2.98	>3.05
72395	21.85	2.95	2.99	>3.07
Dho 925	21.90	2.96	2.99	-
Y 983885	21.91	2.97	3.01	-
14303 m	21.99	2.99	3.04	3.05
14321 m	22.14	3.03	3.09	3.03
Calcalong Creek	22.25	3.07	3.04	-
QUE 94281	22.36	3.10	3.13	-
Y 793274	22.38	3.10	3.13	-
Intermediate	22.13*	3.03*	3.05*	-

m-matrix.

Table 3. Values of A , $d(A)$, $d(Fe/Si)$, and $dexp(g/cm^3)$ of third group of lunar meteorites and Apollo samples.

Meteorite/Rock	A	$d(A)$	$d(Fe/Si)$	$dexp$ [15,16]
NWA 773	22.57	3.16	3.29	3.24
EET 87521	22.81	3.23	3.25	-
NWA 4898	22.82	3.23	3.23	3.27
15545	23.01	3.29	3.39	-
12009	23.10	3.32	3.36	-
LAP 02205	23.18	3.34	3.31	3.35
Dho 287 (lith A)	23.18	3.34	3.41	-
MIL 05035	23.21*	3.35	3.33	3.35
NWA 4734	23.23	3.36	3.50	3.41
15555	23.23	3.36	3.41	3.35
12051	23.25	3.36	3.33	3.32
12063	23.33	3.39	3.38	3.36
NWA 032	23.35	3.39	3.40	-
Y 793169	23.40	3.41	3.41	-
Asuka 881757	23.41	3.41	3.41	-
NWA 2977	23.41*	3.41	3.27	3.41
70215	23.69	3.49	3.43	3.46
Mare crust	23.15*	3.33*	3.34*	-

#Mean values for Demidova et al. [9] bulk composition.

*Values predicted by eq. (4).

Equation (3) leads to the following values of grain densities of lunar meteorites: NWA 482: 2.89 g/cm³ (2.84-2.87 g/cm³), NWA 5000: 2.97 g/cm³ (2.87 g/cm³), NWA 4932: 2.94 g/cm³ (2.91 g/cm³), NWA 4898: 3.23 g/cm³ (3.27 g/cm³), LAP 02205: 3.34 g/cm³ (3.35 g/cm³), where values shown in parentheses are grain densities measured by Kiefer and coworkers [15], and by Macke [16].

Table 4. Range of A , $d(A)$, $d(Fe/Si)$, and $dexp(g/cm^3)$ values for lunar rocks. A=anorthositic 1st group, I=intermediate, basaltic-anorthositic 2nd group, B=basaltic 3rd group, GC=Global Moon's crust, mGC=mean global crust, mUC=mean upper crust, mLC=mean lower crust.

	A	$d(A)$	$d(Fe/Si)$	$dexp$ [15]
A	21.4-21.9	2.82-2.97	2.74-2.98	2.71-2.92
I	21.8-22.4	2.94-3.10	2.98-3.13	3.03-3.10
B	22.5-23.7	3.16-3.49	3.23-3.50	3.24-3.46
GC	21.4-23.7	2.82-3.49	2.74-3.50	2.71-3.46
GC				2.85-3.55 [#]
mGC	21.7 [7]	2.90	2.92	-
mUC				2.86* [2]
mLC				2.94-3.04*

[#]Grain densities estimated using FeO and TiO₂ content by $d(Fe-Ti)$ relation [3], and *by modeling crust mineralogy [2].

Predicted mean grain density: i) global lunar crust: 2.90 - 2.92 g/cm³, ii) highland crust: 2.85 - 2.88 g/cm³, and iii) mare crust: 3.33 - 3.34 g/cm³.

Predicted mean atomic weight: i) global lunar crust: 21.7 (range: 21.4 - 23.7), ii) highland crust: 21.62 (21.4 - 21.9), iii) intermediate crust: 22.13 (21.8 - 22.4), and iv) mare crust: 23.15 (23.5 - 23.7).

Conclusion: Grain density of lunar surface materials can be estimated by mean atomic weight, and by Fe/Si ratio.

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