DENSITY, POROSITY AND MAGNETIC SUSCEPTIBILITY OF LUNAR ROCKS.

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Introduction: Observations of the Moon's gravity and topography by Lunar Prospector and Kaguya [1-3] provide important constraints on the Moon's internal structure. Ongoing work by Lunar Reconnaissance Orbiter as well as by GRAIL in a few years will continue to sharpen our knowledge of the Moon's gravity and topography. In order to use this flood of data to understand the Moon's interior, it is necessary to have a comprehensive data base of lunar rock densities and porosities. Many density measurements were reported in the first few years after the Apollo landings, but Talwani et al. [4] concluded that more than half of these measurements have uncertainties exceeding 10%, which makes the measurements useless for geophysical modeling. Many other measurements do not document the measurement method and uncertainty. Another essential parameter is rock porosity. For example, in Kiefer's gravity model of the Marius Hills volcanic field [5], the uncertainty in the model results is dominated by uncertainty in the crustal porosity. Very few measurements of lunar rock porosity exist in the literature. We know of only 11 Apollo samples that have well documented measurements of both density and porosity made on the same sample [6-10]. Here, we report new density and porosity measurements for 5 Apollo samples and 3 lunar meteorites. These new measurements are a significant increment in our total data base for lunar rock properties.

Measurement: Our methods, originally developed for meteorite research, are outlined in [11]. They are fast, non-destructive and non-contaminating. Grain density is measured by helium ideal-gas pycnometry. Bulk density is measured by the glass bead method developed by [12]. We used beads of average diameter 750 μm, large enough to be easily seen by the unaided eye and removed easily from the sample after completion of measurement. Porosity is calculated directly from bulk and grain densities: $P = 1 - \left(\rho_{bulk} / \rho_{grain}\right)$. Magnetic susceptibility is measured with a handheld SM-30 magnetic susceptibility meter, and corrected for sample geometry according to the calibration by [13].

We measured five fragments taken from Apollo samples. 12051 is an ilmenite basalt from the Surveyor crater [14a]. 14303 and 14321 are crystalline-rich breccias from Frau Mauro [14b,c]. 15418 is a granulitic breccia [14d], and 15555 is a basalt [14e]. These samples range in mass from 10.0 to 33.0 g. We also measured three fragments of lunar meteorites (all breccias): Northwest Africa [NWA] 482 (9.87g), NWA 773 (13.22g) and NWA 5000 (7.00g). Data are represented in tables 1 and 2.

Table 1: Grain and bulk densities of lunar samples.

NAME	Mass (g)	ρ_{grain} (g/cm^3)	ρ_{bulk} (g/cm^3)
A 12051, 19	12.19	3.32 ± 0.02	3.26 ± 0.05
A 14303, 14	22.26	3.05 ± 0.01	2.51 ± 0.03
A 14321,220	10.01	3.03 ± 0.03	2.36 ± 0.04
A 15418,179	28.68	3.12 ± 0.01	2.65 ± 0.02
A 15555, 62	32.98	3.35 ± 0.01	3.11 ± 0.03
NWA 482	9.87	2.85 ± 0.03	2.82 ± 0.10
NWA 773	13.22	3.24 ± 0.03	2.86 ± 0.06
NWA 5000	7.00	2.80 ± 0.05	2.72 ± 0.07

Table 2: Porosities and magnetic susceptibilities of lunar samples.

NAME	Mass (g)	Porosity (%)	Mag. Susc. (log χ)
A 12051, 19	12.19	1.9 ± 1.7	2.83 ± 0.08
A 14303, 14	22.26	17.6 ± 1.0	3.37 ± 0.08
A 14321,220	10.01	22.2 ± 1.5	3.19 ± 0.08
A 15418,179	28.68	15.0 ± 0.7	2.95 ± 0.08
A 15555, 62	32.98	7.3 ± 0.9	2.91 ± 0.08
NWA 482	9.87	1.3 ± 3.7	3.41 ± 0.08
NWA 773	13.22	11.6 ± 2.2	3.46 ± 0.08
NWA 5000	7.00	2.9 ± 3.1	2.73 ± 0.08

Discussion: Lunar basalts usually have a high concentration of Fe and thus are considerably denser than terrestrial basalts. Lunar basalts are typically classified by their Ti abundance, and sometimes also by other elements such as Al and Mg [15,16]. Titanium is particularly important because of the high density of ilmenite. Prior studies of lunar basalts include 5 high Ti basalts [6, 8, 9] and only one low Ti basalt [7]. The basalts measured here, 12051 and 15555, are both low Ti basalts. One of the long term objectives of our study is to be able to use remote sensing observations [e.g., 17, 18] to constrain plausible basalt densities in various locations and thus improve the quality of regional gravity models. To do this, additional measurements of the full range of lunar basalt compositions, including intermediate Ti, high Mg, and high Al basalts, are needed.

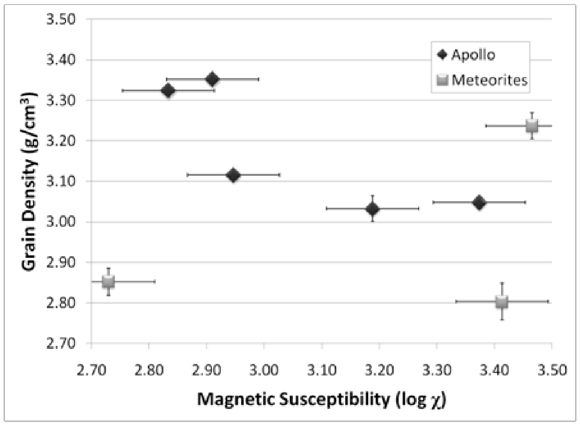

Figure 1: Grain density vs. magnetic susceptibility for lunar samples.

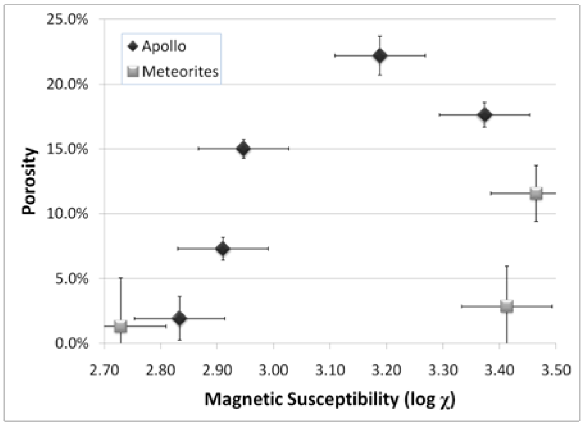

Figure 2: Porosity vs. magnetic susceptibility for lunar samples.

Samples 14303 and 14321 are from the Fra Mauro formation, which is Imbrium basin ejecta. The samples were collected about 1 km apart and have essentially identical grain densities and only slightly different porosities. Chung et al. [19] measured the bulk density of another split of 14321. Our result matches theirs within measurement uncertainty. Because of the importance of basin ejecta across much of the Moon's surface, additional measurements of samples from other basins are needed, including the Descartes and Cayley formations at Apollo 16 and the Imbrium and Serenitatis rims at Apollos 15 and 17.

The Moon's upper crust is believed to be dominantly anorthosite, changing to norite in the lower crust [20]. Sample 15418 is a brecciated gabbroic anorthosite, approximately 70% plagioclase. Our measured bulk density is about 5% less than two measurements on other splits of 15418 [21,22]. 15418 is visually heterogeneous [23], and our sample may differ slightly in either composition or porosity from the previously measured samples. 15418's porosity, 15%, is similar to the 18-20% measured on lunar anorthosite 60025 [24]. The grain density of anorthosite NWA 5000 is similar to 60025 [10].

An intriguing observation is that two of the lunar meteorites, NWA 482 (an impact melt breccia) and NWA 5000, have very low porosities. This is consistent with earlier measurements by point counting, which measures porosity but not density, on other lunar meteorites [24]. This may mean that impact ejection of material from the Moon is easiest for low porosity rocks. NWA 773 is a regolith breccia dominated by clasts of olivine gabbro [25]. The strength of the clasts may have permitted ejection despite its higher porosity.

Acknowledgments: Apollo samples were provided on loan by NASA Johnson Space Center, Lunar Sample Collection. Lunar meteorite access was provided by: (NWA 5000) Arthur Ehlmann at Texas Christian University; (NWA 482) Carl Agee and Jim Karner at the Institute of Meteoritics, University of New Mexico; and (NWA 773 – sample BM2001,M23) Caroline Smith at the Natural History Museum, London UK. This work was supported by grant NNX09AD91G from the NASA Planetary Geology and Geophysics Program.

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