"LUNAR SOIL DENSITY AND POROSITY"

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Data sources used specifically for inferring lunar soil density or porosity are core tube samples, lunar drill samples, astronaut footprints, LRV and MET tracks, boulder tracks, and penetration resistance. These data sources have been utilized separately or in combination as a part of the Soil Mechanics Experiment (S-200) and related baseline research which began during the Surveyor Program. Now that the Soil Mechanics Experiment is completed, it has been possible to collect density data from all sources and develop a consistent pattern which characterizes average lunar soil density, its variation both laterally and with depth, and the degree of variability from the average. This paper presents those results.

The results from studies of each of the individual data sources listed above are summarized in Table 1. The results in Table 1 and related studies may be used to conclude the following:

(1) The average relative density and porosity for the upper 15 cm in intercrater areas is essentially the same for all six Apollo landing sites and perhaps for all soil-covered locations on the lunar surface--if areas are considered on a scale of a few hundred meters.

(2) The best estimates for the average bulk densities for the lunar surface are as follows:

Depth Range, cm	Bulk Density, ρ - g/cm^3
0-15	1.50 ± .05
0-30	1.58 ± .05
30-60	1.74 ± .05
0-60	1.66 ± .05

(3) The variation of average bulk density, ρ, with depth can be described by

$$\rho = \rho_o + k \ln (z+1)$$

where z = depth in cm
ρ_o = 1.27 g/cm^3
k = 0.121

but deviations from the general pattern of density increase with depth may be very frequent and pronounced.

(4) The best estimates for the average relative density for the lunar surface are as follows:

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TABLE 1 - Summary of Results from Lunar Soil Density Studies

Source	Depth Range, cm	Bulk Density or Absolute Density g/cm^3	Relative Density* %	Standard Deviation for Relative Density
Core tube samples	0-15	1.50 ± .05	64**	
	0-30	1.58 ± .05	74**	
	30-60	1.74 ± .05	92**	
	0-60	1.66 ± .05	83**	
Lunar drill samples	0-30	1.69 ± .08		
	30-60	1.77 ± .08		
Astronaut footprint analyses	0-15		65-66	≃10
LRV and MET tracks	0-15		48-63 by Procedure 1	
	0-15		62-71 by Procedure 2	
Boulder tracks	0-300 or 400		65	≃20
Penetration resistance	0-60		83-84	≥10?

*Relative Density = $D_r = \frac{\rho_{max}}{\rho_{min}} \frac{(\rho - \rho_{min})}{(\rho_{max} - \rho_{min})} \times 100\%$

where ρ_{max} = maximum density

ρ_{min} = minimum density

**Calculated, based on average $G_s = 3.1$, $e_{max} = 1.7$ and $e_{min} = 0.7$.

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Depth Range, cm	Relative Density, D_R - %
0-15	65 ± 3
0-30	74 ± 3
30-60	92 ± 3
0-60	83 ± 3

(5) Statistical studies of footprints, LRV and MET tracks, and boulder tracks show that relative density varies considerably on a scale of 1 or 2 meters laterally and indicate that a best estimate of the standard deviation is about 15 percentage points for relative density. Histograms of density data indicate an essentially normal distribution with a slight skewness toward the high density side.

(6) Average values of absolute and relative density for the lunar surface cannot at this time be confidently converted to values of porosity or void ratio because of insufficient data on values of G_s and e_{max} and e_{min} for lunar soil; but based on a very small number of tests--too small to give statistically significant averages--the following averages have been tentatively proposed.

G_s	e_{max}	e_{min}
3.1	1.7	0.7

If these values were indeed valid as averages for the lunar surface, the "best estimate" average values of $\rho = 1.50$ g/cm^3 and $D_R = 65\%$ for the uppermost 15 cm given in conclusions 2 and 4 would correspond to a void ratio of 1.05 and a porosity of 51%.

(7) The average relative density on crater rims for all Apollo sites is about 10 to 12 percentage points lower than for intercrater areas. The standard deviation for crater rim density is also greater than for intercrater areas.

(8) In consideration of the depth ranges to which each of the methods in Table 1 apply, the boulder track data indicate that average relative density on slopes and crater walls where boulder tracks were generally observed is lesser and more variable than for level intercrater areas. This observation is consistent with the hypothesis that downslope movements may loosen lunar soil somewhat.

(9) The apparent mechanism controlling the relative density of lunar soil in the plains areas seems to be that the constant meteorite and micrometeorite bombardment maintains a loose, stirred up surface; but directly beneath the surface, the vibrations due to innumerable shock waves shake and densify the soil to a very high relative density. The sub-surface soil may even be overconsolidated at some locations; i.e., the soil may have been densified under a greater confining stress at some time in the past than is presently applied to it by the overlying soil.