Lunar Exploration Initiative

Briefing Topic:

Parameters of Lunar Soils

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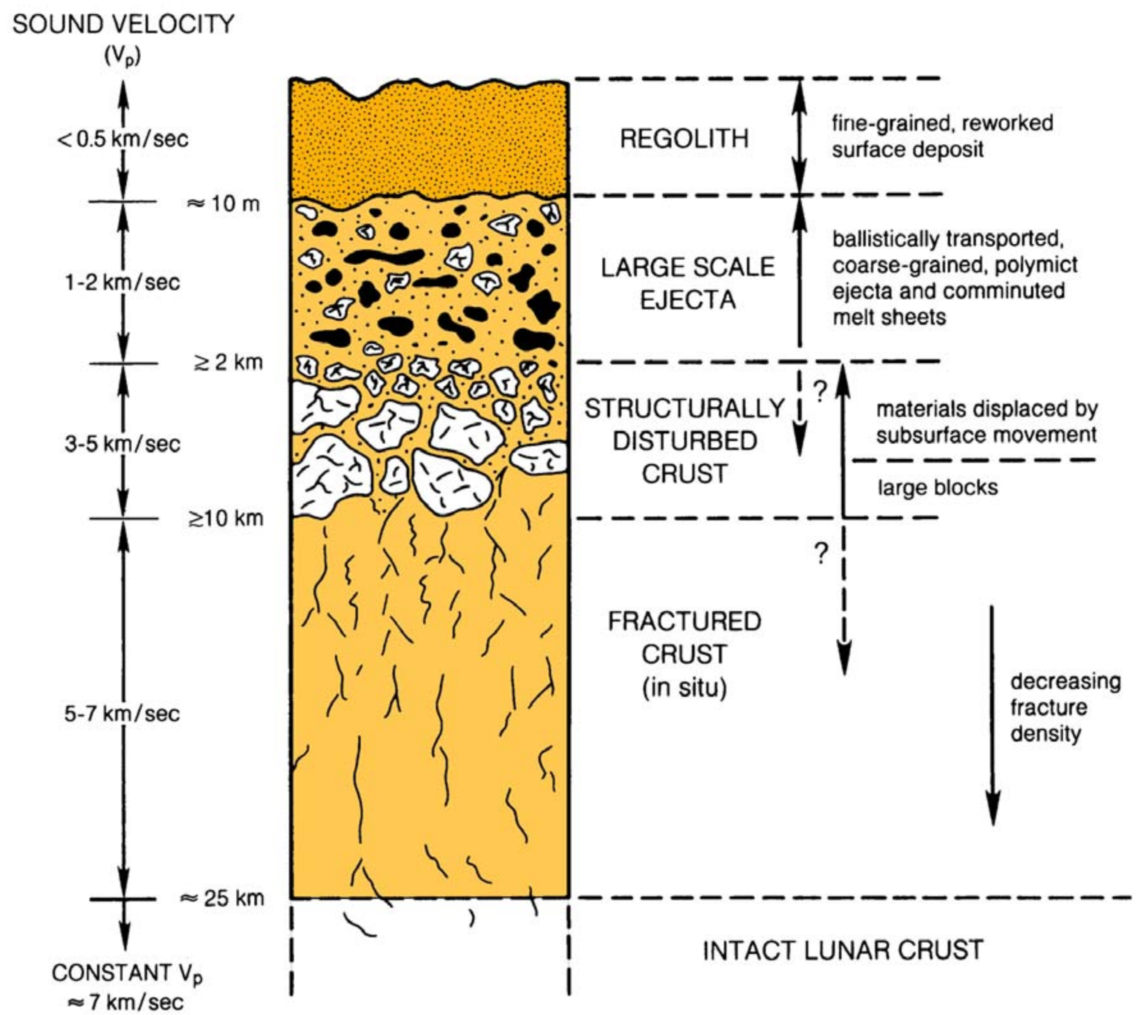
Upper Crust of the Moon



Modified from Hörz et al. (1991) HVF (HGHSB) 91 F4.22

Lunar Regolith

- Regolith
  - Layer or mantle of fragmental and unconsolidated rock material, whether residual or transported, that nearly everywhere forms the surface of land and overlies or covers bedrock (Bates & James, 1980)
  - ~10 m thick in the lunar highlands, where it overlies a mega-regolith that is crudely estimated to be 1 to 3 km thick

- Lunar soil
  - Subcentimeter fraction of (unconsolidated) regolith
  - Rate of accumulation
    - Avg = 1.5 m/Ga (1.5 mm/million yrs)
    - Soil formation was particularly high during 3.8-4.0 Ga bombardment; ~1 order of magnitude higher than in younger regoliths

In contrast -------

- Regolith breccias
  - Polymict breccias are consolidated rocks that contain rock, mineral, and glass fragments in a glassy matrix (agglutinates).

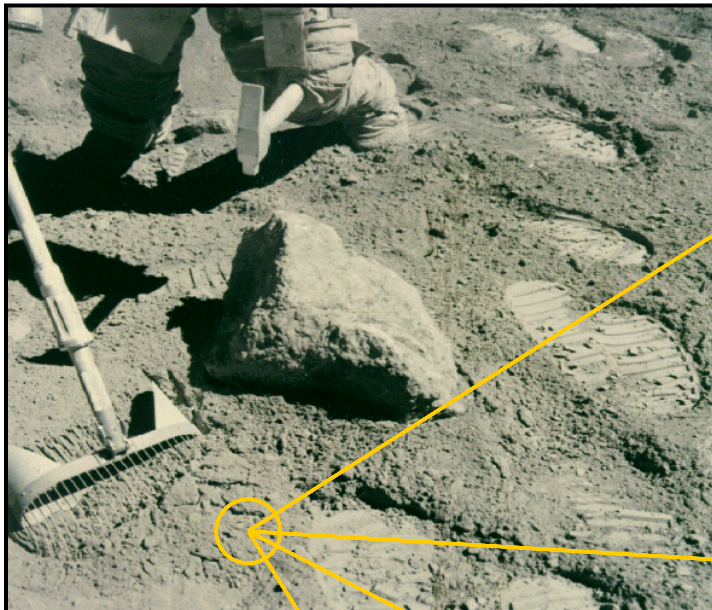
Lunar Soil

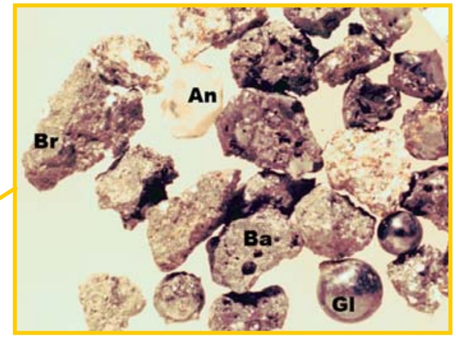
Sub-centimeter fraction of regolith
Mixed with rock fragments
On top of denser (packed) regolith

Lunar Soil

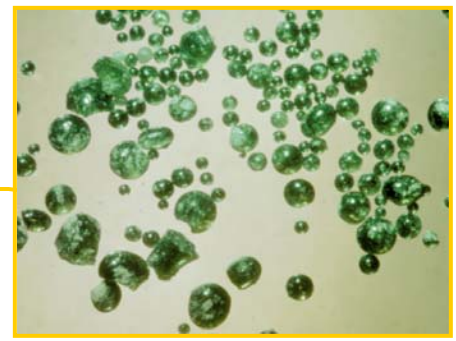
- Produced on an airless body
- Commonly affected by micrometeoritic impact at speeds >10 km/s
  - Comminuting soil
  - Yet, also producing agglutinates
- Solar wind bombardment
  - Producing fission tracks
  - Implanting solar wind gases (^{4}He, ^{20}Ne, ^{36}Ar, ^{84}Kr, ^{132}Xe)
- Apollo samples were typically sieved into discrete ranges of particle sizes
  - Grain mounts were then prepared for petrologic analyses

Lunar Soil



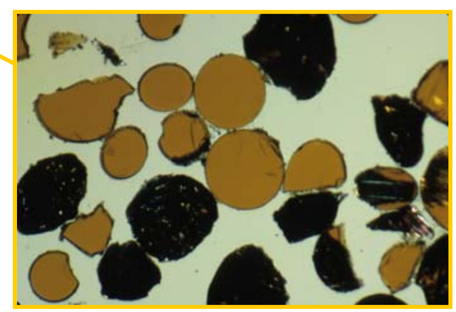


Anthorthosite (An)
Basalt (Ba)
Breccia (Br)
Glass Spherule (Gl)



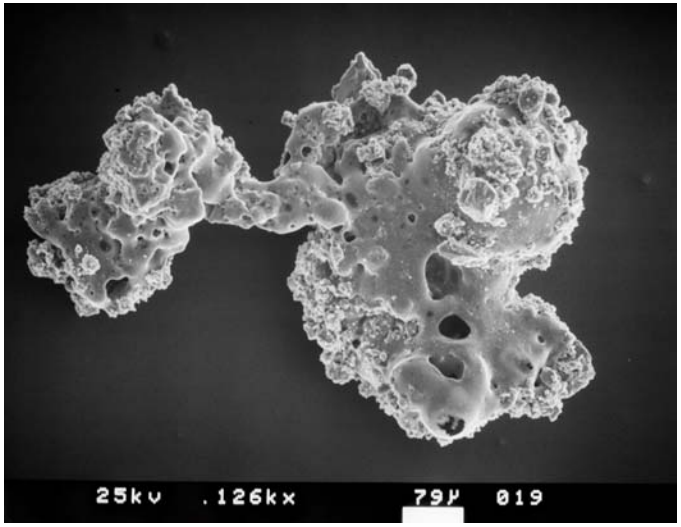
Green glass spherules or vitrophyres

Agglutinates

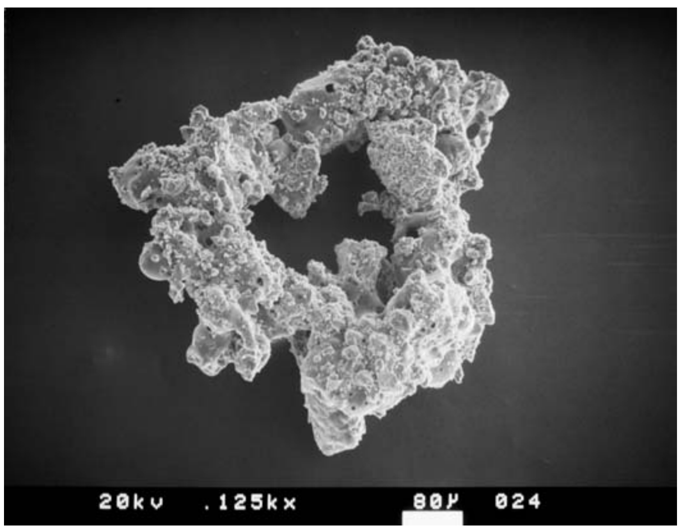


Orange glass spherules or vitrophyres

Lunar Soil Agglutinates



- **Irregular agglutinate with soil particle welding heterogeneously distributed between fragment-poor and fragment-rich areas. The glass in the fragment-poor areas is vesicular. (NASA Photo S87-38811)**



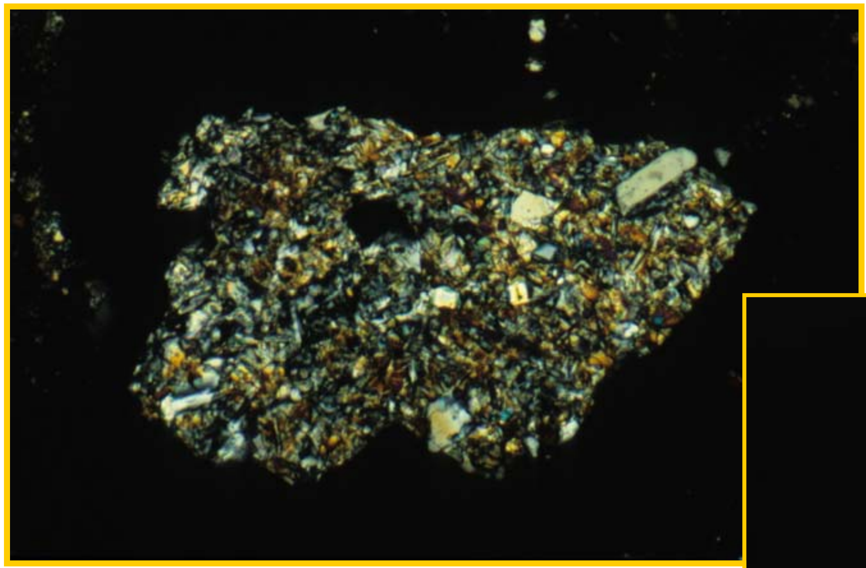
- **Agglutinate with distributed melt (now glass) coated extensively with soil particles. (NASA Photo S87-38812)**

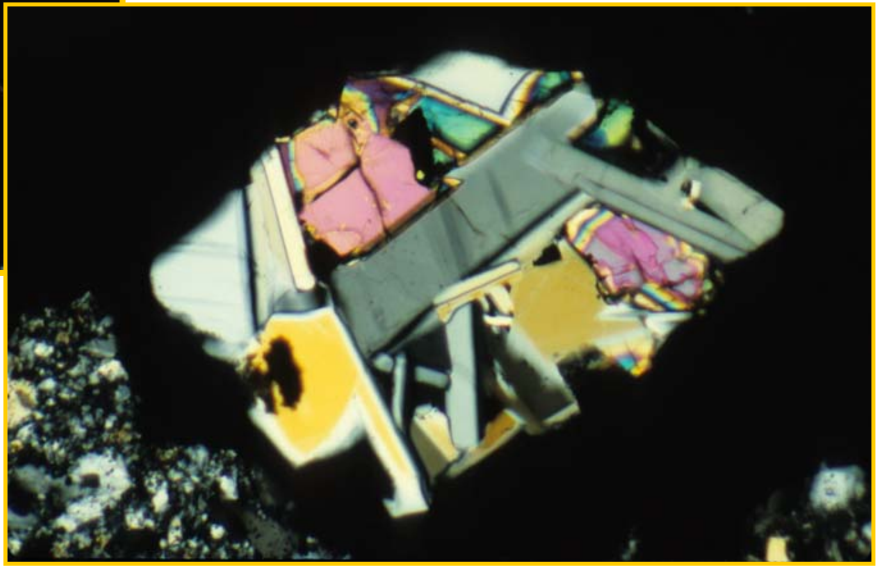
Both particles are part of soil sample 10084
SEM photomicrographs

Lunar Soil Particles

68501,423: A Mature Highland Soil

Microscope views of individual soil particles; transmitted light with x-nicols; width of each view is 2.1 mm.





Lunar Soil Size Fractions

- **Visual estimates in Lunar Receiving Laboratory**
  - 0.5 to 1 mm
  - 1 to 2 mm
  - 2 to 4 mm
  - 4 to 10 mm

- **Petrographic descriptions**
  - <20 μm
  - 20 to 45 μm
  - 45 to 75 μm
  - 75 to 90 μm
  - 90 to 150 μm
  - 150 to 250 μm
  - 250 to 500 μm

Lunar Soil Particle Parameters

	Weight distribution (%)					
	< 1mm	1-2 mm	2-4 mm	4-10 mm	> 10 mm	Sample mass (g)
Soil						
10002	89	3.1	2.3	1.6	3.9	476.3
14003	88	3.9	3.0	3.1	2.1	1077.8
14163	87	5.6	3.8	3.8	0	5126.3
15220	95	0.8	1.9	2.3	0	305.2
15270	95	2.5	1.6	0.5	0	837.1
15400	14	0.8	1.0	1.3	83	618.3
62280	78	7.8	4.7	5.1	4.3	279.6
64500	82	4.7	4.0	4.0	5.2	603.6
68500	86	6.3	4.2	2.9	0.2	602.6
70180	25	0.7	0.5	0.3	74	633.1
71500	85	3.2	2.5	1.9	7.4	706.6
72140	95	2.2	0.8	1.1	0.6	237.1
72500	93	3.3	1.8	1.1	0.4	735.3
73240	78	6.0	5.9	9.1	0.7	245.9
78220	96	2.2	1.1	0.6	0	236.5
78500	81	2.4	1.8	2.2	12	884.7

► Soils particles are dominantly <1 mm in size

Lunar Soil Particle Parameters

Median particle size	40 to 130 µm	
Avg. particle size	70 µm	~10-20% is finer than 20 µm
Avg. elongation	1.35	somewhat elongated
Avg. aspect ratio	0.55	slightly to medium elongated
Avg. roundness	0.22	subangular to angular
Avg. volume coefficient	0.3	elongated
Avg. specific surface area	0.5 m^2/g	irregular, reentrant

► Soil particles are typically irregular and elongated

HVF (COM) 91 S9.1.1; F9.2

Specific Surface Area

- **Surface area of a particle divided by its mass**

Particle Type	Specific Surface Area (m^2/g)
Terrestrial Clays	
Kaolinite	10-20
Illite	65-100
Montmorillonite	50-800
Lunar Soil Range	0.02-0.78
Lunar Soil Average	0.5

► **Clays have higher SSA than lunar soils because of (a) their small size and (b) platy morphology**

Specific Surface Area

- Idealized soil with spherical particles

$$SSA = 6 / (d\ G\ \rho_w) \quad (m^2/g)$$

If G = 3.1 (typical of lunar soils), then soils with the following particle sizes would have the corresponding SSA:

Diameter (µm)	SSA (m^2/g)
1	1.9
10	0.19
100	0.019
1000	0.0019

Lunar soil (with appropriate particle size distribution) would have an idealized SSA (spheres) of 0.065 m^2/g. Observed SSA is 0.5 m^2/g.

► Observed lunar soil SSA are ~8 times greater than that of model spheres because of irregular and re-entrant particle surfaces

Lunar Soil Particles

71061,1 (a typical Apollo 17 mare soil)

	Petrographically Determined Vol%							Visual Estimate %			
	<20 um	20-45 um	45-75 um	75-90 um	90-150 um	150-250 um	250-500 um	0.5-1 mm	1-2 mm	2-4 mm	4-10 mm
Agglutinates	17	17	13	17	9	12	10	-	-	-	-
Basalt, equigran.	-	-	9	15	31	-	-	-	-	-	-
Basalt, variolitic	-	-	1	2	20	3	52	65	100	100	100
Breccia	-	-	2	7	6	8	8	-	-	-	-
Anorthosite	-	-	1	-	<1	-	-	-	-	-	-
Norite	-	-	-	-	-	-	-	-	-	-	-
Gabbro	-	-	-	-	-	-	0.5	5	-	-	-
Plagioclase	-	-	16	7	17	9	9	-	-	-	-
Pyroxene	-	-	21	26	21	17	11	-	-	-	-
Olivine	-	-	-	-	-	1	-	-	-	-	-
Ilmenite	-	-	6	3	5	3	2	-	-	-	-
Glass	-	-	28	22	22	15	8	15	-	-	-
Other	(83)	(83)	2	-	-	1	-	-	-	-	-
Fractional Wt%	18	12	8	3	9	7	7	3	6	7	10

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Lunar Soil Particles

64501 (a typical Apollo 16 highland soil)

	Petrographically Determined Vol%							Visual Estimate %			
	<20 um	20-45 um	45-75 um	75-90 um	90-150 um	150-250 um	250-500 um	0.5-1 mm	1-2 mm	2-4 mm	4-10 mm
Agglutinates	-	23	26	35	44	27	28	-	-	-	-
Basalt	-	-	-	-	-	-	-	-	-	-	-
Breccia	-	23	22	24	26	33	31	-	-	-	-
Anorthosite	-	-	-	<1	-	<1	6	-	-	-	-
Norite	-	-	-	-	-	-	-	-	-	-	-
Gabbro	-	-	-	-	-	-	-	-	-	-	-
Plagioclase	-	34	43	29	25	34	29	-	-	-	-
Pyroxene	-	7	2	2	<1	1	-	-	-	-	-
Olivine	-	2	<1	1	-	-	-	-	-	-	-
Ilmenite	-	1	-	-	-	-	-	-	-	-	-
Glass	-	9	8	9	5	5	4	-	-	-	-
Other	-	<1	-	-	-	-	-	-	-	-	-
Fractional Wt%	-	16	10	4	10	8	9	-	-	-	-

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Specific Gravity

- Specific gravity has been measured for Apollo 11, 12, 14, 15, and 17 soils
- Techniques include nitrogen pycnometry, helium pycnometry, water pycnometry, air pycnometry, and suspension in a density gradient
- Bulk soil values range from 2.9 to 3.5
- Values for specific types of particles

Agglutinates & glass particles	1.0 to > 3.32
Basalt particles	>3.32
Breccia particles	2.9 to 3.1

- **Representative value for lunar soil is 3.1**

HVF (COM) t S9.1.2. + T9.3

Bulk Density

- **Mass of soil (or rock) within a given volume; typical units are g/cm^3**

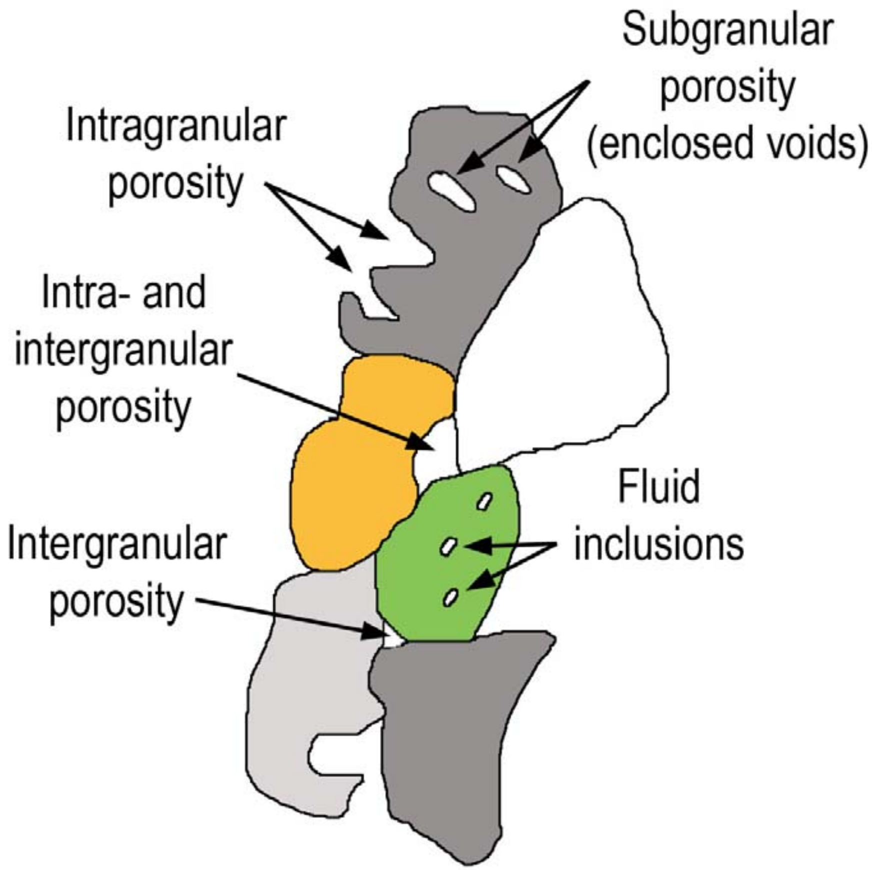
- **Bulk density < particle density, whenever there is porosity (void space between particles in soil or rock)**

- **Relationship between bulk density and porosity:**

$$\rho = G \, \rho_w \, (1-n)$$

where G is specific gravity, ρ_w is density of water or 1 g/cm^3, and n is porosity, expressed as a decimal fraction between 0 and 1 that includes both inter- and intra-granular porosity.

Porosity



Porosity of lunar soils is often ~50%

Intragranular porosity = space between particles

Intergranular porosity = space created by re-entrant surfaces on exterior of particles

Subgranular porosity = voids enclosed within the interior of particles

Fluid inclusions are not a type of porosity, although they usually represent less dense regions

Bulk Density

- **Determined by remote sensing techniques**
  - **Passive VIS, IR, and microwave emissivity and active radar reflectivity**
  - **produced low values of 0.3-0.4 g/cm^3**

- **In situ robotic measurements**
  - **Surveyor 1, 3, and 7; Luna 13; Luna 17/Lunokhod 1; Luna 21/Lunokhod 2**
  - **Values ranged from 0.8 to 1.7 g/cm^3**

- **Correlating lunar observations with those of simulated lunar soil**
  - **Astronaut bootprints, vehicle tracks, boulder tracks, and penetration resistance**
  - **Values ranged from 1.34 to 1.92 g/cm^3**

- **Measured in returned core samples**
  - **Apollo 11, 12, 14, 15, 16, and 17; Luna 16, 20, and 24**
  - **Values range from 0.75 to 2.29 g/cm^3**

► **Representative values range from 1.45 to 1.79 g/cm^3, depending on depth, for intercrater areas**

Bulk Density

- **Bulk density can be influenced by the type of particle packing in a soil**

- **Assume**
  - **Specific gravity (G) = 3.1**
  - **Particles are spherical**

- **Face-centered cubic packing**
  - **Loosest possible arrangement**
  - **Porosity = 47.6%, void ratio = 0.92, bulk density = 1.61 g/cm3**

- **Hexagonal close packing**
  - **Densest possible arrangement**
  - **Porosity = 26.0%, void ratio = 0.35, bulk density = 2.30 g/cm3**

- **Real soils**
  - **Bulk density falls between these two extremes, depending on particle size distribution, shape, texture, orientation, and specific gravity**

Relative Density

- Designed to convey the degree of packing that occurs in granular soils
- Relative density (D_r)

$$D_r = ((e_{max} – e) / (e_{max}-e_{min})) \times 100\%$$

Where e = void ratio of the soil sample and the e_{min} and e_{max} correspond to the minimum porosity (n_{min}) and maximum porosity (n_{max})

Alternatively,

$$D_r = ((1-n_{min}) / (1-n)) \times ((n_{max}-n) / (n_{max}-n_{min})) \times 100\%$$

Or

$$D_r = ((\rho_{max}) / (\rho)) \times ((\rho – \rho_{min}) / (\rho_{max} – \rho_{min})) \times 100\%$$

Relative Density

- **Qualitative description of relative density values**
  - **Relative density of 0 to 15% is very loose**
  - **Relative density of 15 to 35% is loose**
  - **Relative density of 35 to 65% is medium**
  - **Relative density of 65 to 85% is dense**
  - **Relative density of 85 to 100% is very dense**

- **In situ relative density of lunar soil is ~65% in upper 15 cm**

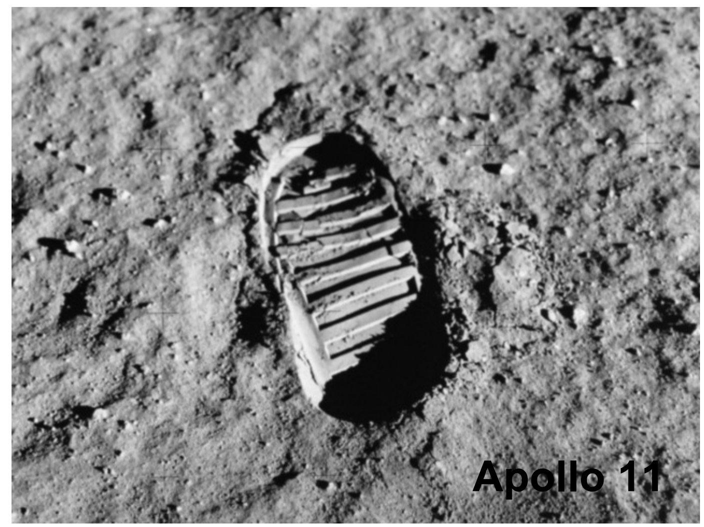
- **In situ relative density increases to >90% below depths of 30 cm**

- **Values are much higher than the 65-75% limit obtained in soils at terrestrial construction sites**

- **Implies lunar soils were not emplaced by some type of sifting mechanism, but were instead extensively shaken and densified, probably as a consequence of repeated impact events**

Compressibility

- **Measured with 1-D oedometers on the Apollo 12 and Luna 16 and 20 missions**
- **Compression index (C_c = decrease in void ratio that occurs when stress increased by an order of magnitude)**
  - **Apollo 12: 0.03 to 0.21**
  - **Luna 16: 0.3**
  - **Luna 20: 0.3**



- **Representative parameters**
  - **0.3 C_c for loose soil (i.e., 30% decrease in void ratio)**
  - **0.05 C_c for dense soil**
  - **0.003 C_r (recompression index)**
  - **0.45 coefficient of lateral stress (K_0) for normally consolidated soil**
  - **0.7 K_0 for recompacted soil**

HVF (COM) 91 T9.9,10

Shear Strength

- **Mohr-Coulomb equation for the shear strength of granular soil**

$$\tau = c + \sigma \tan \varphi$$

Where τ is shear strength (kPa), c is cohesion (kPa), σ is normal stress (kPa), and φ the friction angle (degrees)

- **Surveyor model (best estimate)**
  - **Cohesion = 0.35 to 0.70 kPa**
  - **Friction angle = 35 to 37°**
  - **Other data suggests these values are near the lower limit of lunar soil shear strength**

- **Apollo model (best estimate)**
  - **Cohesion = 0.1 to 1 kPa**
  - **Friction angle = 30 to 50°**
  - **These values are better for most lunar soils (with higher relative densities than those at the Surveyor 3 and 7 sites)**

- **Cohesion increases sharply with depth, increasing by factors of 5 to 7 within ~1/2 meter of surface**

HVF (COM) t S9.1.7.

Lunar Soil Physical Properties*

Depth Range (cm)	Bulk Density Average (g/cm3)	Relative Density (%)	Porosity Average (%)	Void Ratio Average (%)
0-15	1.50 ± 0.05	65 ± 3	52 ± 2	1.07 ± 0.07
0-30	1.58 ± 0.05	74 ± 3	49 ± 2	0.96 ± 0.07
30-60	1.74 ± 0.05	92 ± 3	44 ± 2	0.78 ± 0.07
0-60	1.66 ± 0.05	83 ± 3	46 ± 2	0.87 ± 0.07

Depth Range (cm)	Cohesion Range (k Pa)	Cohesion Average (k Pa)	Friction Angle Range (degrees)	Friction Angle Average (degrees)
0-15	0.44-0.62	0.52	41-43	42
0-30	0.74-1.1	0.90	44-47	46
30-60	2.4-3.8	3.0	52-55	54
0-60	1.3-1.9	1.6	48-51	49

*For intercrater areas

HVF (COM) 91 t + T9.5,6,12

Lunar Soil Summary

- **Bulk density increases with depth, particularly in the uppermost ~50 cm**
  - $\rho = 1.39\ z^{0.056}$
  - $\rho = 1.92\ ((z+12.2)/(z+18))$

- **Relative density increases with depth; for example, at an Apollo 15 site:**
  - **Very loose in upper ~1 cm**
  - **Loose between ~1 and ~2 cm**
  - **Medium between ~2 and ~4 cm**
  - **Dense between ~4 and ~12 cm**
  - **Very dense below ~12 cm**

- **Cohesion varies as a function of geological terrain**
  - **For the same friction angle, the cohesion on an interior crater wall is less than that on an intercrater plain**
  - **For the same friction angle, the cohesion on an intercrater plain is less than that on a crater rim slope**
  - **Based on Lunokhod 1 measurements**

HVF (COM) 91 S9.1.4; F9.19,30

Thermal Conductivity

- **In situ**
  - Heat-flow probes were inserted into holes where cores were extracted in the J-series of missions (A15, 16, and 17)
  - Measurements were successful at the Apollo 15 and 17 sites; a broken cable interrupted the Apollo 16 experiment
  - Conductivity increases with depth
    - 1.5×10^{-5} W/cm^2 K in upper 1 to 2 cm
    - Increases sharply (5 to 7 times) at depth of 2 cm
    - Thermometers buried beneath 80 cm are not affected by thermal day/night cycling
  - A value of 1.5×10^{-4} W/cm K was found at a depth of 1 m in regolith on a mare surface at the Apollo 15 site; heat flow is estimated to be 3.1×10^{-6} W/cm^2 +/- 20%
  - Conductivity at the Apollo 17 site ranged from 1.72 to 2.95×10^{-4} W/cm K +/- 20% in regolith that covers lava flows between two massifs; heat flow is estimated to be 2.2×10^{-6} W/cm^2 +/- 20%

- **Remote Sensing**
  - Microwave data
  - This technique suggests a lunar surface heat flow of 3 to 4×10^{-6} W/cm^2, which is similar to the heat flow measured at the A15 and A17 sites
  - The similarity in heat flow suggests the conductivity measured in situ at A15 and A17 sites is similar to that elsewhere on the Moon

LCCKW 72; LKC 73; HVF (VRHOM) 91 t S3.6.

Summary

- Compared to terrestrial soils, lunar soils
  - Lack organic matter and clays
  - Contain abundant glass
  - Have much higher relative densities

- Lunar soils
  - Accumulate at a rate of ~1.5 mm/million years
  - Dominated by <1 mm particles
  - Mean particle sizes of 40 to 130 μm
  - Average particle size of ~65 to 70 μm
  - Representative specific gravity of 3.1
  - Bulk density that ranges from 1.45 to 1.79 g/cm3, depending on depth
  - Relative density is greater than 65% and quickly exceeds 90% within ~1/2 m of surface
  - Porosity ranges from ~44 to ~54%, decreasing with depth
  - Cohesion of soils in intercrater areas is greater than that on interior crater walls but less than that on crater rims

Principal References

- Carrier, W.D. III, G.R. Olhoeft, and W. Mendell (1991) Physical properties of the lunar surface, In *Lunar Sourcebook*, G.H. Heiken, D.T. Vaniman, and B.M. French (eds.), Cambridge University Press, Cambridge.
- Hörz F., R. Grieve, G. Heiken, P. Spudis, and A. Binder (1991) Lunar surface processes, In *Lunar Sourcebook*, G.H. Heiken, D.T. Vaniman, and B.M. French (eds.), Cambridge University Press, Cambridge.
- And references therein.