Lunar Regolith –
Understanding for Science and Exploration

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Overview

• What new advances have been made in understanding the properties of the lunar regolith?
• What are key outstanding questions with regard to the lunar regolith?
  – SRQ: Strategic Regolith Questions
  – RKG: Regolith Knowledge Gaps
Regolith Properties

This is where all of the action is:

- Volatile adsorption, adhesion, formation
- Micro-scale physics
- Radiation interactions
- Space weathering

Volatile storage
  - Long term
  - Short term
Regolith Definition

**Regolith:** The layer or mantle of loose incoherent rock material, of whatever origin, that nearly everywhere underlies the surface of the land and rests on bedrock. A general term used in reference to unconsolidated rock, alluvium or soil material on top of the bedrock. Regolith may be formed in place or transported in from adjacent lands. – Terrestrial definition.

**Regolith:** Surficial layer covering the entire lunar surface ranging in thickness from meters to tens of meters formed by physical desegregation of larger fragments into smaller ones over time (impact or thermal processes).

Particle size ranges from enormous boulders to micron-sized particles

*The lunar regolith is not just JSC-1.*
<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
<th>Units</th>
<th>Notes</th>
<th>Sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulk density ($\rho$)</td>
<td>1.58 ± 0.05: 0-30 cm</td>
<td>g/cm³</td>
<td>Intercrater areas</td>
<td>p 492 LSB</td>
</tr>
<tr>
<td></td>
<td>1.74 ± 0.05: 30-60 cm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Relative density ($D_R$)</td>
<td>74 ± 3: 0-30 cm</td>
<td>%</td>
<td>Intercrater areas</td>
<td>T9.6 LSB</td>
</tr>
<tr>
<td></td>
<td>82 ± 3: 30-60 cm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Porosity (n)</td>
<td>49 ± 2: 0-30 cm</td>
<td>%</td>
<td></td>
<td>T9.5 :SB</td>
</tr>
<tr>
<td></td>
<td>44 ± 2: 30-60 cm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Void ratio (e)</td>
<td>0.96 ± 0.07: 0-30 cm</td>
<td>m²</td>
<td></td>
<td>LSB</td>
</tr>
<tr>
<td></td>
<td>0.78 ± 0.07: 30-60 cm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Permeability (Q)</td>
<td>$1 - 7 \times 10^{12}$</td>
<td></td>
<td>Surveyor vernier engines</td>
<td>Choate et al. 1968</td>
</tr>
<tr>
<td>Diffusivity</td>
<td>7.7 He</td>
<td>cm²/sec</td>
<td>Function of gas species</td>
<td>Martin et al. 1973</td>
</tr>
<tr>
<td></td>
<td>2.3 Ar</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.8 Kr</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Compression index ($C_t$)</td>
<td>0.3: loose</td>
<td></td>
<td>sample mass 1.2 to 200 g</td>
<td>T9.9/9.10 LSB</td>
</tr>
<tr>
<td></td>
<td>0.05: dense</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.01-0.11: range</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Recompression index ($C_r$)</td>
<td>0.003 average</td>
<td></td>
<td></td>
<td>T9.9 LSB</td>
</tr>
<tr>
<td></td>
<td>0.000-0.013 range</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coefficient of lateral stress</td>
<td>0.45: normally consolidated</td>
<td></td>
<td></td>
<td>T9.9 LSB</td>
</tr>
<tr>
<td>($K_o$)</td>
<td>0.70: recompacted</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>
### Regolith Properties 2 – Apollo Era

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
<th>Units</th>
<th>Notes</th>
<th>Sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Friction angle ($\phi$)</td>
<td>30-50</td>
<td>degrees</td>
<td></td>
<td>T9.11 LSB</td>
</tr>
<tr>
<td>Cohesion (c)</td>
<td>0.1-1.0</td>
<td>kPa</td>
<td></td>
<td>19.11 LSB</td>
</tr>
<tr>
<td>Modulus of subgrade reactions (k)</td>
<td>1-200 range 8 average</td>
<td>kPa/cm</td>
<td></td>
<td>LSB p 519</td>
</tr>
<tr>
<td>thermal conductivity</td>
<td>$1.5 \times 10^3$ Apollo 15 $1.72-2.95 \times 10^3$ Apollo 17 $1.5 \times 10^5$ 0.2 cm</td>
<td>W/cm K</td>
<td></td>
<td>LSB p 37-38</td>
</tr>
<tr>
<td>Thermal diffusivity ($\chi$)</td>
<td>$2-6 \times 10^{-3}$</td>
<td>cm²/sec</td>
<td>Temperature, density dependent</td>
<td>Horai et al.</td>
</tr>
<tr>
<td>Heat capacity (specific heat)</td>
<td>$c = C_4 \cdot T^4 + C_3 \cdot T^3 + C_2 \cdot T^2 + C_1 \cdot T + C_0$</td>
<td>J/kg/K</td>
<td>Temperature dependent</td>
<td>D. Paige</td>
</tr>
<tr>
<td>C₄ = 3.8697908 x 10⁹</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C₃ = -4.1426332 x 10⁶</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C₂ = -2.0296199 x 10³</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C₁ = 3.6432101F+00</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C₀ = -5.8395023 x 10¹</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DC electrical conductivity</td>
<td>see section TBD</td>
<td>mho/m</td>
<td>Temperature dependent</td>
<td>LSB9.2.1</td>
</tr>
<tr>
<td>Relative dielectric permittivity (k)</td>
<td>1.908</td>
<td></td>
<td>Function of density, temperature and frequency</td>
<td>LSB 9.2.4 Olhoeft and Strangway 1975</td>
</tr>
<tr>
<td>Loss tangent</td>
<td>$10^{0.44 \cdot 2.943}$ $10^{0.045 \cdot (1.02 + % FeO) \cdot 2.754}$</td>
<td></td>
<td>Function of density, temperature, frequency and chemistry</td>
<td>LSB 9.2.4 Olhoeft and Strangway 1975</td>
</tr>
</tbody>
</table>
Regolith Structure Stratigraphy

Chang’ e Yutu Ground Penetrating Radar
Multiple reflectors and scattering points
Identify multiple ejecta layers
Reflectors have variable lateral continuity
Regolith Stratigraphy

Upper regolith composed of numerous, variable layers. Layering is highly localized and individual layers can not be traced for significant distances.

Apollo 12
12015/12028: 42 cm long, 10 layers, 61-595 mm

Apollo 15
15001-15006: 236 cm long, 42 layers, all poorly sorted, median 44-89 mm
Near rille, 15010/15011, 60 cm long, coarser grained than elsewhere, mean 85 mm

Apollo 16
Drilling: 221 cm long, 3 major subdivisions, 46 textural units, poorly sorted, median 56-72 mm
60009/60010: general increase with depth, 85 mm surface, 200 mm at 55 cm

Apollo 17
70009-70002: 284 cm long, 5-8 stratigraphic units
New models of thermally driven crack propagation show that rock breaks down must faster due to thermal stress than impact.

Survival times for different rocks size. Blue lines: new model, red line: model of Miyamoto et al. Dashed line: Impact induced breakdown
Lunar Particle Size-Frequency Distribution

Origin of regolith on airless bodies
   Micrometeorite impact
   Thermal fatigue

Need to understand the observed size-frequency distribution of the regolith from boulders to micron-size particles for comparison against models and experiments.

No single source for all size ranges. Compiling data from modern to ancient sources: Surveyor, Apollo, Lunar Orbiter, and LRO to build a complete particle size-frequency distribution. Part of the problem is that original surface data from Surveyor and Apollo surface pictures is lost to history.
Regolith Gardening – Exposure of Immature Regolith

Recent impacts – resolved impact craters and splotches
1.36 × 10^5 splotches (D≥10 m) annually

Splotches
1.09 × 10^5 >10 m / year
≥1 m 1.52 × 10^9 / year – 40.2 ± 1.6 km^-2

Overturn
20 cm: 99% of surface overturned 1.0 × 10^7 yrs.
2 cm: 8 × 10^4 yrs.
100X faster than Gault et al. (1973)
and Ghent et al. (2014)

Spreyerer et al. (2016)

17 March 2013 impact, 18 m crater, secondaries found >30 km distant
### Regolith Density

<table>
<thead>
<tr>
<th>Depth</th>
<th>Density (g cm(^{-3}))</th>
<th>Mare</th>
<th>Highlands</th>
</tr>
</thead>
<tbody>
<tr>
<td>A11: 0-13 cm</td>
<td>1.54-1.75</td>
<td>A15: &lt;30 cm</td>
<td>1.3-1.36</td>
</tr>
<tr>
<td>A12: 0-9 cm</td>
<td>1.98</td>
<td>&gt;30 cm</td>
<td>1.66-1.8</td>
</tr>
<tr>
<td>9-41 cm</td>
<td>1.96</td>
<td>A14: 0-30 cm</td>
<td>1.6-1.7</td>
</tr>
<tr>
<td>A15: &lt;30 cm</td>
<td>1.62-1.64</td>
<td>A17: 0-90 cm</td>
<td>1.99</td>
</tr>
<tr>
<td>&gt;30 cm</td>
<td>1.75-1.91</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A17: 0-90 cm</td>
<td>1.99</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Source Book: 1.58
Regolith - Thermal Properties

Apollo – Temperature vs. Depth

Temperature variation $f$ (forcing period)
Greenhagen et al.
$\rho(z) = \rho_d - (\rho_d - \rho_s) e^{\frac{z}{H}}$

Profile Fits: “H-parameter”

Regolith - Thermal Properties

$H \approx 9 \text{ cm}$

$H \approx 6 \text{ cm}$
Latitude Variability

Hayne - H Parameter
Latitude Variability - Radar

Radar observations from the Earth
Decrease porosity with latitude

Median grain size

Thompson et al. 2016 – Mini RF

Jeong et al. 2016 – L Band Earth-based
**Regolith Porosity**

**Surface Porosity**

83 ± 2%

Photometry (Hapke Sato, 2016)

Hapke and Van Horn (1963) 80-90%

70% PSR

Lyman α (Gladstone et al., 2012)

49 ± 2% 0-30 cm: LSB

44 ± 2% 30-60 cm: LSB

Duricrust – mm thick

Ultrafine particles (< 2 μm) dominate uppermost few grains (Noble, 2010)

**Samples (Macke et al., 2012)**

Basalts 5-10%

Imbrium Ejecta – Regolith Breccia 15-25%
Dielectric Breakdown

SEP induced electrical discharge
Breakdown results in narrow channels
current causing melting and vaporization
Weathering of regolith – increase surface porosity

Jordon et al. (2015, 2016)
Volatile Cycling – Regolith Breathing
LEND – Hydrogen Sequestration

McClanahan et al., 2016

Livengood et al., 2015
Shallow Regolith Hydrogen

Hydration of surface layer
Indications of dirunal variation

Scattering of protons and interaction with H enhancement of albedo protons

Schwadron et al. (2016), Wilson et al. (2016), Looper et al. (2016)

The latitude trend in the proton albedo suggests a 1-10 cm layer of hydrated regolith that is more prevalent near the poles (Schwadron et al., 2016).

Simulation of proton albedo for wet v. dry regolith
LAMP/LADEE/ARTEMIS

Strong correlation between solar wind alpha particle flux and the total content of the helium exosphere

Fraction of the exosphere is decoupled from the solar wind.

Slowly diffusing implanted solar wind helium or radiogenic helium from the interior.
Knudsen Regolith Diffusion

Diffusion of gas into and out of the regolith
Porosity, permeability, density, grain size, molecular weight, sticking

d mean free path between grains 10’s microns
at low T, sticking becomes important Q

\[ \tau = \tau_0^{(Q/RT)} \]

Permeability: \(1-7 \times 10^{-12} \text{ m}^2\) (< 25 cm)
~sand

Friesen and Heymann (1972), Frisillo et al. (1974), Martin et al. (1973), LaMarche, et al. (2011)
RKGs

- Physical properties
  - Latitude
  - Geologic unit
  - Slope
  - PSRs
  - Optical surface*
- Diffusion / absorption properties
  - Porosity
  - Permeability
  - Diffusivity
  - Tortuosity
  - Defects
  - Activation energy

- Does the regolith really breathe?
- Thermal fatigue v. catastrophic disruption
- Turnover rate