Some Expected Characteristics of Lunar Dust: A Geological View Applied to Engineering

Kenneth W. Street, Christian M. Schrader and Doug Rickman

Compared to the Earth the geologic nature of the lunar regolith is quite distinct. Even though similar minerals exist on the Earth and Moon, they may have very different properties due to the absence of chemical modification in the lunar environment. The engineering properties of the lunar regolith reflect aspects of the parent rock and the consequences of hypervelocity meteor bombardment. On scales relevant to machinery and chemical processing for In-Situ Resource Utilization, ISRU (such as water production), the lunar regolith compositional range is much more restricted than terrestrial material. This fact impacts predictions of properties required by design engineers for constructing equipment for lunar use. In this paper two examples will be covered.

1) Abrasion is related to hardness and hardness is a commonly measured property for both minerals and engineering materials. Although different hardness scales are routinely employed for minerals and engineering materials, a significant amount of literature is available relating the two. As one example, we will discuss how to relate hardness to abrasion for the design of lunar equipment. We also indicate how abundant the various mineral phases are and typical size distributions for lunar regolith which will impact abrasive nature. 2) Mineral characteristics that may seem trivial to the non-geologist or material scientist may have significant bearing on ISRU processing technologies. As a second example we discuss the impact of traces of F-, Cl-, and OH-, H2O, CO2, and sulfur species which can radically alter melting points and the corrosive nature of reaction products thereby significantly changing bulk chemistry and associated processing technologies. For many engineering uses, a simulant’s fidelity to bulk lunar regolith chemistry may be insufficient. Therefore, simulant users need to engage in continuing dialogue with simulant developers and geoscientists.
Some Expected Characteristics of Lunar Dust:
A Geological View Applied to Engineering

Kenneth W. Street
Tribology and Mechanical Components Branch
NASA – John Glenn Research Center
Cleveland, OH 44135 USA
216-433-5032
kenneth.w.street@nasa.gov

Christian M. Schrader
BAE Systems
NSSTC/NASA - Marshall Space Flight Center
Huntsville AL 35805
256-961-7883

Doug Rickman
National Space Science and Technology Center
NASA - Marshall Space Flight Center
Huntsville, AL 35805 USA
256-961-7889
doug.rickman@nasa.gov

Presented at the Geological Society of America Meeting
Houston TX, October 9, 2008
Lunar Geologic History

Initial lunar rock ~ norite.
Subsequent basaltic volcanic (& other) flows.
Hypervelocity impacts largely destroyed original rock.
Resulting broken geologic material = regolith.

Except for some outcrops in or around the mare,

All interactions with people and equipment will be with regolith!
Particle Size -

Net result of continuing meteor bombardment.

Surface of Moon is ground mixture of fragments.

Mixture believed to be meters deep everywhere.

For Apollo mission samples
- typical average particle sizes from ~ 30 to 100 um.
Subsequent Geologic Processing

Sorting -

All Terrestrial particles are sorted.
    Based on size, shape and composition.

No Terrestrial segregation processes operate in a vacuum.

Energy input lunar surface sufficient to cause particle motion.
    Can mix but not sort.

What designers can expect:
    for any reasonable sized sample
    from top few meters
    it is possible, and even probable to have:
    Particles of all size ranges and
    Any lunar component in the sample.
### Significant Lunar Minerals Physical Properties.

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Mohs</th>
<th>Mode: Cleavage</th>
<th>Mode: Fracture</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anorthite</td>
<td>6</td>
<td>{001} p, {010} g</td>
<td>Conchoidal to uneven; brittle</td>
<td>A</td>
</tr>
<tr>
<td>Bytownite</td>
<td>6.0-6.5</td>
<td>{001} p, {010} g</td>
<td>Conchoidal to uneven; brittle</td>
<td>M</td>
</tr>
<tr>
<td>Labradorite</td>
<td>7</td>
<td>{001} p, {010} g</td>
<td>Conchoidal to uneven; brittle</td>
<td>M</td>
</tr>
<tr>
<td>Olivine</td>
<td>6.5-7.0</td>
<td>-</td>
<td>Conchoidal to uneven; brittle</td>
<td>M</td>
</tr>
<tr>
<td>Fayalite</td>
<td>6.5-7.0</td>
<td>{010} moderate, {100} weak</td>
<td>Conchoidal</td>
<td>-</td>
</tr>
<tr>
<td>Forsterite</td>
<td>6.5-7.0</td>
<td>{100}, {010} i - g; {001} po -f</td>
<td>Conchoidal</td>
<td>-</td>
</tr>
<tr>
<td>Clinoenstatite</td>
<td>5.0-6.0</td>
<td>{110} g - p</td>
<td>Brittle</td>
<td>M</td>
</tr>
<tr>
<td>Pigeonite</td>
<td>6</td>
<td>{110} p</td>
<td>Conchoidal to uneven; brittle</td>
<td>M</td>
</tr>
<tr>
<td>Hedenbergite</td>
<td>6</td>
<td>{110} g</td>
<td>Conchoidal to uneven</td>
<td>M</td>
</tr>
<tr>
<td>Augite</td>
<td>5.5-6.0</td>
<td>{110} g</td>
<td>Uneven</td>
<td>M</td>
</tr>
<tr>
<td>Enstatite</td>
<td>5.0-6.0</td>
<td>{210} g - p</td>
<td>Conchoidal</td>
<td>A</td>
</tr>
<tr>
<td>Spinel</td>
<td>7.5-8.0</td>
<td>No cleavage</td>
<td>Conchoidal</td>
<td>m</td>
</tr>
<tr>
<td>Hercynite</td>
<td>7.5-8</td>
<td>No cleavage</td>
<td>Uneven</td>
<td>m</td>
</tr>
<tr>
<td>Ulvospinel</td>
<td>5.5-6.0</td>
<td>No cleavage</td>
<td>Uneven</td>
<td>m</td>
</tr>
<tr>
<td>Chromite</td>
<td>5.5</td>
<td>No cleavage</td>
<td>Uneven</td>
<td>m</td>
</tr>
<tr>
<td>Troilite</td>
<td>4</td>
<td>No cleavage</td>
<td>Uneven</td>
<td>t</td>
</tr>
<tr>
<td>Whitlockite</td>
<td>5</td>
<td>No cleavage</td>
<td>Uneven to sub-conchoidal</td>
<td>t</td>
</tr>
<tr>
<td>Apatite</td>
<td>5</td>
<td>No cleavage</td>
<td>Uneven to conchoidal</td>
<td>t</td>
</tr>
<tr>
<td>Ilmenite</td>
<td>5.5</td>
<td>No cleavage</td>
<td>Conchoidal</td>
<td>m</td>
</tr>
<tr>
<td>Native Iron</td>
<td>4.5</td>
<td>{001} i - f</td>
<td>Hackly</td>
<td>t</td>
</tr>
</tbody>
</table>

%: A-abundant, M-major, m-minor, t-trace  
Cleavage: p = perfect;  g = good;  f = fair;  l = indistinct;  po = poor
Material Testing Methods

Hardness Testing

• Indentation:
  – Hardness based on different shaped indenters
  – Brinell, Knoop, Rockwell, Vickers, …..

• Scratch
  – Mohs, Diamond Stylus, ….

Toughness Determination

• Measure area under stress-strain curve

(Abrasion – A key issue in Lunar exploration!)
### Table 2. Approximate Correlation Between Hardness Scales.

<table>
<thead>
<tr>
<th>Vickers (10 kg)</th>
<th>Brinell (500g)</th>
<th>Brinell (3 kg)</th>
<th>Rockwell B</th>
<th>Rockwell C (10 g)</th>
<th>Knoop (1 kg)</th>
<th>Knoop (1 kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1865</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>80</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>832</td>
<td>-</td>
<td>739</td>
<td>-</td>
<td>65</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>595</td>
<td>-</td>
<td>560</td>
<td>120</td>
<td>55</td>
<td>840</td>
<td>605</td>
</tr>
<tr>
<td>254</td>
<td>201</td>
<td>240</td>
<td>100</td>
<td>23</td>
<td>376</td>
<td>250</td>
</tr>
<tr>
<td>156</td>
<td>133</td>
<td>153</td>
<td>81</td>
<td>0</td>
<td>223</td>
<td>145</td>
</tr>
<tr>
<td>70</td>
<td>53</td>
<td>-</td>
<td>0</td>
<td>-</td>
<td>-</td>
<td>60</td>
</tr>
</tbody>
</table>

**Note:** ASTM Tables available for more exact conversion.
Relating Hardness Scales:
Metal (indentation) vs. Mineral (scratch)

Most of Moon!!

- Spinel

[a = parallel and b = perpendicular to axis]
Effect of Hardness on Abrasiveness

Note: Water adsorption lowers mineral hardness.

=> On the moon things will be worse!!!
Hardness vs. Toughness

<table>
<thead>
<tr>
<th>Material</th>
<th>Wear, g</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chert</td>
<td>50</td>
</tr>
<tr>
<td>Silica</td>
<td>40</td>
</tr>
<tr>
<td>Feldspar</td>
<td>30</td>
</tr>
<tr>
<td>Dolomite</td>
<td>20</td>
</tr>
</tbody>
</table>

- 1020 steel
- Pearlite WCl
- NiHard 1

Hardness vs. Geometry

SEM of JSC-1a

50 micro meter

Caveats !!!

- Polymers (elastic)
- Surface coatings, treatments
  - and substrate effects

Major Omissions !!!
In-Situ Resource Utilization Chemical Issues

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Chemical Composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anorthite</td>
<td>$\text{CaAl}_2\text{Si}_2\text{O}_8$</td>
</tr>
<tr>
<td>Bytownite</td>
<td>$(\text{Ca,Na})(\text{Si,Al})_4\text{O}_8$</td>
</tr>
<tr>
<td>Labradorite</td>
<td>$(\text{Ca,Na})(\text{Si,Al})_4\text{O}_8$</td>
</tr>
<tr>
<td>Olivine</td>
<td>$(\text{Mg,Fe})_2\text{SiO}_4$</td>
</tr>
<tr>
<td>Fayalite</td>
<td>$\text{Fe}_2\text{SiO}_4$</td>
</tr>
<tr>
<td>Forsterite</td>
<td>$\text{Mg}_2\text{SiO}_4$</td>
</tr>
<tr>
<td>Clinoenstatite</td>
<td>$\text{Mg}_2[\text{Si}_2\text{O}_6]$</td>
</tr>
<tr>
<td>Pigeonite</td>
<td>$(\text{Mg,Fe}^{+2},\text{Ca})_2[\text{Si}_2\text{O}_6]$</td>
</tr>
<tr>
<td>Hedenbergite</td>
<td>$\text{CaFe}^{+2}[\text{Si}_2\text{O}_6]$</td>
</tr>
<tr>
<td>Augite</td>
<td>$(\text{Ca,Na})(\text{Mg,Fe,Al,Ti})[(\text{Si,Al})_2\text{O}_6]$</td>
</tr>
<tr>
<td>Enstatite</td>
<td>$\text{Mg}_2[\text{Si}_2\text{O}_6]$</td>
</tr>
<tr>
<td>Spinel</td>
<td>$\text{MgAl}_2\text{O}_4$</td>
</tr>
<tr>
<td>Hercynite</td>
<td>$\text{Fe}^{+2}\text{Al}_2\text{O}_4$</td>
</tr>
<tr>
<td>Ulvospinel</td>
<td>$\text{TiFe}^{+2}\text{O}_4$</td>
</tr>
<tr>
<td>Chromite</td>
<td>$\text{Fe}^{+2}\text{Cr}_2\text{O}_4$</td>
</tr>
<tr>
<td>Troilite</td>
<td>$\text{FeS}$</td>
</tr>
<tr>
<td>Whitlockite</td>
<td>$\text{Ca}_9(\text{Mg,Fe}^{+2})(\text{PO}_4)_6(\text{PO}_3\text{OH})$</td>
</tr>
<tr>
<td>Apatite</td>
<td>$\text{Ca}_5(\text{PO}_4)_3(\text{OH,F,Cl})$</td>
</tr>
<tr>
<td>Ilmenite</td>
<td>$\text{Fe}^{+2}\text{TiO}_3$</td>
</tr>
<tr>
<td>Native Iron</td>
<td>$\text{Fe}$</td>
</tr>
</tbody>
</table>

While attempting to manufacture oxygen, ..... we strike Halogens, Sulfur and Phosphorus!
Issues with Cl, S and P

Halogens (Cl) produce:

\[ \text{Cl} \rightarrow \text{Cl}_2 \text{ and/or HCl} \quad \text{(Corrosive and Toxic)} \]

Sulfur (as sulfide):

\[ \text{S} \rightarrow \text{H}_2\text{S, H}_2\text{SO}_3 \text{ and or H}_2\text{SO}_4 \quad \text{(Ditto)} \]
\[ \text{S} \text{ poisons Expensive Catalysts} \]

Phosphorus (as phosphate):

Same as Sulfur

Causes steel to become brittle
Simulant vs. Regolith Composition

Lunar Highlands:  An >90%

NU-LHT-1M range:  An 75-85%

OB-1:  An ~ 75%?  (Shawmere)

Lunar Mare:  An 75-95%

JSC-1:  An 64-71% (Carpenter 2005)

JSC-1A:  An 70% (average -- Hill et al., 2007)

JSC-1AF:  An 70% (Carpenter, 2006)

MLS-1:  An 44-50% (Carpenter, 2005; Hill et al., 2007)

Na to Ca ratio plagioclase series is solid solution
Ca is anorthite
Na is albite

Ca/Na ratio determines An number
Why Mineral Chemistry Matters

Albite, An 0%, melts at ~750°C

Anorthite, An 100%, melts at ~1230°C

About average lunar highland composition

JSC-1 series

Data below for: Modest confining Pressure
Hydrothermal Alteration

(a)

\( P_{\text{H}_2\text{O}} = 5 \text{ kbar} \)

Melt

Liquidus

Melt + Crystals

Solidus

Crystals

Albite, An 0%, melts at ~750°C

Anorthite, An 100%, melts at ~1230°C

About average lunar highland composition

JSC-1 series
Systems with Complete Solid Solution

Plagioclase (Ab-An, NaAlSi$_3$O$_8$ - CaAl$_2$Si$_2$O$_8$)


Duplicate of prior slide
But NO Water (therefore no hydrothermal alteration) and at ambient Pressure

Note Temp increase!
Conclusions:
- Engineering is constrained by Regolith properties
- Geologic data is useful in engineering design
- A comparison of geologic properties to engineering design considerations is presented
- Some processes may concentrate trace components

Acknowledgement: J.R. Skok & Ashley Boudreaux for compiling and developing literature data on mineral properties and lunar mineral abundances.
Blank
Hardness vs. Toughness

Brittle: Ceramics, Minerals

Tough (Ductile): Metals (Carbon Steel)

Hardness ≠ Toughness

Toughness = Area under Stress-Strain curve
Experimentally Determined Melting Intervals of Gabbro