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.

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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!

Subsequent Geologic Processing

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.

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

%: A-abundant, M-major, m-minor, t-trace

Cleavage: p = perfect; g = good; f = fair; I = indistinct; po = poor

Material Testing Methods

Hardness Testing

- Indentation:
  - Hardness based on different shaped indenters
  - Brinell, Knoop, Rockwell, Vickers, **…..**
- Scratch
  - Mohs, Diamond Stylus, **….**

Tougness Determiantion

- Measure area under stress-strain curve

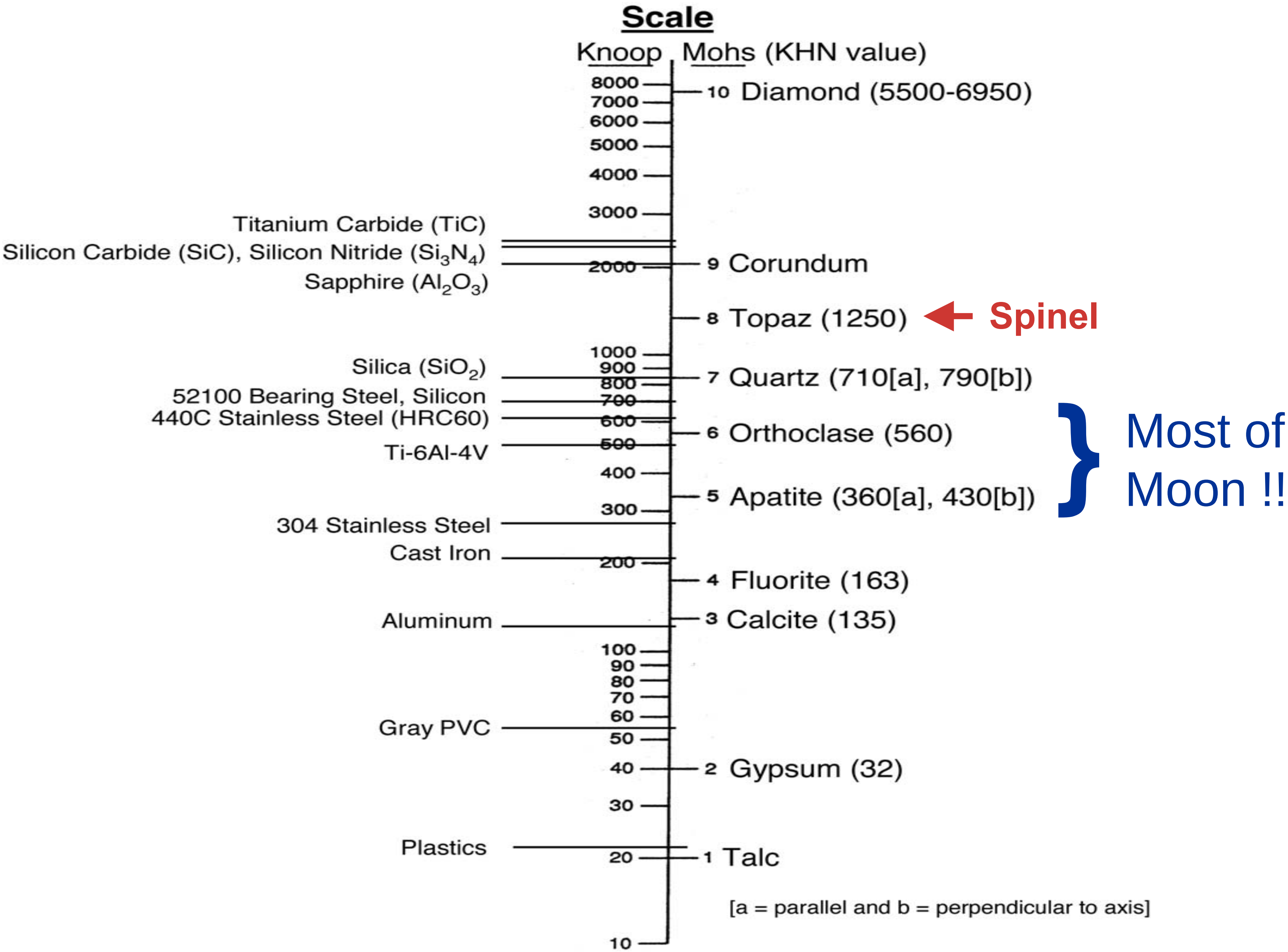
(Abrasion – A key issue in Lunar exploration!)

Table 2. Approximate Correlation Between Hardness Scales.

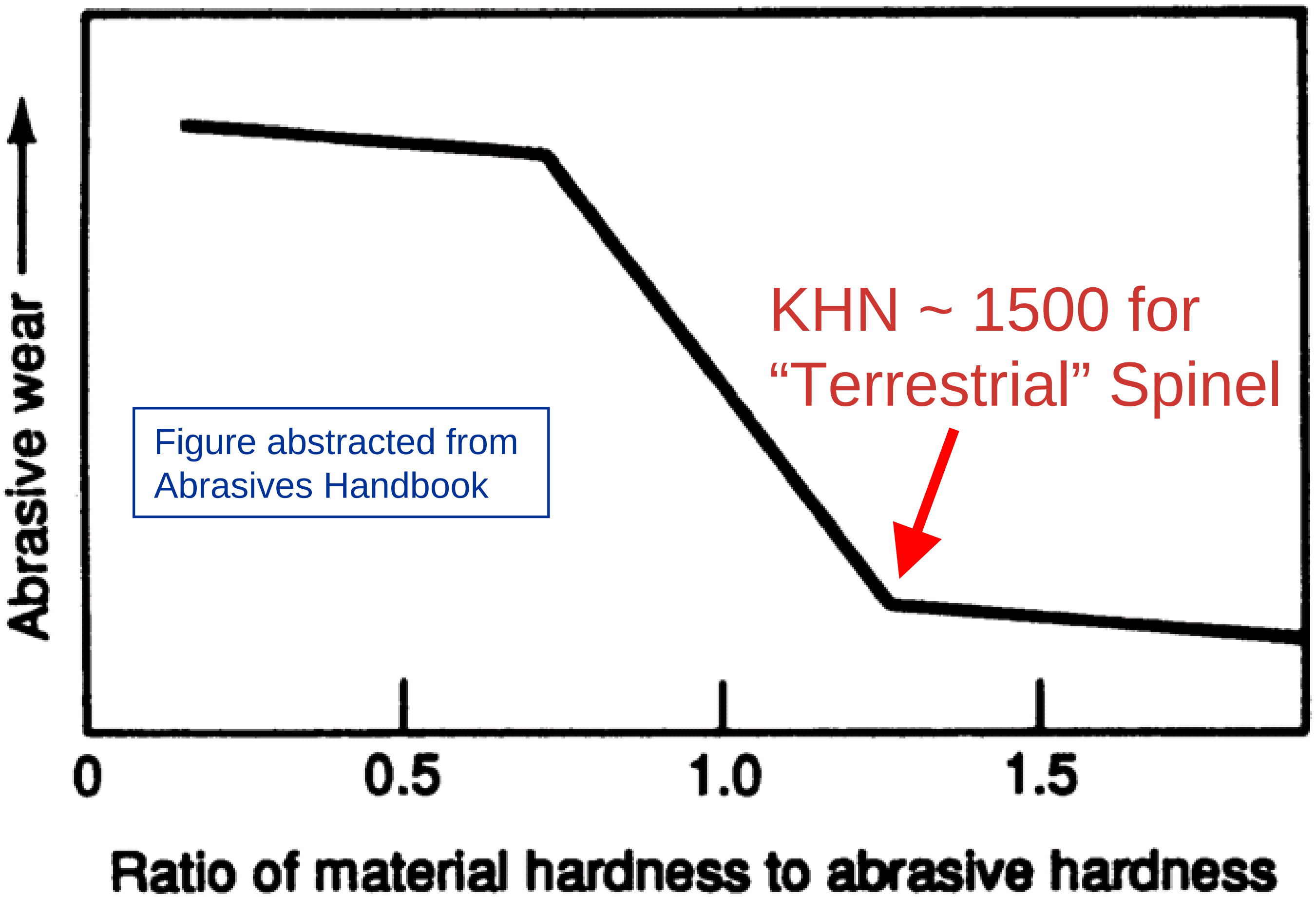
Hardness Values (load)						
Vickers (10 kg)	Brinell (500g)	Brinell (3 kg)	Rockwell B	Rockwell C	Knoop (10 g)	Knoop (1 kg)
1865	-	-	-	80	-	-
832	-	739	-	65	-	-
595	-	560	120	55	840	605
254	201	240	100	23	376	250
156	133	153	81	0	223	145
70	53	-	0	-	-	60

Note: ASTM Tables available for more exact conversion

Relating Hardness Scales:
Metal (indentation) vs. Mineral (scratch)



Effect of Hardness on Abrasiveness

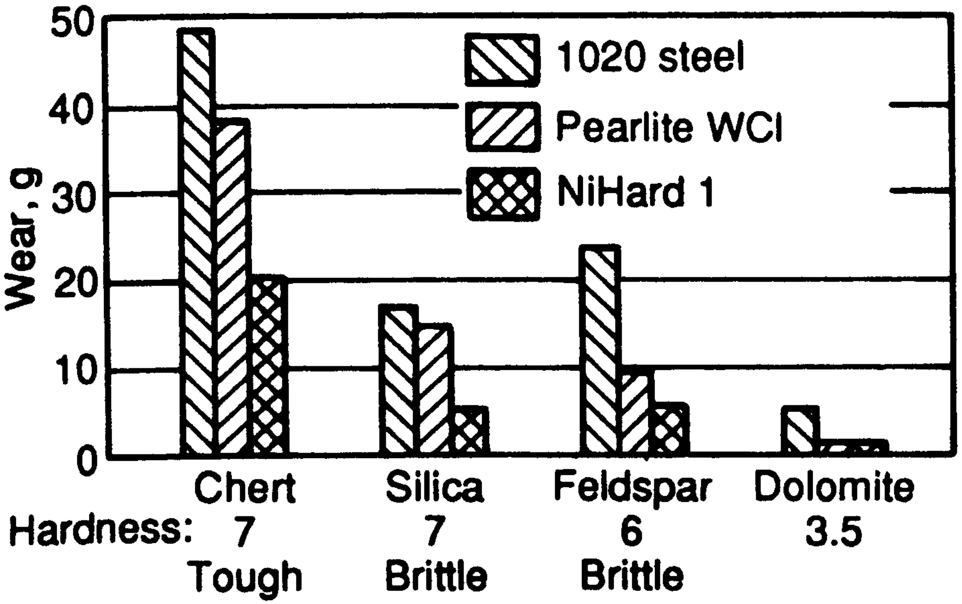


Note: Water adsorption lowers mineral hardness.

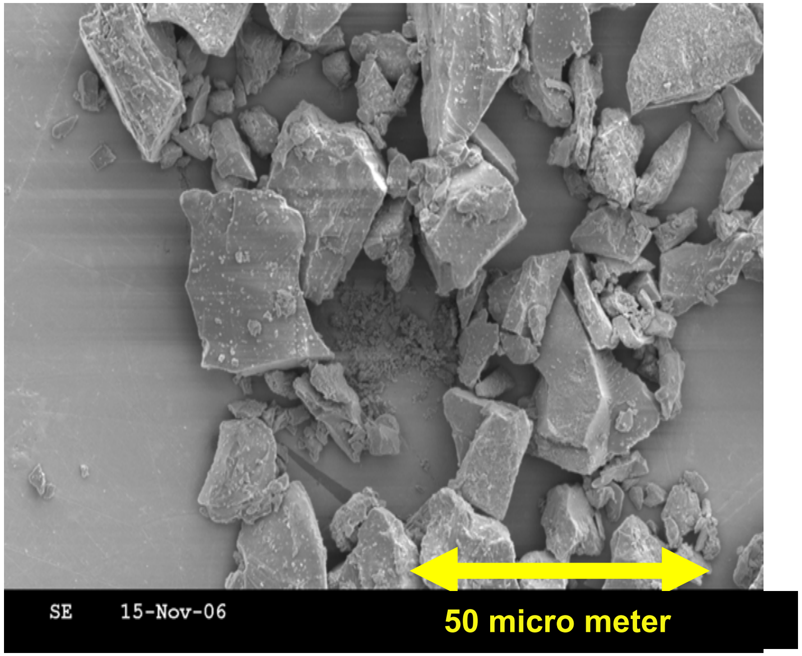
=> **On the moon things will be worse!!!**

Caveats !!!

Hardness vs. Toughness



Hardness vs. Geometry



SEM of JSC-1a

Major Omissions !!!

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

In-Situ Resource Utilization Chemical Issues

Mineral	Chemical Composition
Anorthite	$CaAl_2Si_2O_8$
Bytownite	$(Ca,Na)(Si,Al)_4O_8$
Labradorite	$(Ca,Na)(Si,Al)_4O_8$
Olivine	$(Mg,Fe)_2SiO_4$
Fayalite	Fe_2SiO_4
Forsterite	Mg_2SiO_4
Clinoenstatite	$Mg_2\,[Si_2O_6]$
Pigeonite	$(Mg,Fe^{+2},Ca)_2[Si_2O_6]$
Hedenbergite	$CaFe^{+2}[Si_2O_6]$
Augite	$(Ca,Na)(Mg,Fe,Al,Ti)[(Si,Al)_2O_6]$
Enstatite	$Mg_2[Si_2O_6]$
Spinel	$MgAl_2O_4$
Hercynite	$Fe^{+2}Al_2O_4$
Ulvospinel	$TiFe^{+2}{}_2O_4$
Chromite	$Fe^{+2}Cr_2O_4$
Troilite	FeS
Whitlockite	$Ca_9(Mg,Fe^{+2})(PO_4)_6(PO_3OH)$
Apatite	$Ca_5(PO_4)_3(OH,F,Cl)$
Ilmenite	$Fe^{+2}TiO_3$
Native Iron	Fe

While attempting to manufacture oxygen, …..

we strike Halogens, Sulfur and Phosphorus!

Issues with Cl, S and P

Halogens (Cl) produce:

$Cl \longrightarrow Cl_2$ and/or HCl (Corrosive and Toxic)

Sulfur (as sulfide):

$S \longrightarrow H_2S$, H_2SO_3 and or H_2SO_4 (Ditto)

S 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)

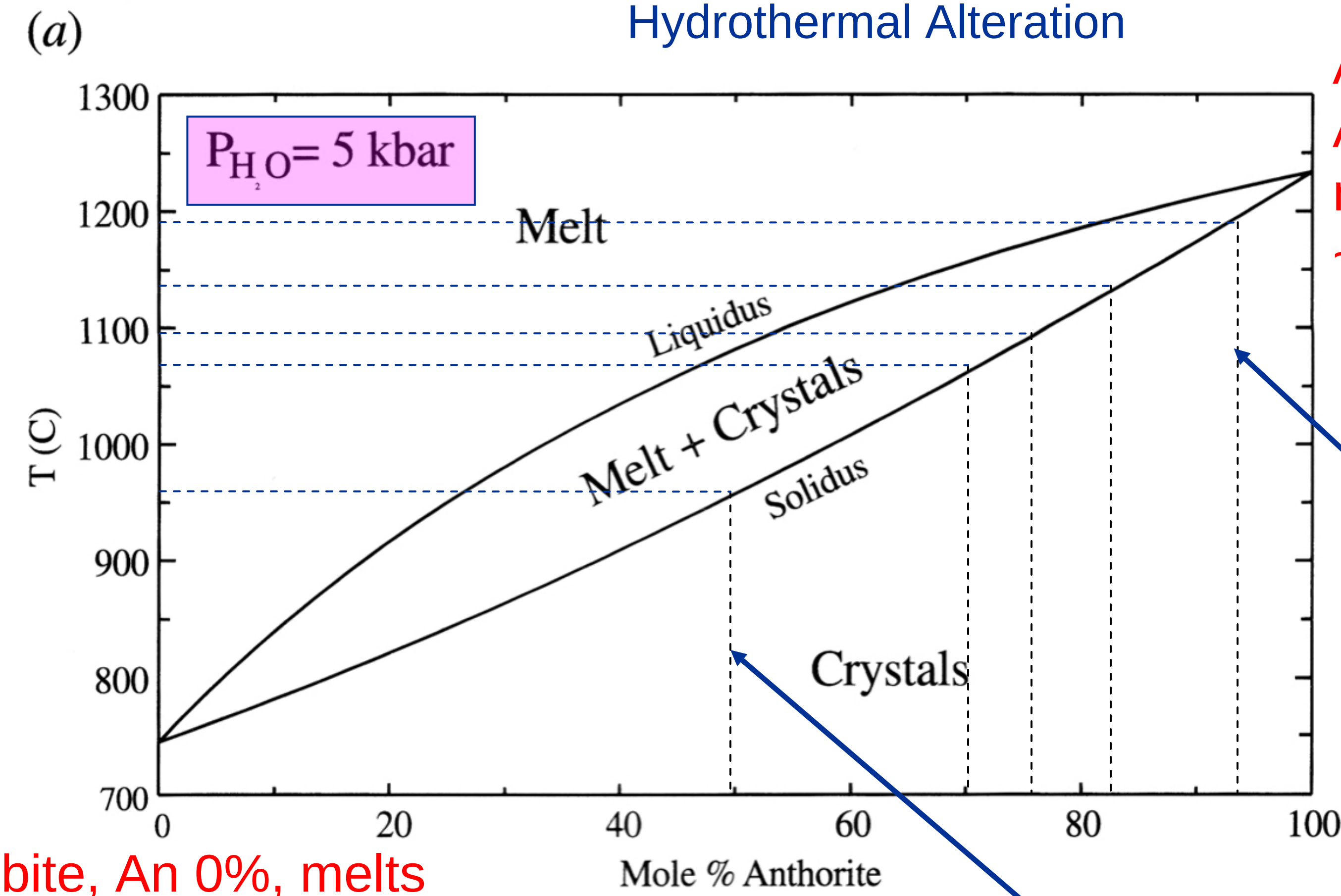
MLS-1: An 44-50% (Carpenter, 2005; Hill et al., 2007)

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

Data below for: Modest confining Pressure
Hydrothermal Alteration



Anorthite, An 100%, melts at ~1230°C

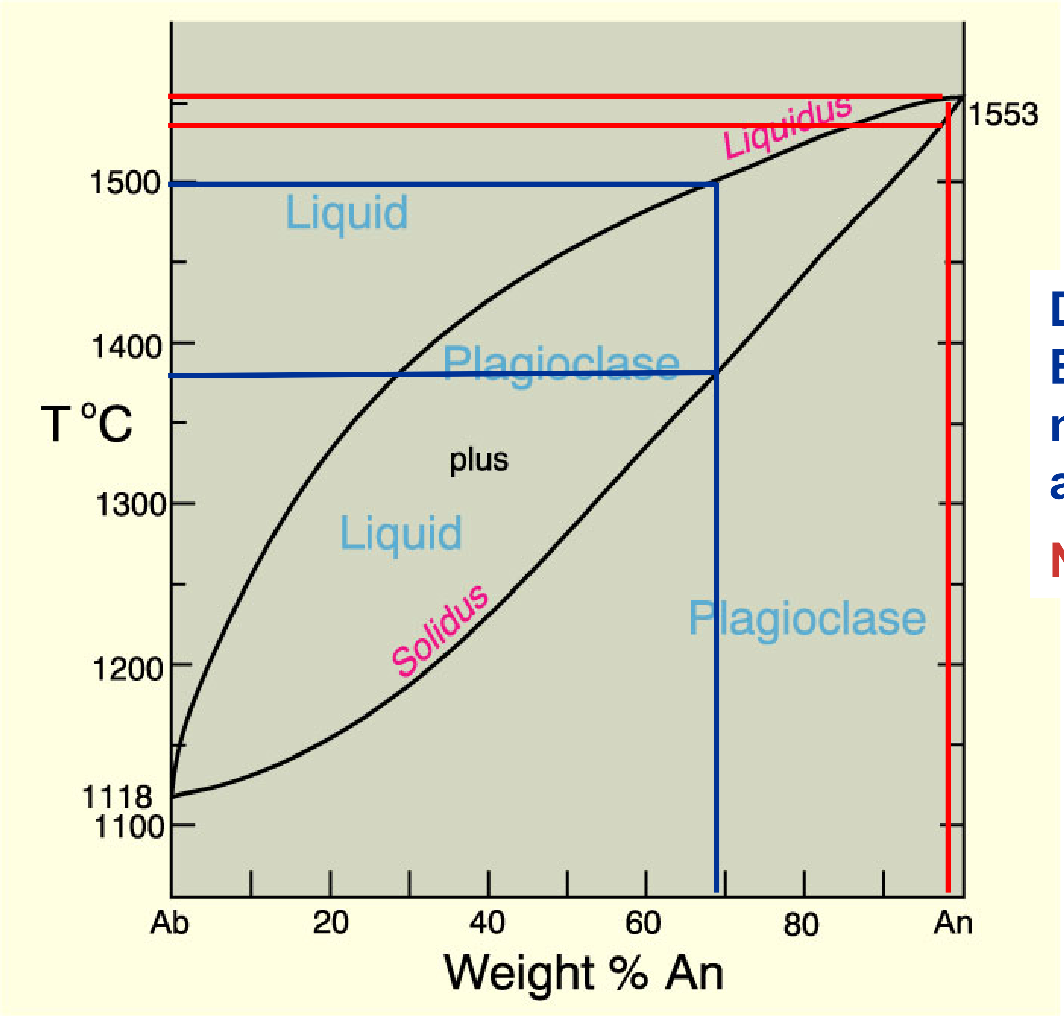
About average lunar highland composition

Albite, An 0%, melts at ~750°C

JSC-1 series

Systems with Complete Solid Solution

Plagioclase (Ab-An, $NaAlSi_3O_8$ - $CaAl_2Si_2O_8$)



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

Note Temp increase!

Isobaric T-X phase diagram at atmospheric pressure. After Bowen (1913) Amer. J. Sci., 35, 577-599.

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.**

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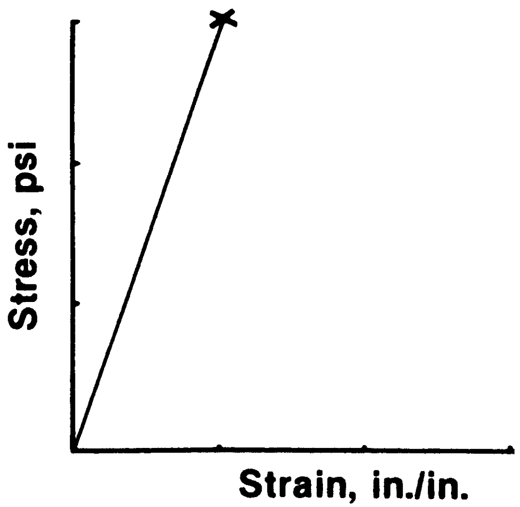
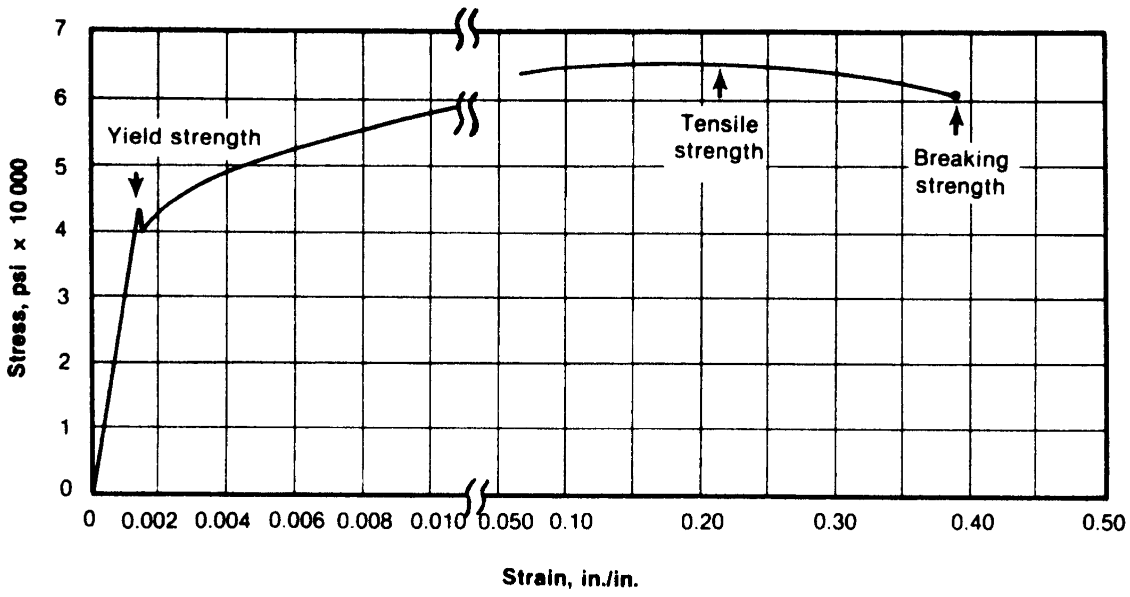
Hardness vs. Toughness





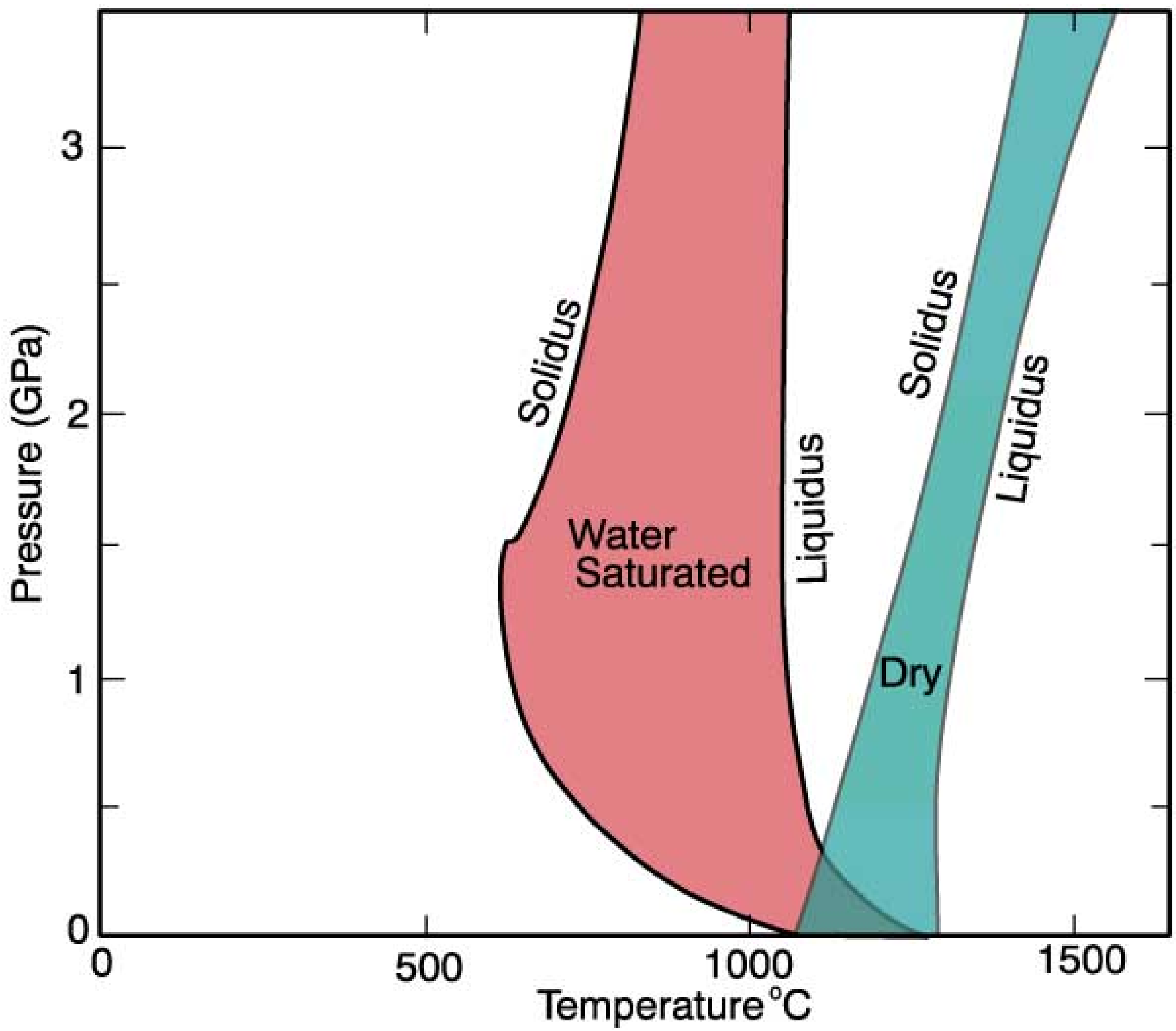
Brittle: **Ceramics, Minerals**

Tough (Ductile): **Metals (Carbon Steel)**

Hardness ≠ Toughness

Toughness = Area under Stress-Strain curve

Experimentally Determined Melting Intervals of Gabbro



After Lambert and Wyllie (1972). J. Geol., 80, 693-708.