MICROMECHANICAL AND MICROSTRUCTURAL ANALYSIS OF LUNAR CONCRETE

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INTRODUCTION: In-Situ Resource Utilization (ISRU)

ISRU harnesses planetary resources at mission destinations to enhance the capabilities of human exploration

- ❑ **GEOPOLYMER**

  A cement-like system comprising an aluminosilicate source and an alkaline activator

- ❑ **ALUMINOSILICATE**

  Lunar regolith is a rich aluminosilicate source

- ❑ **ALKALINE ACTIVATOR**

  The lunar soil contains extractable water and alkalis

ALUMINOSILICATE + ACTIVATOR = GEOPOLYMER

INTRODUCTION: Planetary Simulants

❑ OFF PLANET RESEARCH LUNAR HIGHLANDS (OPRH2N):

- OPRH2N is simulant representative lunar Highland region on moon, which makes up of around 60% of moon surface area.
- Composition: 70% anorthosite, 30% basaltic cinder

Fig.1. Lunar Regolith (Simulant)

Fig.2. Lunar Concrete (Geopolymer)

OBJECTIVES

- **Optimize** the mixture composition of lunar geopolymer concrete
  - Solution-to-simulant ratio
  - Silica modulus
  - Curing temperature
- **Characterize** the microstructure and micromechanical properties of lunar geopolymer concrete
- **Compare** the properties of lunar geopolymers and simulants to terrestrial cement hydrates and aggregates

METHODOLOGY: Materials & Mixture Proportions

Mixture Parameters

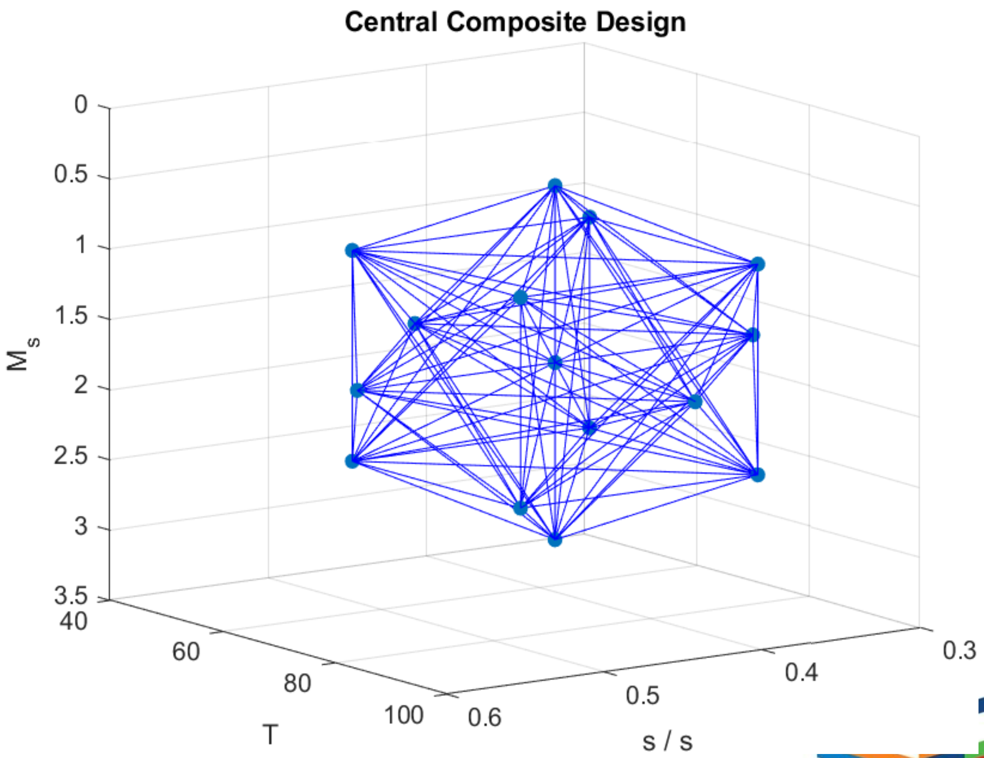
Parameter	Range	Central Value
Solution/simulant ratio (s/s)	0.35 - 0.55	0.425
Silica modulus (M_s)	0.5 - 3	1.75
Curing temperature (T)	55 – 95 °C	70 °C

OPRH2N Composition

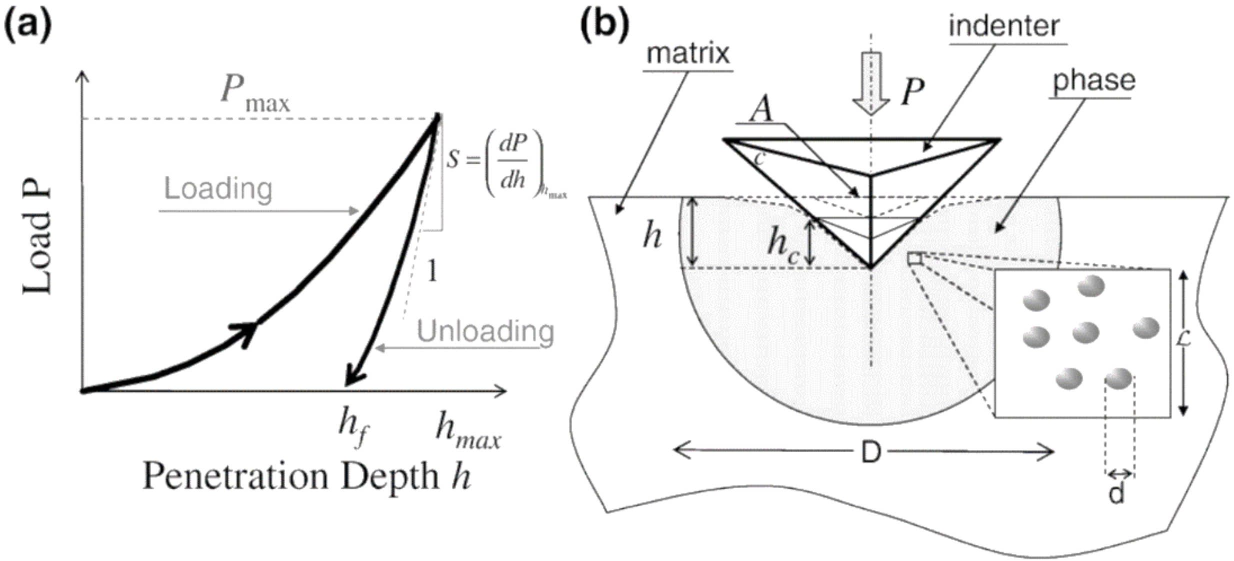
Minerals	Weight %
Plagioclase	70.4
Amorphous glass	26.5
Olivine	3.1

METHODOLOGY: Central Composite Design

Response Parameter	Range
Compressive Strength	6 – 37 MPa



METHODOLOGY: Nanoindentation

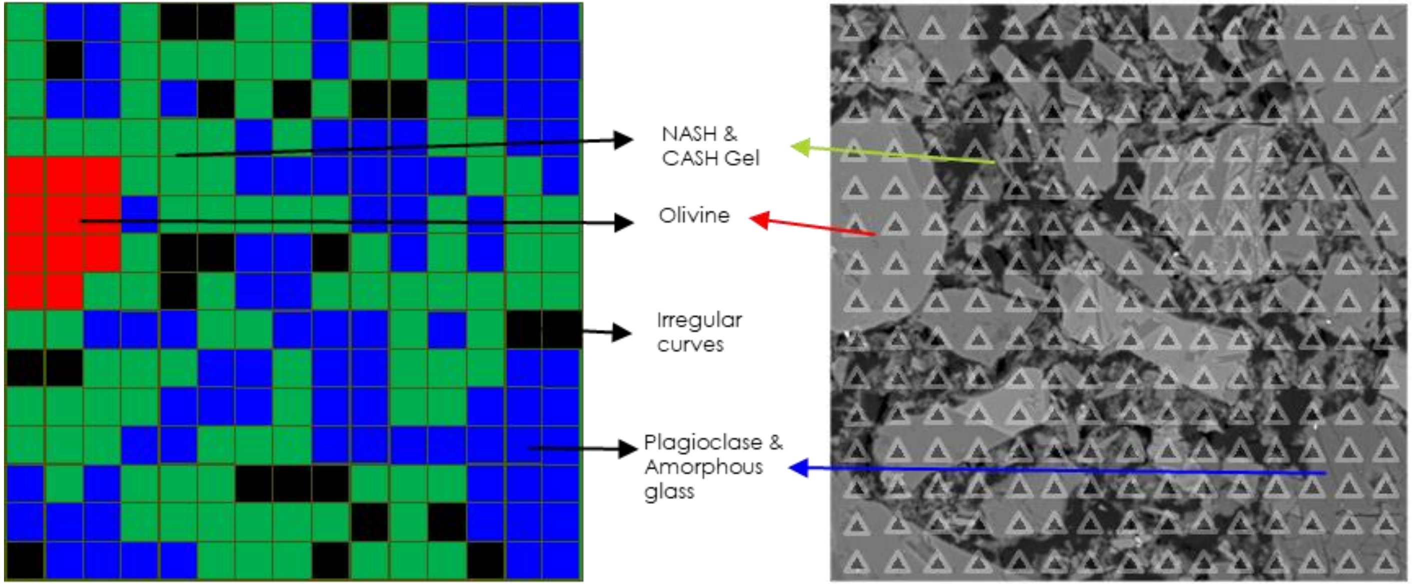


P= Load
A= Contact Area
S= Stiffness

$$H = \frac{P}{A}$$

$$E = \frac{\sqrt{\pi}}{2} \frac{S}{\sqrt{A}}$$

MICROSTRUCTURE : PHASES DECONVULTION



NANO-INDENTATION TEST RESULTS

Hydrated Portion Phases	Unhydrated Portion Phases
NASH GEL	Amorph. Glass & Plagioclase
CASH GEL	Olivine

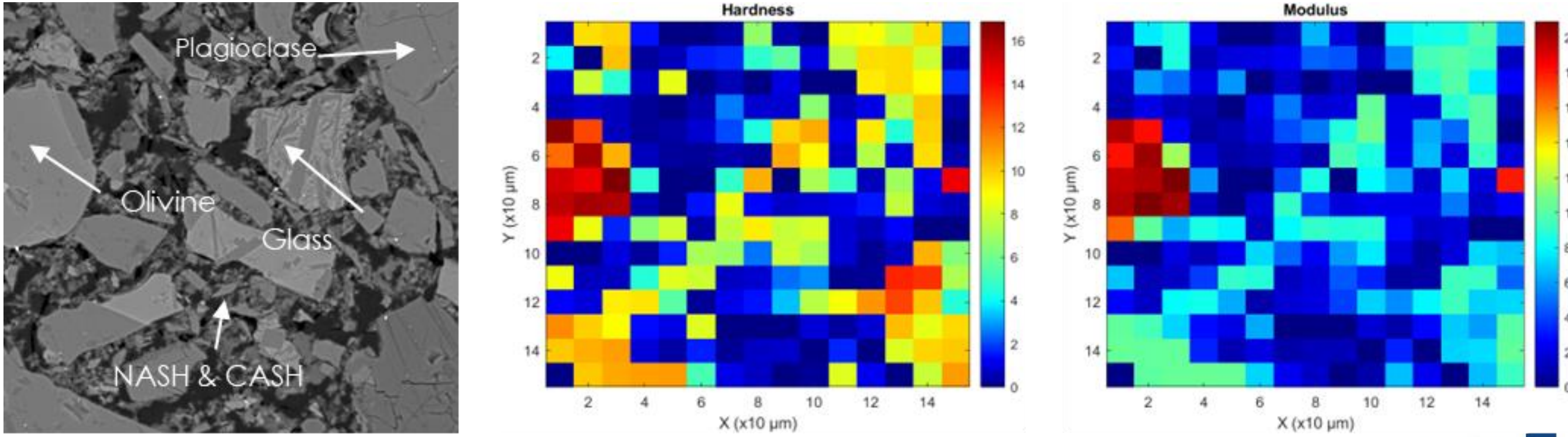


Fig.5. Left: Microstructure, Middle: microhardness, Right: reduced modulus

STATISTICAL ANALYSIS

Hydrated Portion Phases	Unhydrated Portion Phases
NASH GEL	Amorph. Glass & Plagioclase
CASH GEL	Olivine

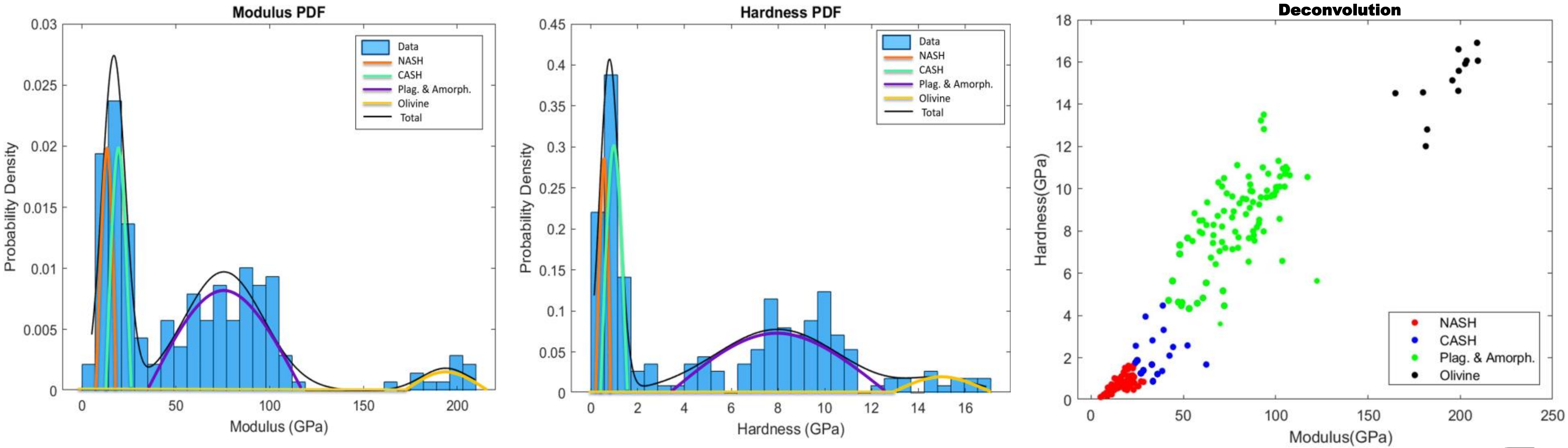
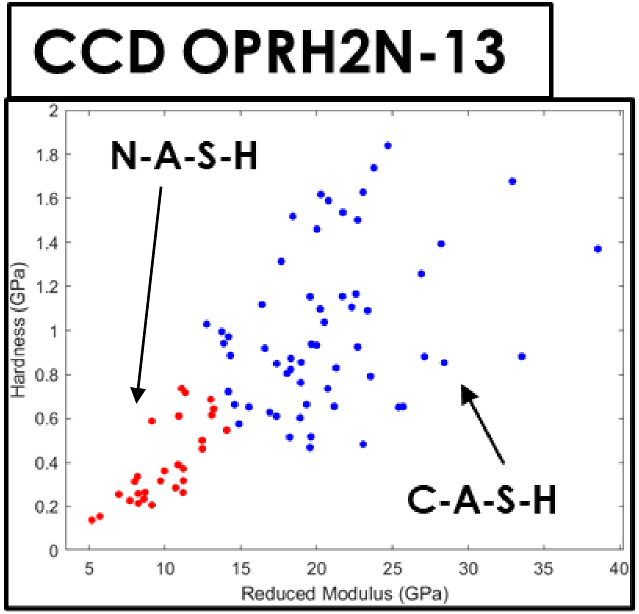


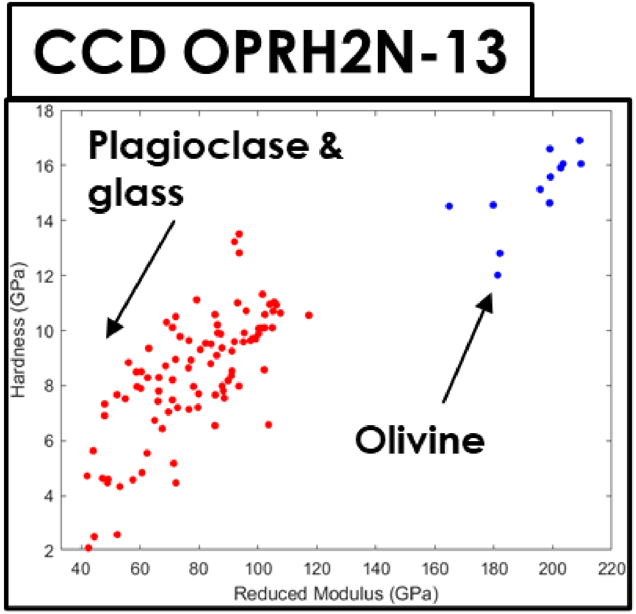
Fig.6. Left: reduced Modulus PDF, Middle: microhardness PDF, Right: 4 phases characterization deconvolution.

STATISTICAL ANALYSIS

Hydrate portion phases:



Unhydrated portion phases:



LITERATURE

PHASES	REDUCED MODULUS	MICRO HARDNESS	REFERENCE
C-A-S-H GEL	**7.9 to 19.5 GPa** 4 to 20 GPa	**0.30 to 0.78 GPa** 0.11 to 0.75 GPa	(Das et al. 2015, Lee et al. 2016 Němeček et al. 2011, Pelisser et al. 2013, Lee et al. 2016)
N-A-S-H GEL	**20.9 to 34.9 GPa** 15 to 45 GPa	**0.98 to 1.41 GPa** 0.77 to 1.57 GPa	(Constantinides and Ulm 2007, Hay et al. 2020, Yang et al. 2022, Wilson et al. 2018)
AMORPHOUS GLASS[1] & PLAGIOCLASE[2]	**52.5 to 82.2 GPa** 33 to 80 GPa	**3.7 to 9.5 GPa** 7 to 9 GPa	(Husien 2010, Kese et al. 2005, Maruvanchery and Kim 2020; Tang et al. 2022)
OLIVINE	**78.9 to 193.8 GPa** 108 to 169 GPa	**9.5 to 16.4 GPa** 12 to 15 GPa	(Kranjc et al. 2016, Nie et al. 2023, Tang et al. 2022)

**** Bold = Values from this study***
1 Lower microhardness and reduced modulus values.
2 Higher microhardness and reduced modulus values.

COMPRESSIVE STRENGTH

$^{s}/_{s}$= Solution to Simulant *T*= Temperature (°C) M_s=Silica Modulus CS= Compressive strength (MPa)

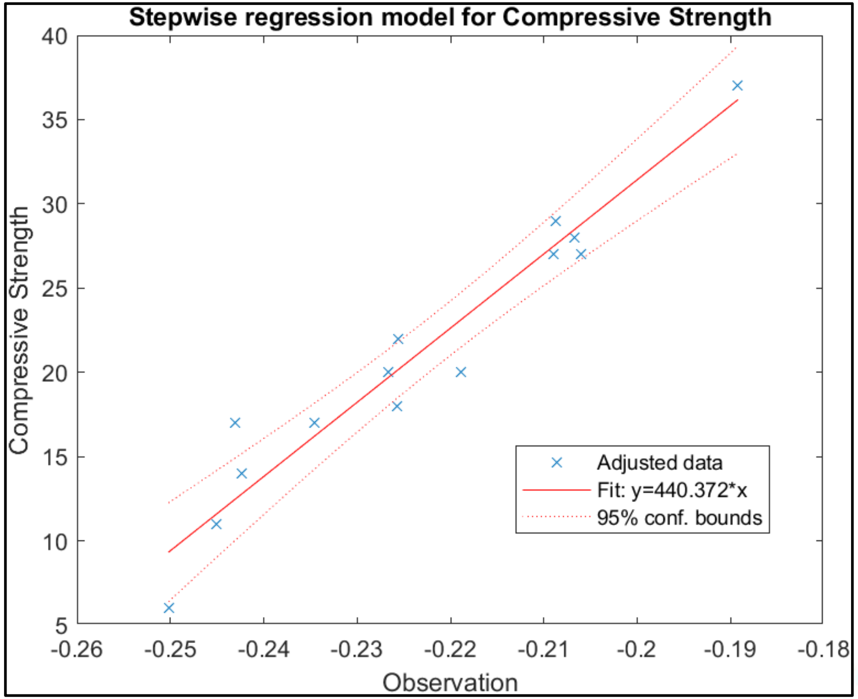
Regression model:

- CS ~ 1 + M_s + $^{s}/_{s} : T$ + $^{s}/_{s}{}^{2}$ + $M_s{}^{2}$

Estimated Coefficients:

	Estimate	p-Value
(Intercept)	120	0.015
$^{s}/_{s}$	-354	0.040
T	-0.751	0.490
M_s	3.87	0.073
$^{s}/_{s} : T$	1.44	0.127
$^{s}/_{s}{}^{2}$	262	0.130
$M_s{}^{2}$	1.94	0.241

p-value = 0.00011



CONCLUSION

- The compressive strength of lunar concrete is **indirectly** related to **solution/simulant ratio** and **curing temperature**, and **directly** related to **silica modulus**.
- The lunar concrete includes four microstructural phases: **N-A-S-H**, **C-A-S-H**, **glass/plagioclase**, and **olivine** (in increasing order of hardness)
- The **hardness and reduced modulus values** for all the identified phases **align** with those reported in the **literature**.
- The lunar regolith based geopolymers should exhibit **similar micromechanical properties** to **terrestrial geopolymers**, at least when cured at standard pressure and gravity.

Thank You!

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