Geopolymer Concrete – A greener alternative on Earth and a feasible material for the Moon

Peter J. Collins

Aleksandra Radlińska, Jennifer Edmunson, Michael Fiske, and Louise Strutzenberg

Earth Day 2022

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A brief overview of the following presentation

Ordinary Portland Cement (OPC) Concrete

Geopolymer Concrete

Geopolymer Concrete for the Moon

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Concrete is the most used human made material on Earth but currently is estimated to contribute up to 8% of the CO_2 emissions

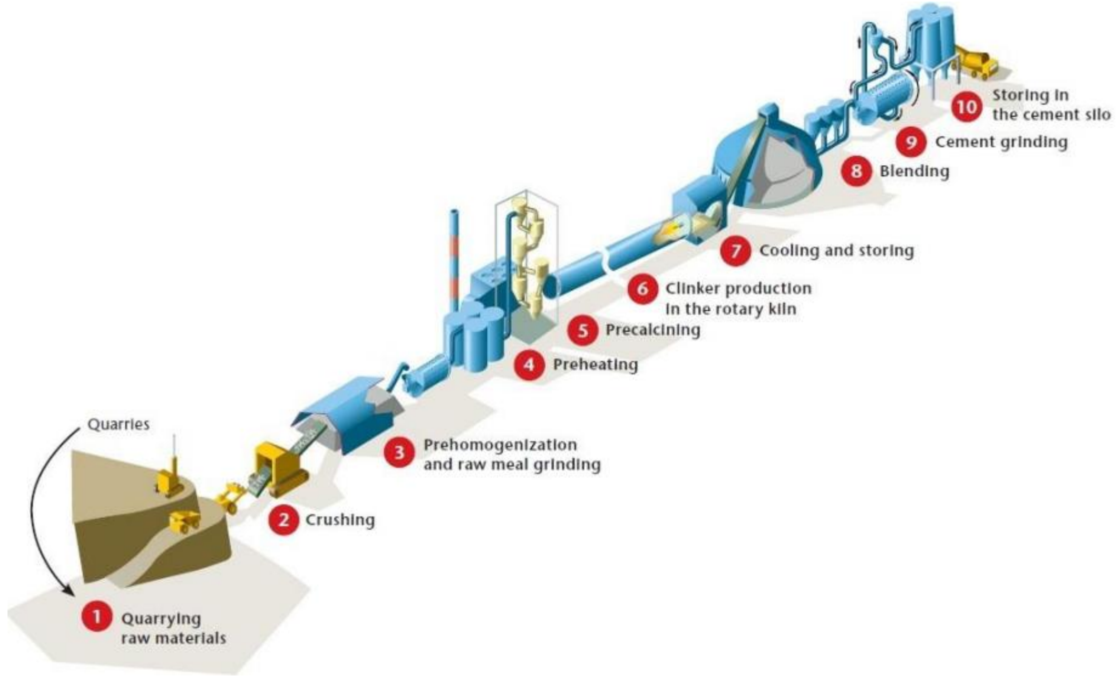

Image: WBCSD/IEA 2009a

- Carbon dioxide from production:
  - The transformation of limestone to lime in the kiln
  - $CaCO_3 \longrightarrow CaO + CO_2$
- Energy to heat the kiln

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Concrete materials cannot be replaced

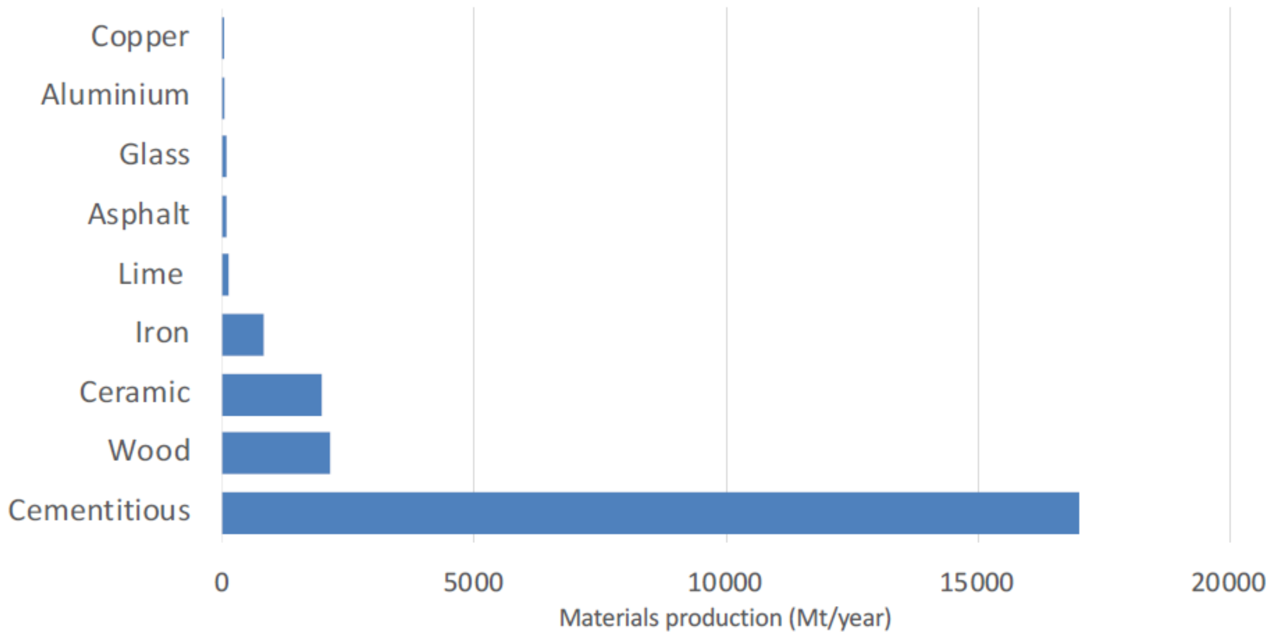

Image adapted from Karen Scrivener - EPFL

Material	Energy Data – MJ/kg	Carbon Data – $kgCO_2/kg$
Cement	4.6	0.83
Concrete	0.95	0.13
Aluminum (average of recycled and virgin)	155	8.24
Steel (average of recycled and virgin)	24.40	1.77
Timber	8.5	0.46
Plastics	80.50	2.53
Insulation	45.0	1.86

Hammond, G.P. and Jones, C.I., “Embodied energy an
materials,” *Proc. Inst. Civil Energy, in press.*

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There are ways to reduce CO_2 emissions

- Admixtures
- Supplementary Cementitious Materials
- Limestone Cement
- Geopolymer Concrete

Kosmatka et al., 2003

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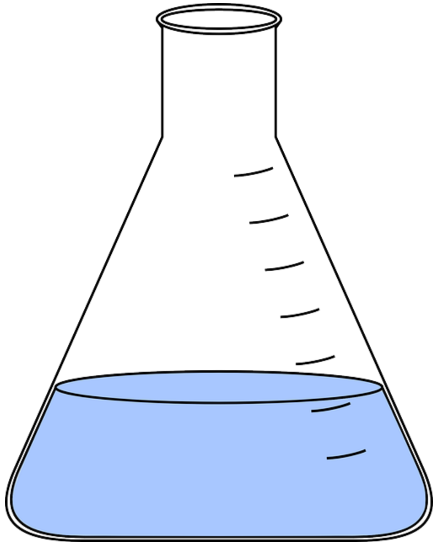
Geopolymer concrete requires an alkaline solution to be mixed with an aluminosilicate glassy source.

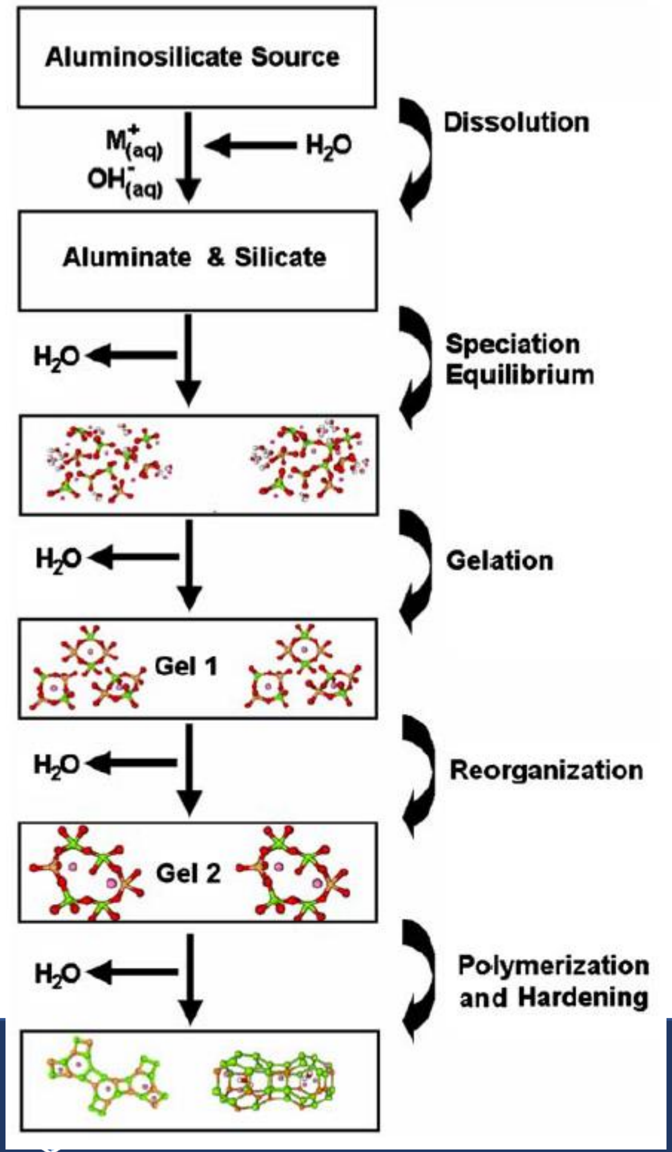


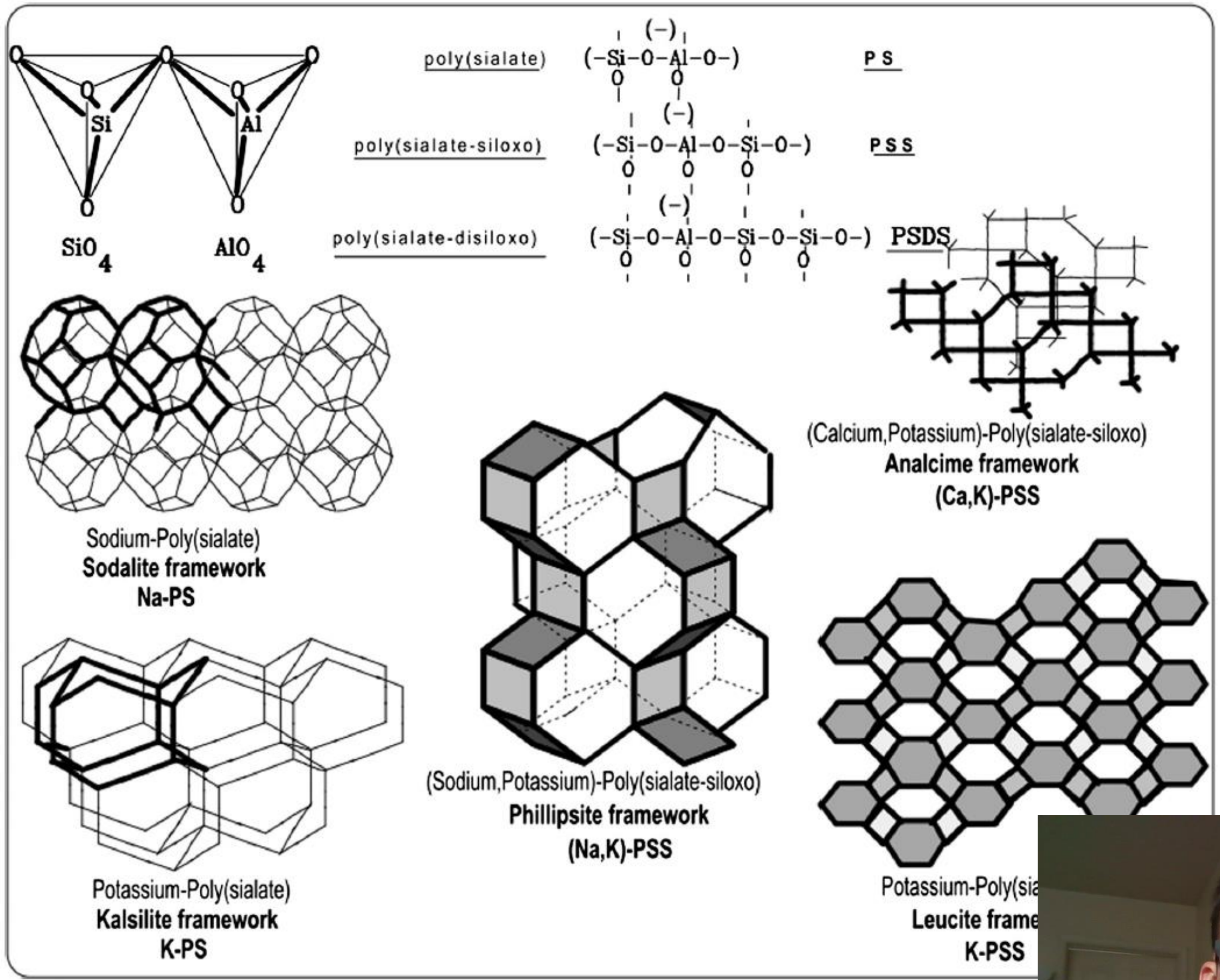
Alkaline Solution
- Sodium hydroxide and sodium silicate

Aluminosilicate Glassy Source
- Fly Ash
- Slag
- Calcined Clay
- Lunar regolith

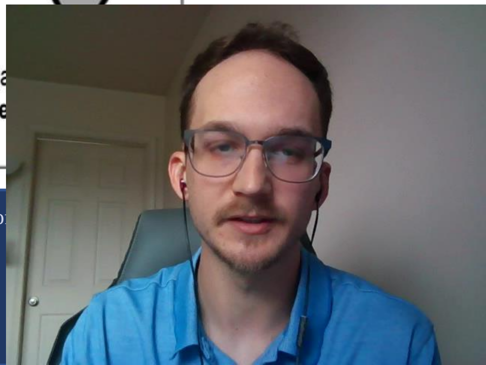
Geopolymer Concrete

Different alkaline solutions and aluminosilicate glasses can be used depending on the desired design properties.





P. Duxson, A. Fernández-Jiménez, J.L. Provis, G.C. Lukey, A. Palomo, J.S.J. Van Deventer, Geopolymer technology: The current state of art, J. Mater. Sci. 42 (2007) 2917–2933. doi:10.1007/s10853-006-0637-z.



Geopolymers won't ever replace OPC but do have exhibit properties for certain applications.

- Fire resistance
- Chemical durability
- Waste immobilization
  - Nuclear waste
  - Oilfield wells
  - Heavy metal mines
- Future space exploration

geopolymer.org

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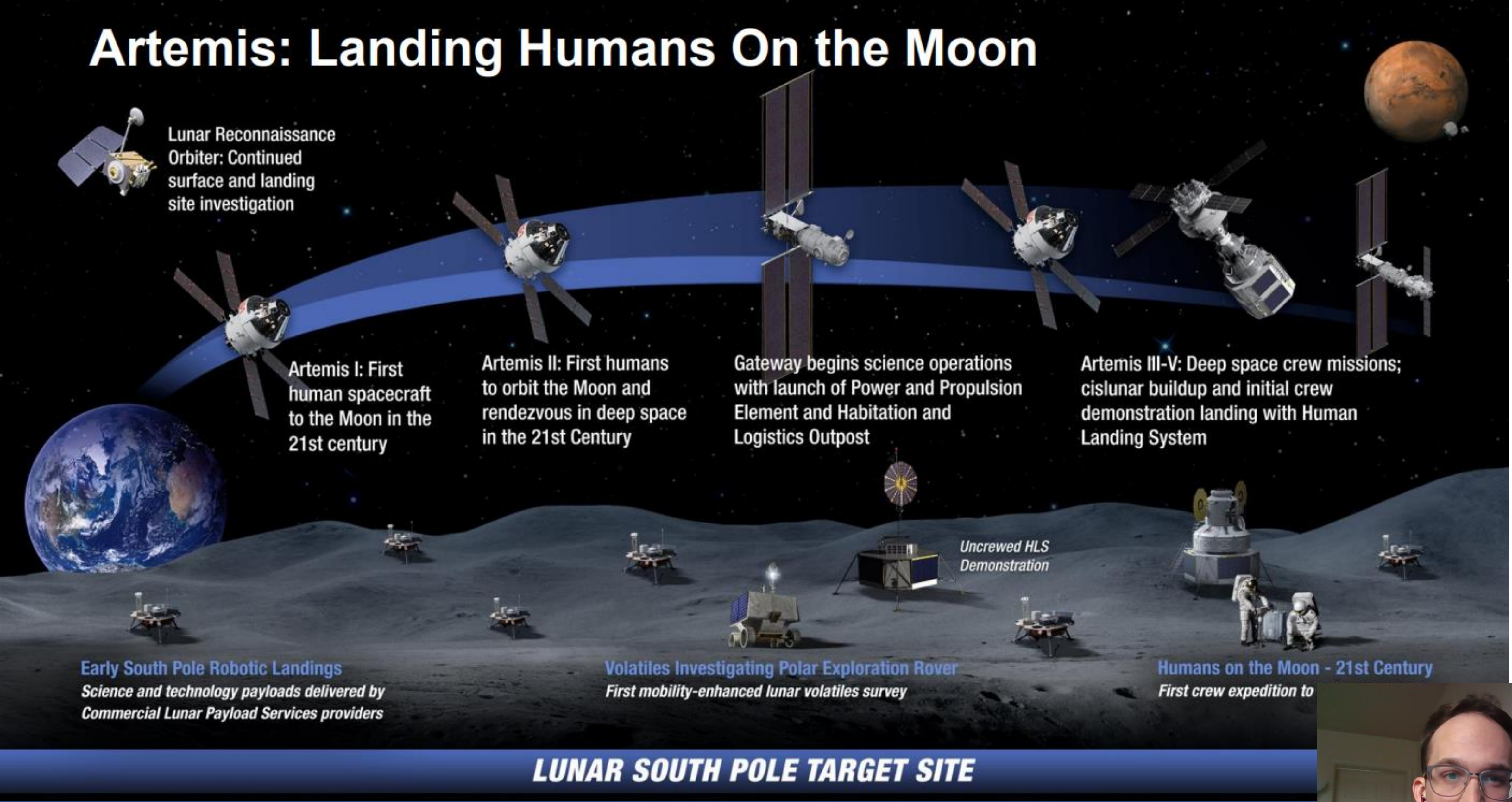

Image: NASA

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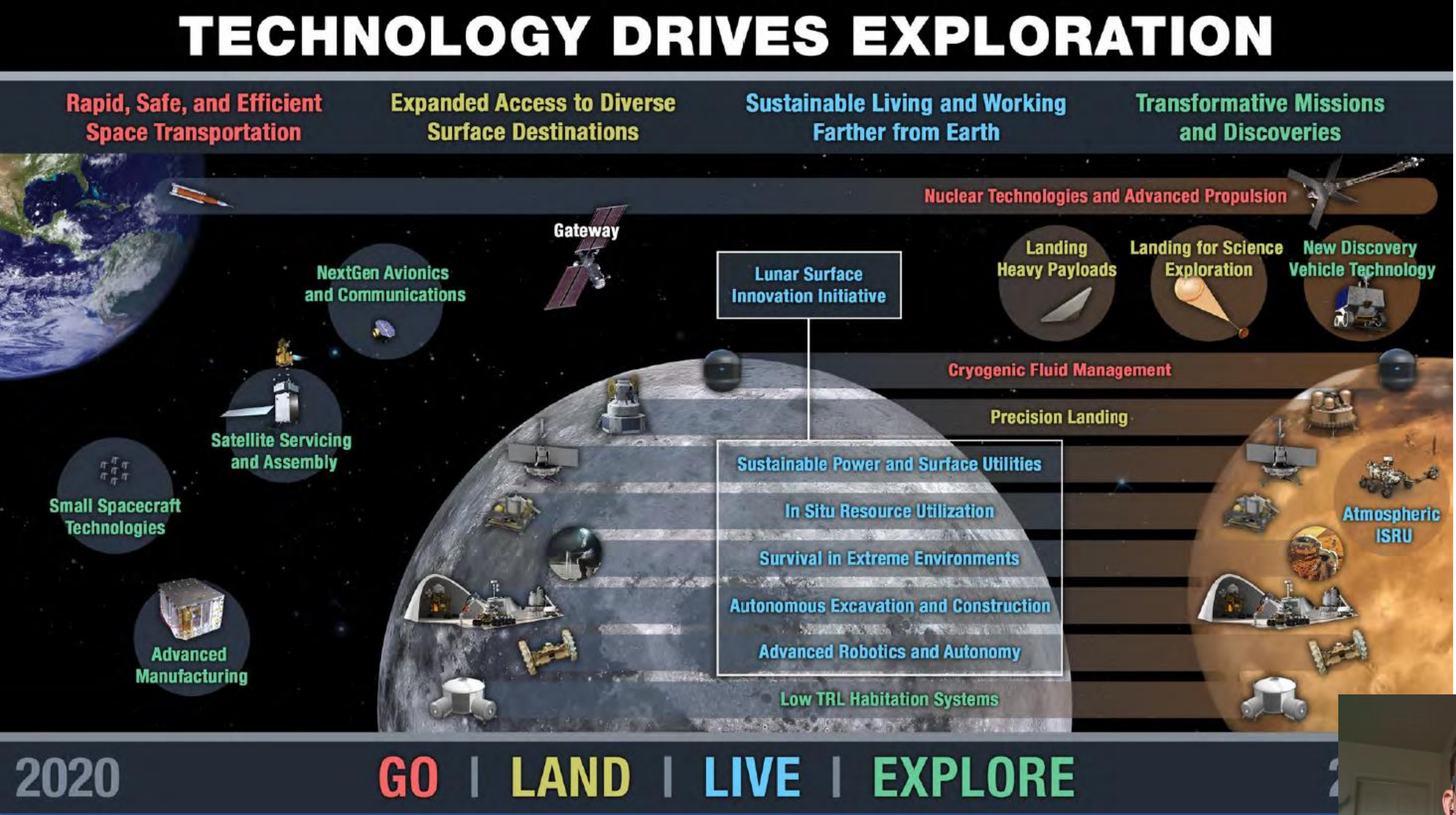

Image: NASA

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The lunar surface poses an extreme environment for concrete materials.

Environment Challenges

- Reduced gravity (1.62 m/s^2)
- Atmosphere pressure of 3×10^{-13} Pa
  - Radiation
  - Meteoroid Impacts
- Extreme temperatures (-171 to 111 °C)
- Synodic period of 656 hours
- Moonquakes

Supporting reasons for the creation of a geopolymer lunar concrete.

- The goal is to utilize as much in-situ lunar resources as possible
- Regolith in the "as is" condition makes up most of the mass
- The calcium content of the lunar regolith is minimal in terms of creating an OPC.
- The solution for mixing can be extracted for regolith (with added sodium)

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Lunar regolith simulants are the only way to progress geopolymer lunar concrete.

JSC-1A – Mare EAC-1A – Mare OPRH2N – Highlands

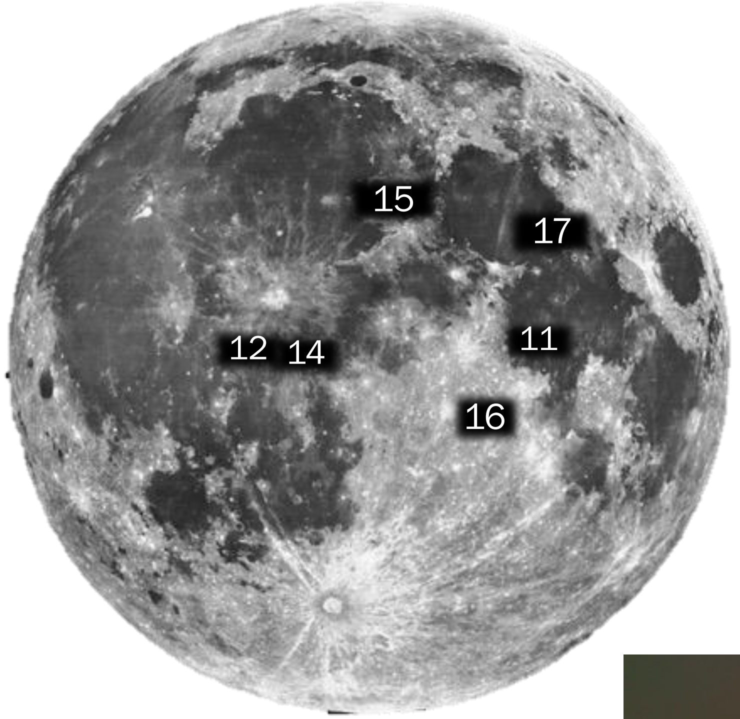
JSC-2A – Mare OPRL2N – Mare

All the lunar regolith simulants underwent characterization and analysis in terms of geopolymer lunar concrete.

Characterization Techniques

- X-ray diffraction
- X-ray fluorescence
- Helium pycnometry
- Laser particle size distribution
- Reactivity testing

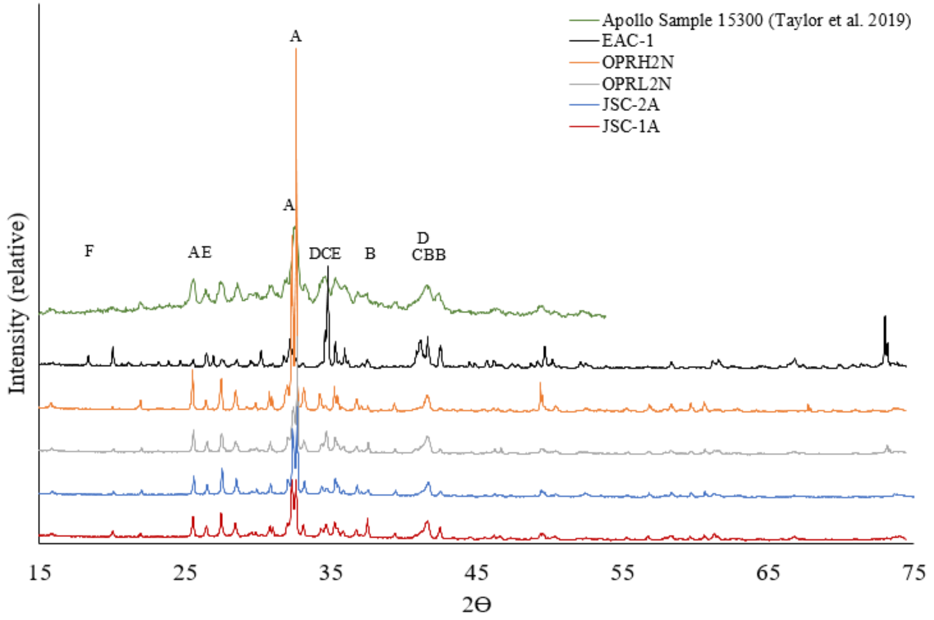
Comparison to Apollo sample data



Mare – Dark regions

Highlands – Light regions

The amorphous content for the mare simulants is higher than most Apollo samples.

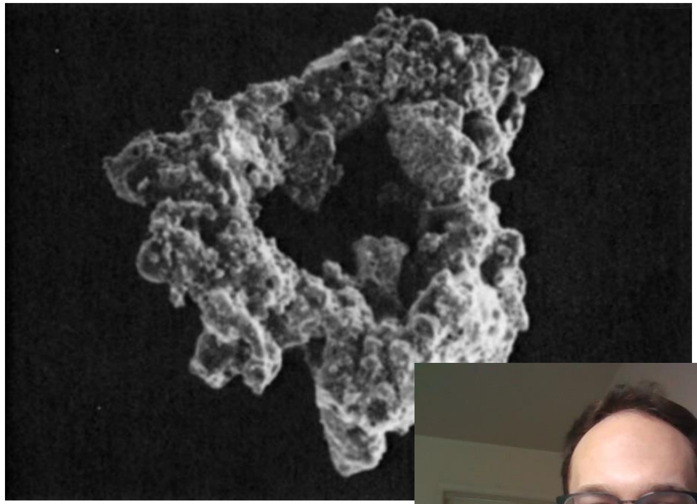


	Amorphous	Plagioclase (A)	Forsterite (B)	Diopside (C)	Augite (D)	Nepheline (E)	Analcime (F)	Chi-square
Powder Diffraction File	-	01-073-6461	04-011-6594	01-083-3676	01-073-8553	01-083-4902	01-073-6448	-
JSC-1A	49.9%	35.3%	6.8%	-	8.0%	-	-	2.62
JSC-2A	51.0%	37.6%	4.0%	-	7.5%	-	-	2.06
OPRL2N	45.4%	36.4%	6.0%	-	12.3%	-	-	2.67
OPRH2N	26.5%	70.4%	-	-	3.1%	-	-	3.71
EAC-1A	26.2%	11.6%	8.1%	25.1%	19.2%	8.3%	1.6%	2.79

Apollo Amorphous Content Data

Mission	Average (%)	Standard Deviation (%)	Minimum Value (%)	Maximum Value (%)
Apollo 11	35.9 (only 1 sample)			
Apollo 12	28.6	5.3	16.8	34.2
Apollo 14	37.2	5.7	26.1	43.5
Apollo 15	38.6	6.3	24.2	54.5
Apollo 16	27.8	8.8	4.6	38.6
Apollo 17	31.1	6.7	13.8	41.7

Apollo Data – Compiled from Taylor et al. 2019



Agglutinate Image from the Lunar S

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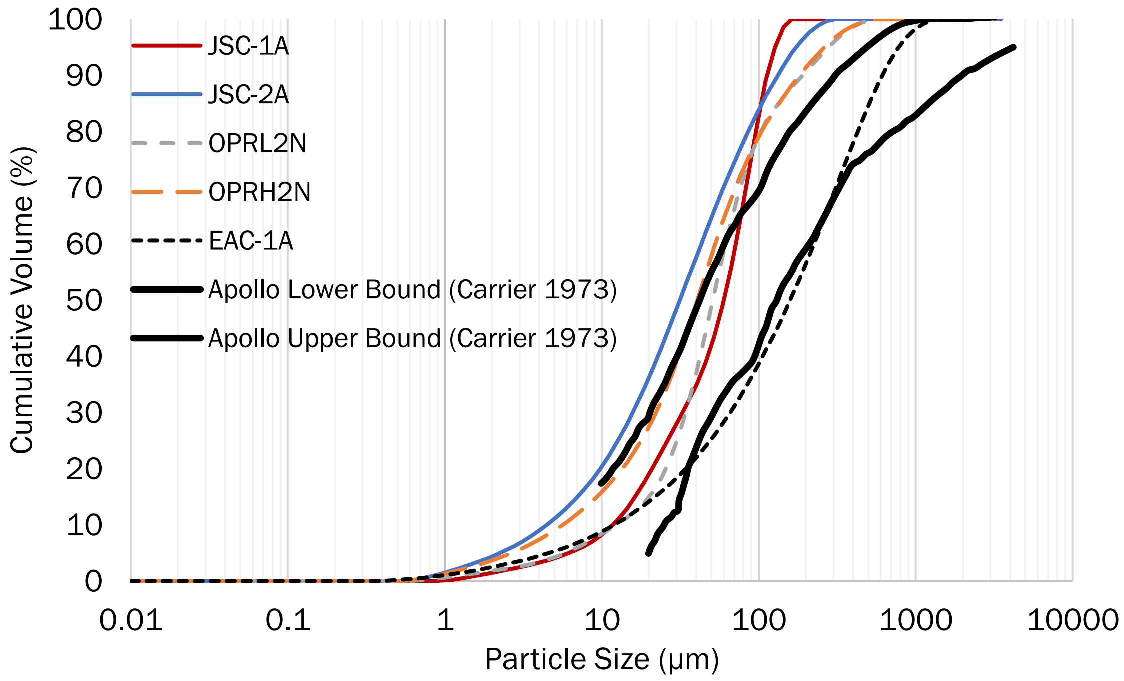
The silicon to aluminum ratio for the lunar regolith simulants is on par with the Apollo samples and all the simulants fall outside the particle size bounds of the Apollo samples at some point.

	SiO_2	Al_2O_3	Si/Al
JSC-1A	44.6	15.14	**2.50**
JSC-2A	45	15	**2.55**
OPRL2N	46	16	**2.44**
OPRH2N	48	25	**1.63**
EAC-1A	42	10	**3.57**
Apollo 11	42.04	13.92	**2.57**
Apollo 12	46.4	13.5	**2.92**
Apollo 14	47.93	17.6	**2.31**
Apollo 15	46.66	16.99	**2.33**
Apollo 16	45.11	26.82	**1.43**
Apollo 17	45.08	20.6	**1.86**

Apollo Data – Rose Jr. et al. 1975



	D_{50} (µm)
JSC-1A	68.2
JSC-2A	35.3
OPRL2N	58.0
OPRH2N	46.2
EAC-1A	181.0

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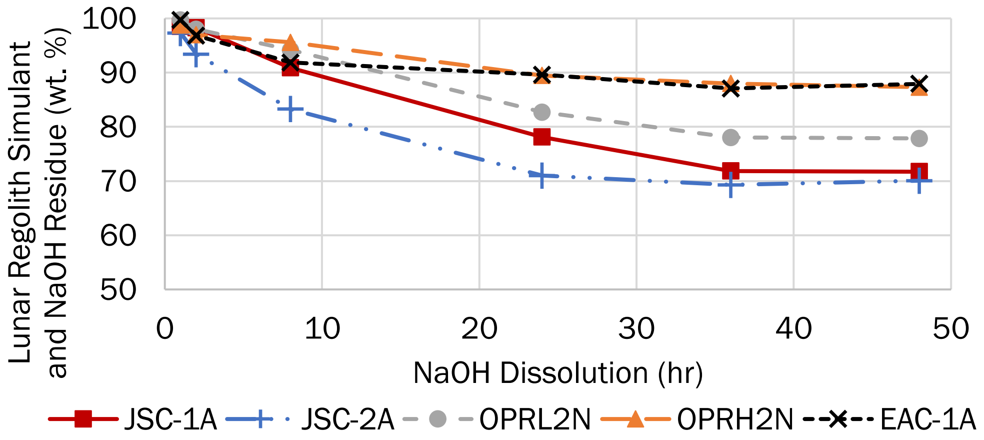
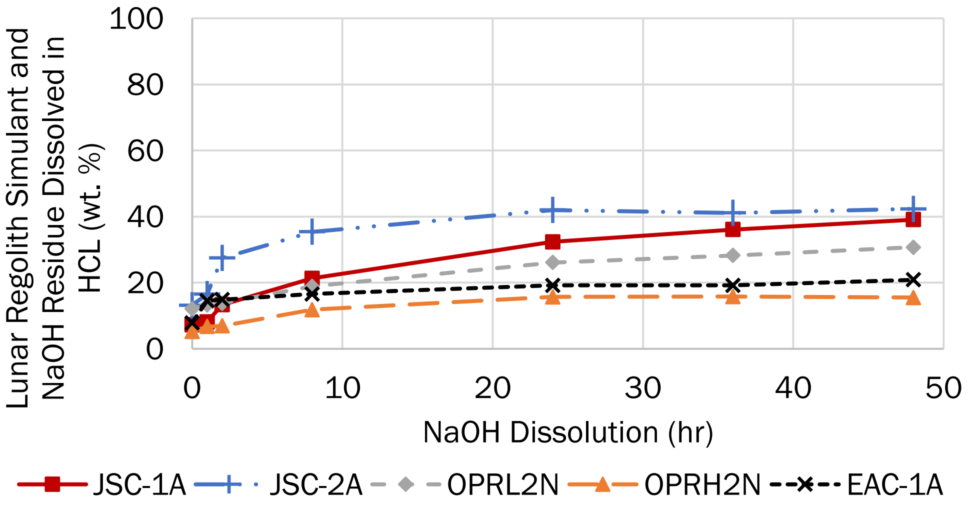
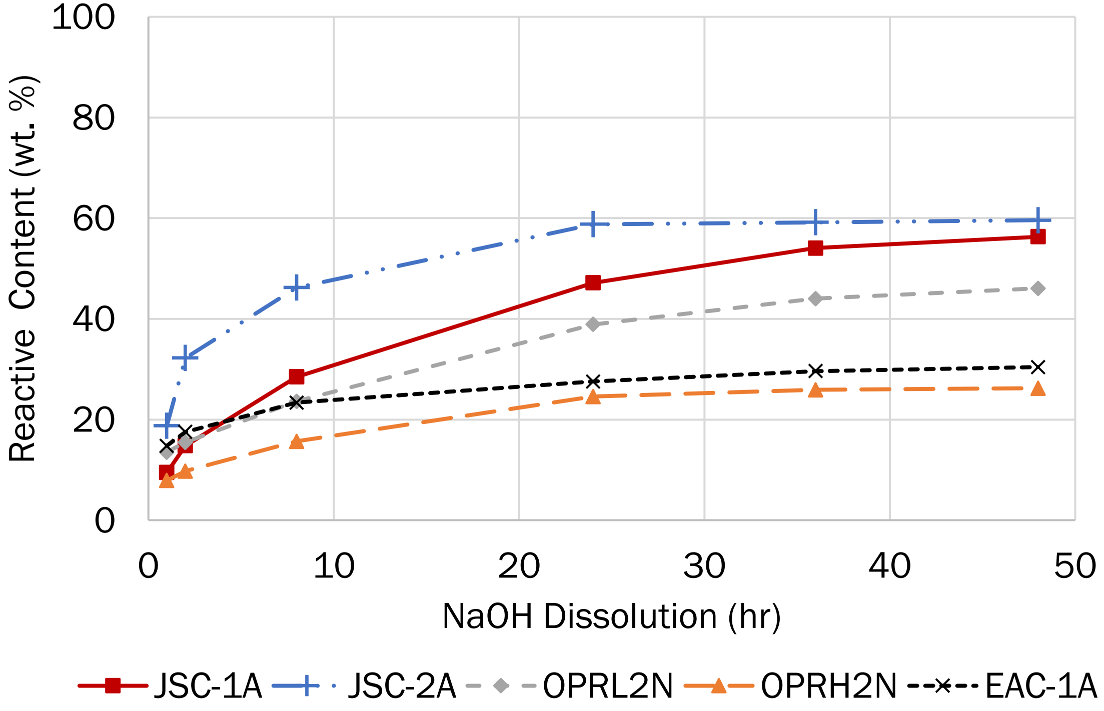
The amorphous content is in good agreement with the reactivity at 48 hours.







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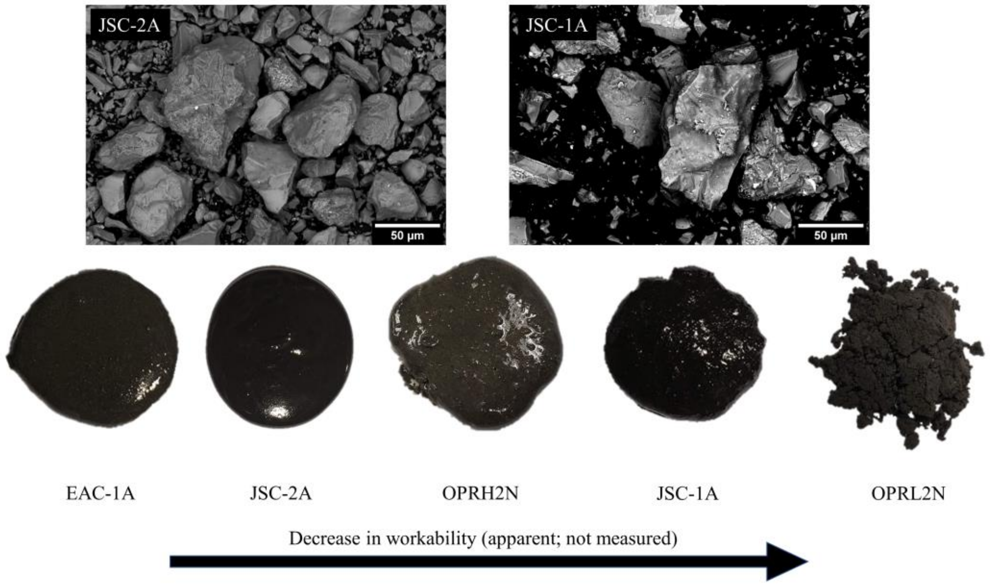
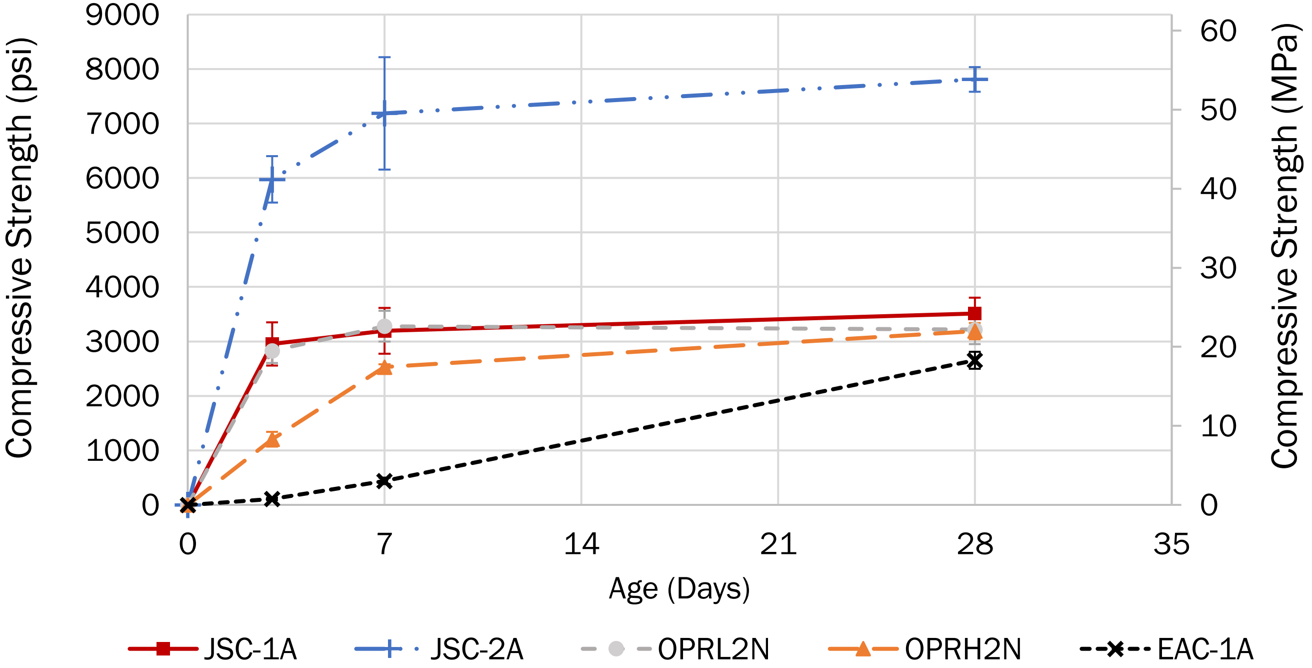
Notable differences in the compressive strength and workability of the mixtures.





- Sodium silicate and 10 M sodium hydroxide mixture (SiO_2/Na_2O = 2.0, pH = 14.31)
  - Solution to simulant = 0.35
  - Cured at 80 °C for three days

Conclusions

- Concrete cannot be replaced as it is the most widely used human made material on Earth
- Geopolymer concrete can help reduce the CO_2 emissions of the concrete industry and has specific uses that are advantageous
- Geopolymer concrete is a feasible material for constructing infrastructure on the lunar surface
- It is important to keep in mind that no lunar regolith simulant is a perfect match to the actual lunar regolith

Acknowledgements

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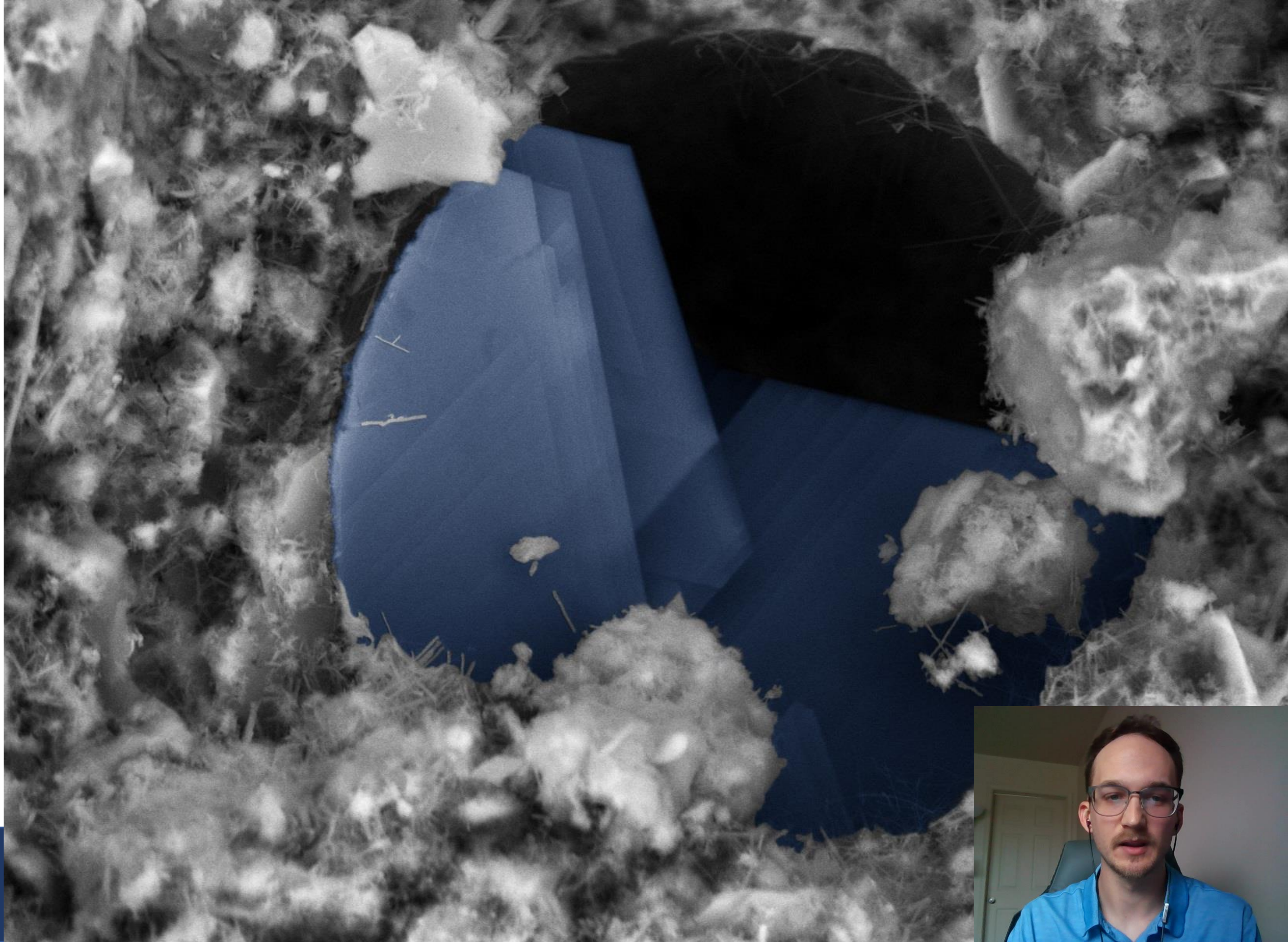
- PQ Corporation for providing the sodium silicate
- Professor Matthias Sperl and Dr. Karsten Tell for providing JSC-2A and EAC-1A

Thank you!



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