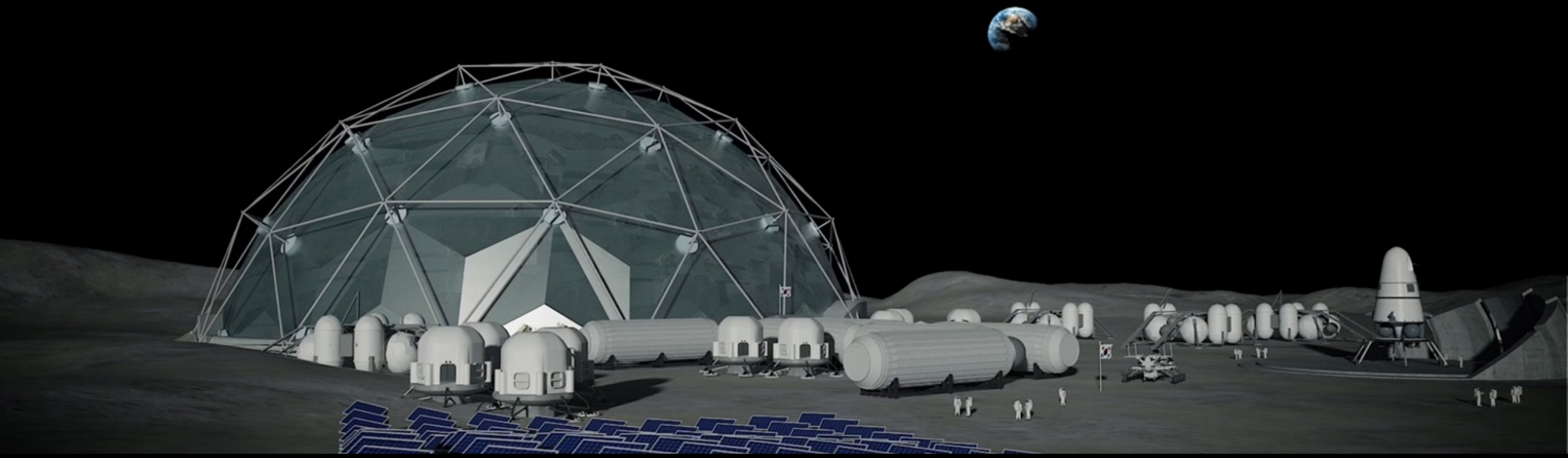
XXIII SPACE RESOURCES ROUNDTABLE
June 6-9, 2023



Microwave sintering of lunar regolith simulant in vacuum for ISRU construction

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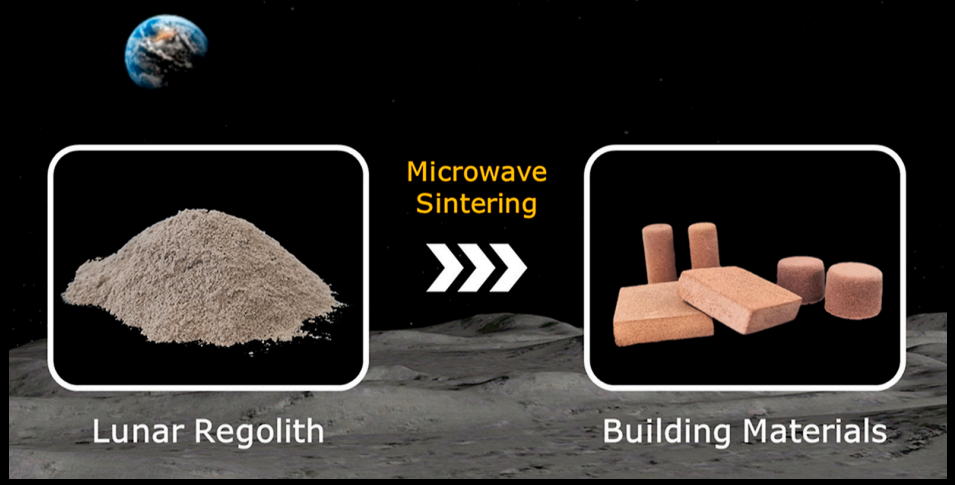
Geotechnical Information Technology

Drilling equipment & Geotechnical Information Tech.

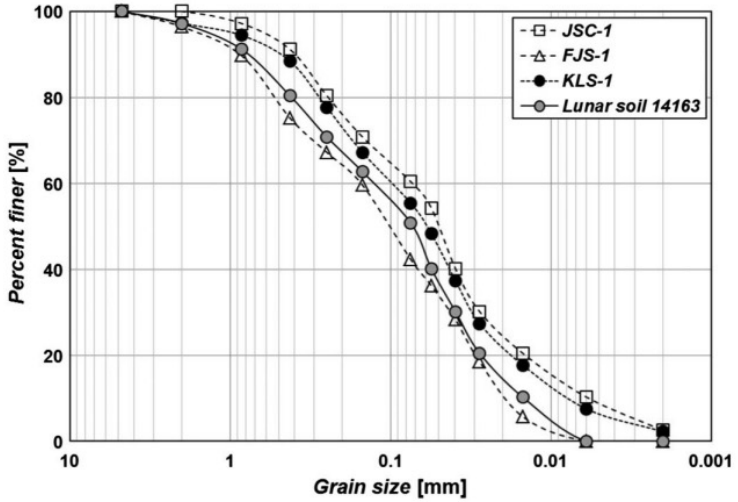
In-Situ Material Solidification Technology



Planetary Surface Environment Simulation

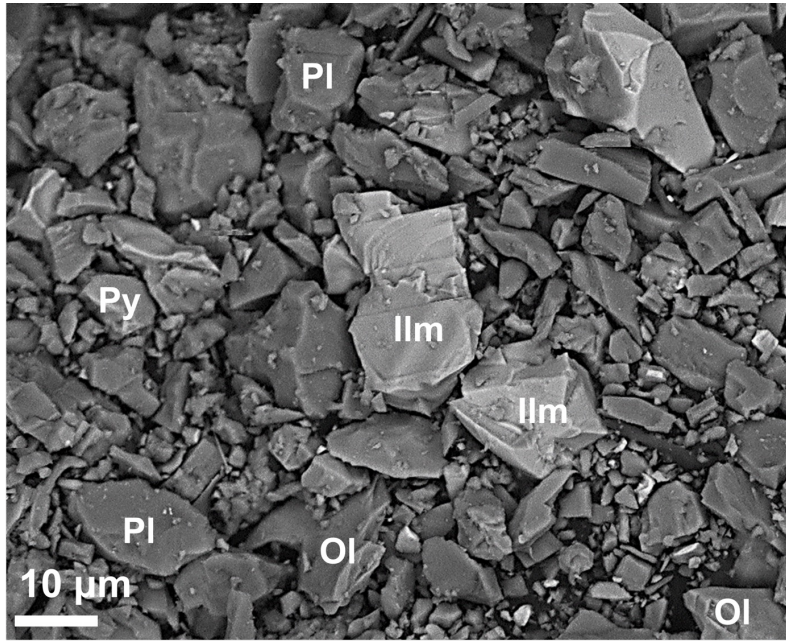
Lunar regolith simulant, KLS-1 (Korean Lunar Simulant Type-1)

Lunar regolith simulant



	Apollo 14 lunar soil 14163	KLS-1
SiO_2	47.3	48.00
TiO_2	1.6	1.67
Al_2O_3	17.8	15.30
Cr_2O_3	0.2	-
FeO	10.5	6.64
Fe_2O_3	0.0	4.75
MnO	0.1	0.17
MgO	9.6	9.64
CaO	11.4	8.38
Na_2O	0.7	3.42
K_2O	0.6	1.52
P_2O_5	-	0.33
S	-	0.01
Total	99.8	99.83

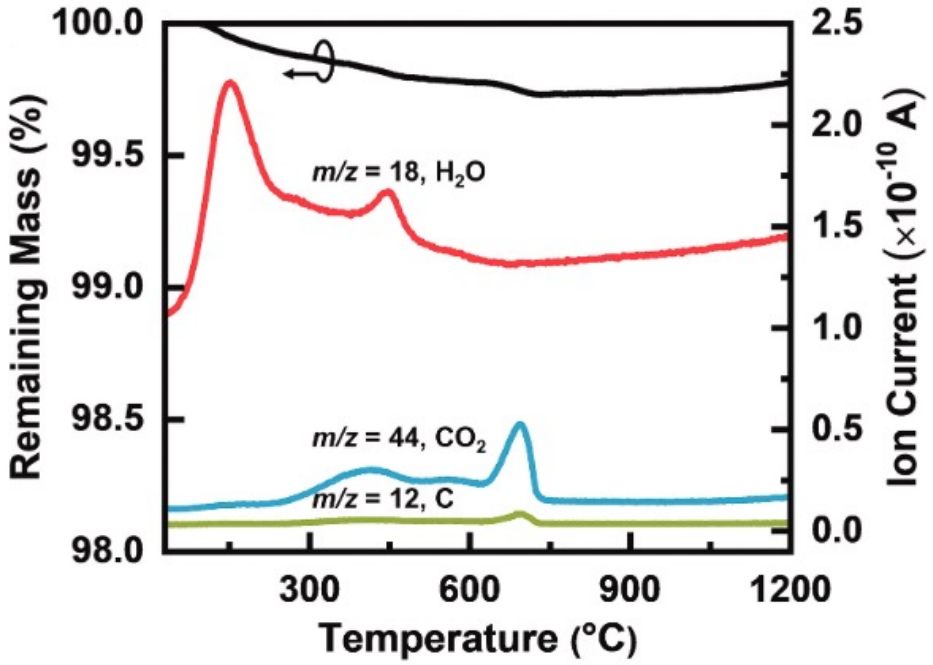
56.9 wt.% Plagioclase (Pl)
21.7wt.% Olivine (Ol)
19.0 wt.% Pyroxene (Py)
2.4 wt.% Ilmenite (Ilm)



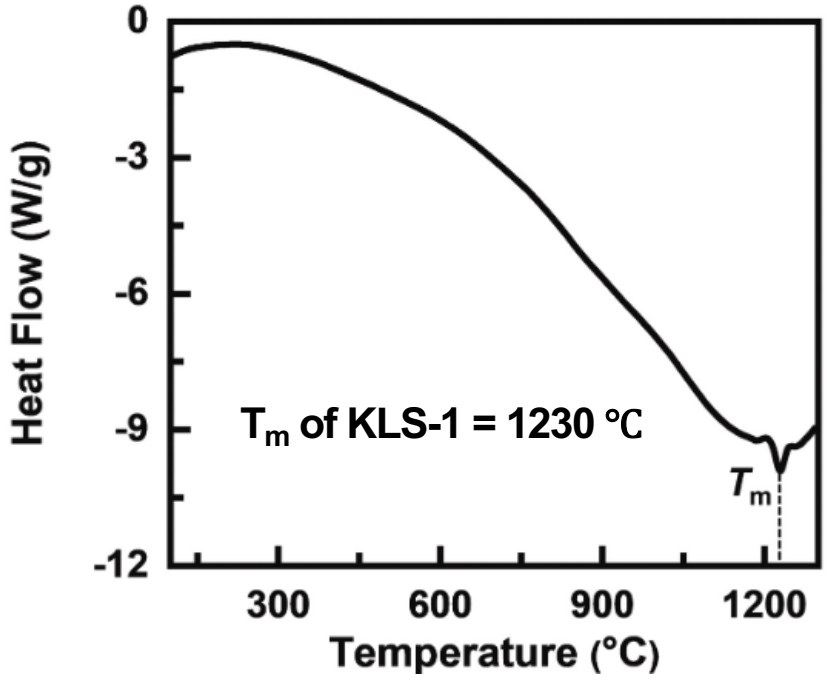
Ryu et. al. (2018). Development and geotechnical engineering properties of KLS-1 lunar simulant. *Journal of Aerospace Engineering*, *31*(1), 04017083.

Thermal properties of KLS-1

- **Simultaneous thermal analysis – mass spectrometry (STA-MS) data of KLS-1**
  - Total of 0.2 % of weight loss occurred in the temperature range of 30 to 1200 °C.
  - The gases emitted from the KLS-1 are mainly H_2O and CO_2.
  - Water is emitted at temperatures below 600 °C.



- **Differential scanning calorimetry data of KLS-1**
  - Endothermic peak at 1230 °C is attributed to the KLS-1 melting.
  - Sintering was tested below the melting point (T_m).



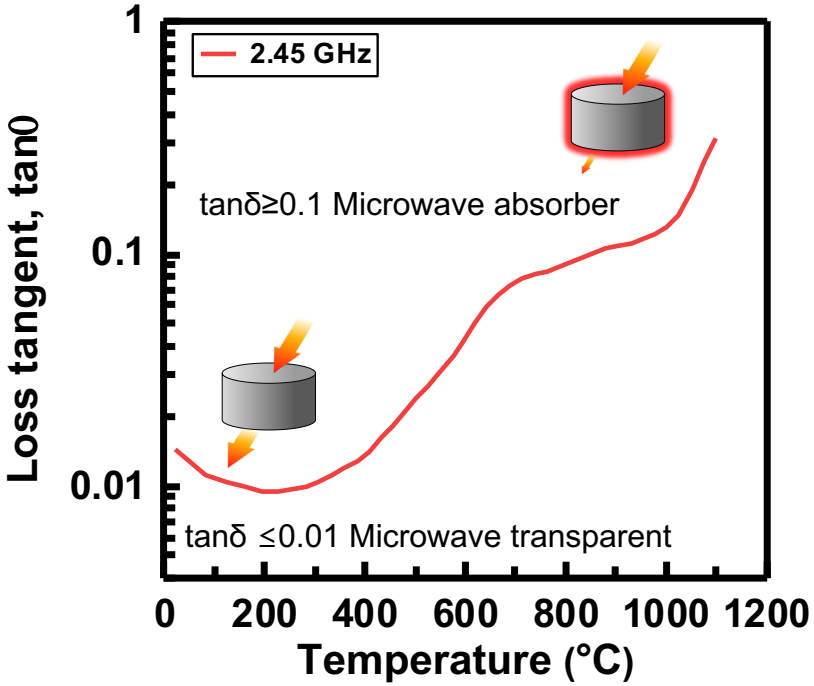
Kim et al. "Microstructural, mechanical, and thermal properties of microwave-sintered KLS-1 lunar regolith simulant." *Ceramics International* 47.19 (2021): 26891-26897.

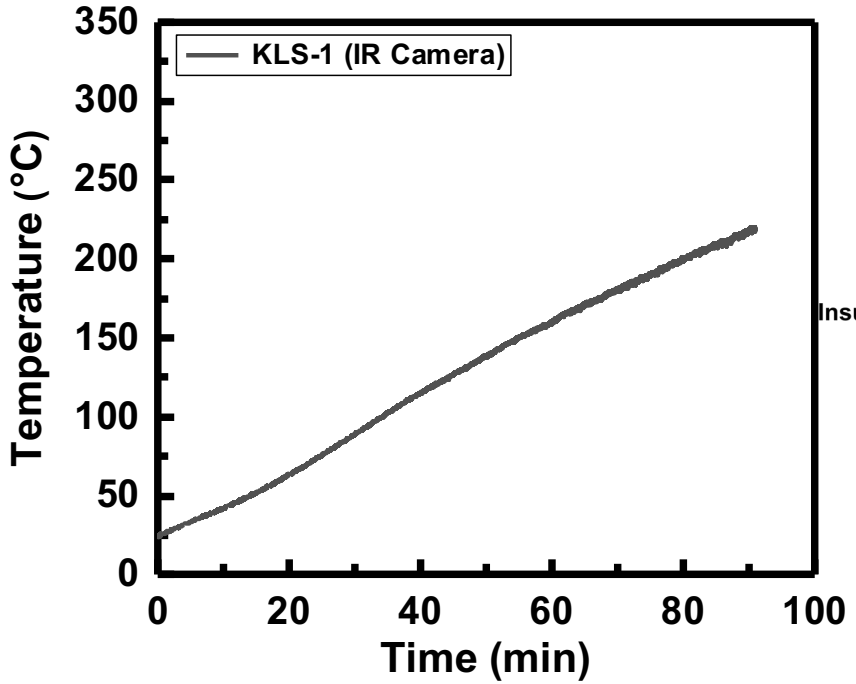
Poor microwave-absorbing property of KLS-1

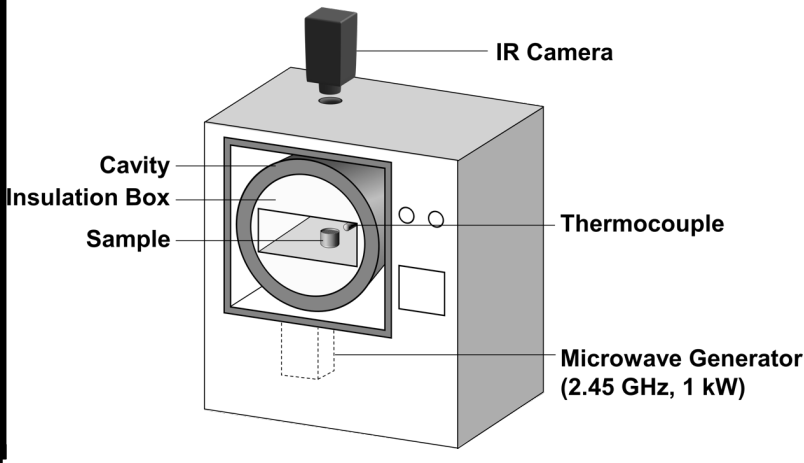
$$P = 2\pi f \varepsilon_0 \varepsilon_r' tan\delta |E|^2$$

$$\frac{\Delta T}{\Delta t} = \frac{P}{\rho C_P}$$

- KLS-1 has a low loss tangent value of about 0.01 at room temperature, indicating that it has a poor microwave absorption property.
- The loss tangent increases with increasing temperature, allowing it to absorb microwaves more efficiently at higher temperatures.
- Poor microwave absorption at relatively low temperatures indicates difficulty in initiating direct microwave heating.





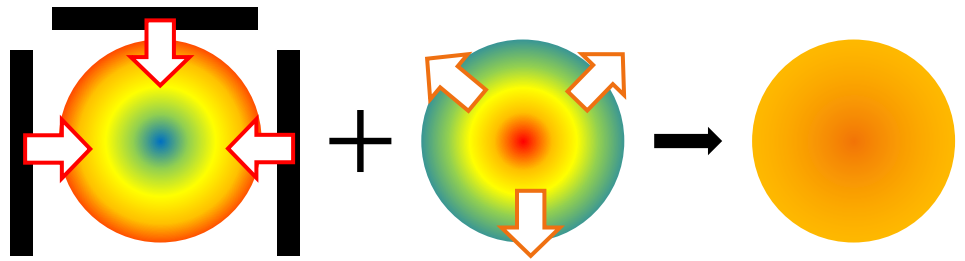


Susceptor assisted hybrid microwave sintering

- The SiC susceptor not only provided pre-heating of a material with poor microwave-absorbing properties (KLS-1), but also maintained heat distribution within the sample during sintering

(2.45 GHz)

Sample	Temp. (℃)	tanδ	Property
KLS-1	24	0.014	Microwave transparent
	500	0.024	
	1000	0.130	
SiC[1]	25	0.388	Microwave absorber
	800	0.404	
	1350	0.789	



Conventional heat transfer from susceptor to sample

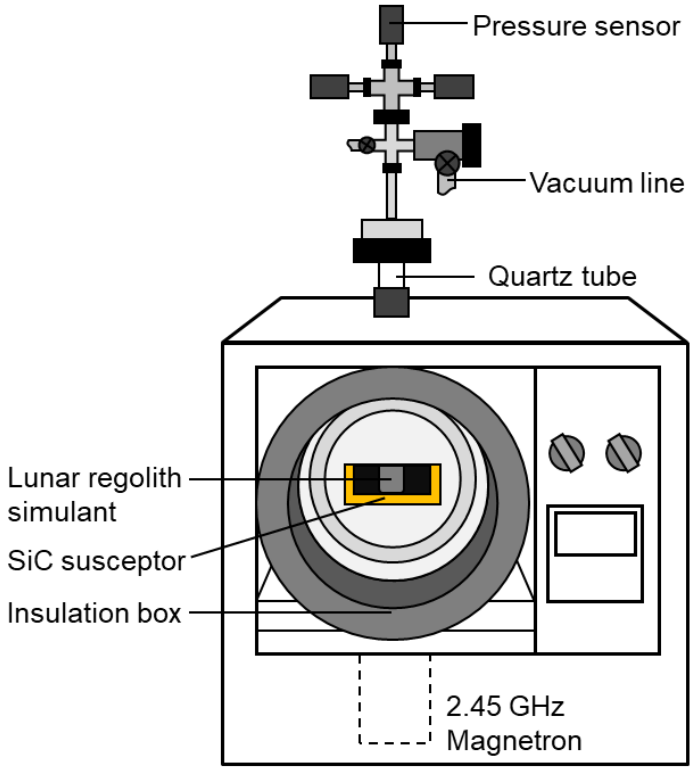
Heat generation inside the material due to interaction with microwaves

Final product

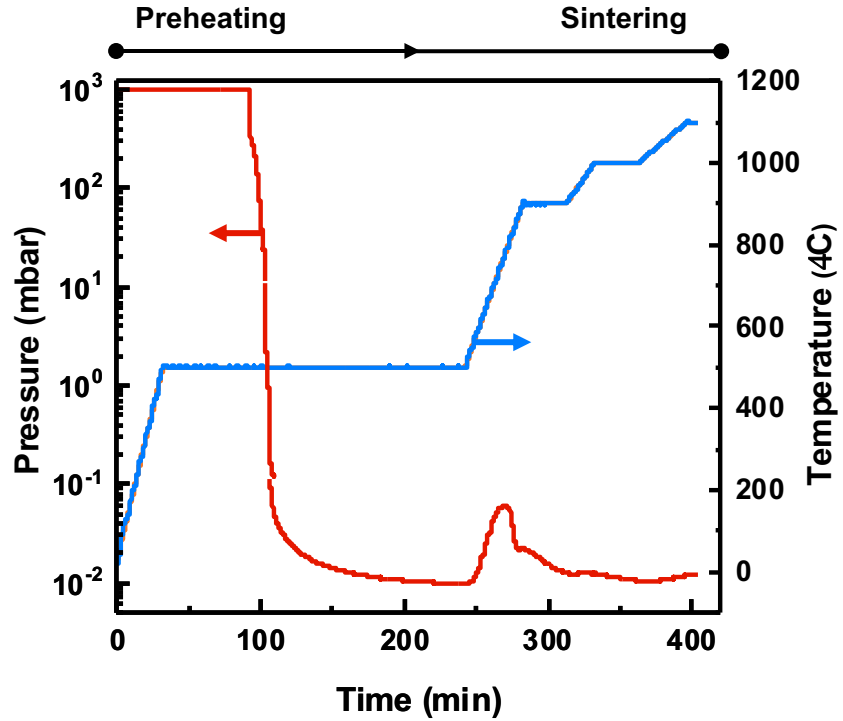
[1]Greenacre "Measurement of the high-temperature dielectric properties of ceramics at microwave frequencies." (1998): 1346-1346.

Vacuum Microwave Sintering Experiments

- **Vacuum-microwave sintering equipment**



Microwave: 2.45 GHz, max. 1 kW
Material: 35 g of KLS-1
Susceptor: SiC
Preheating: 500 ℃, 1hr
Sintering temperature: 1060, 1080, 1100, and 1120 °C
Vacuum degree: ~10^{-2} mbar
Heating rate: <5 ℃/min



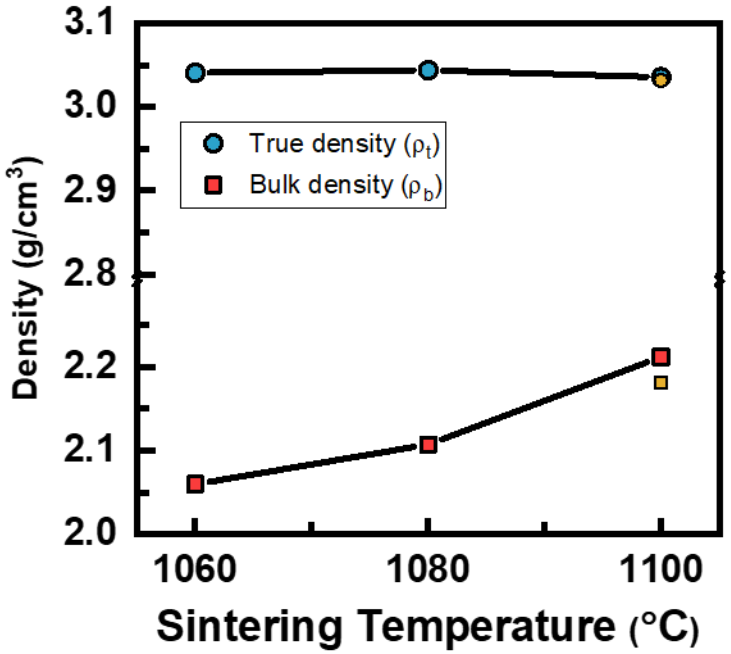
The effect of sintering temperature on the structure

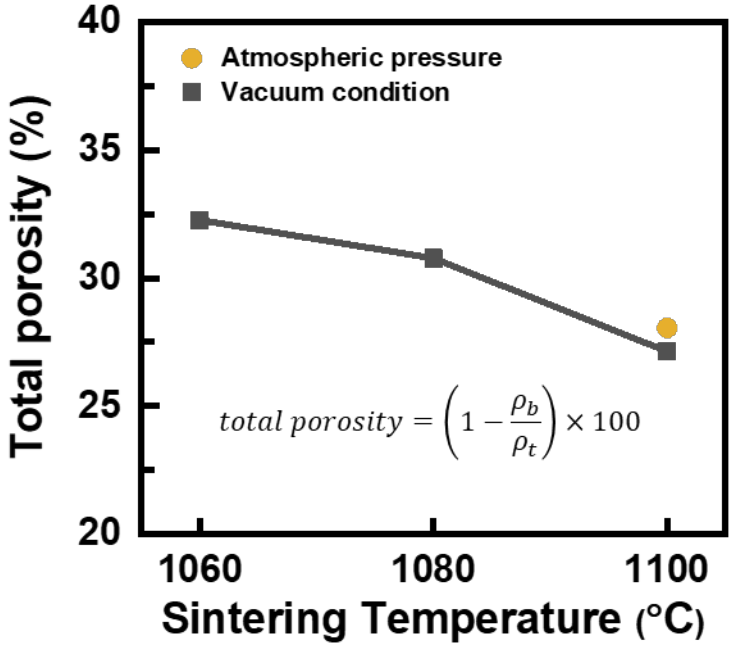
- Vacuum microwave sintered KLS-1 with a diameter of 24 mm and a height of 33 mm were produced.
- Homogeneous sintered bodies were produced at a temperature of 1060 °C to 1100 °C under vacuum conditions.
- Sample sintered at 1120 °C under vacuum conditions has a large number of pores inside.

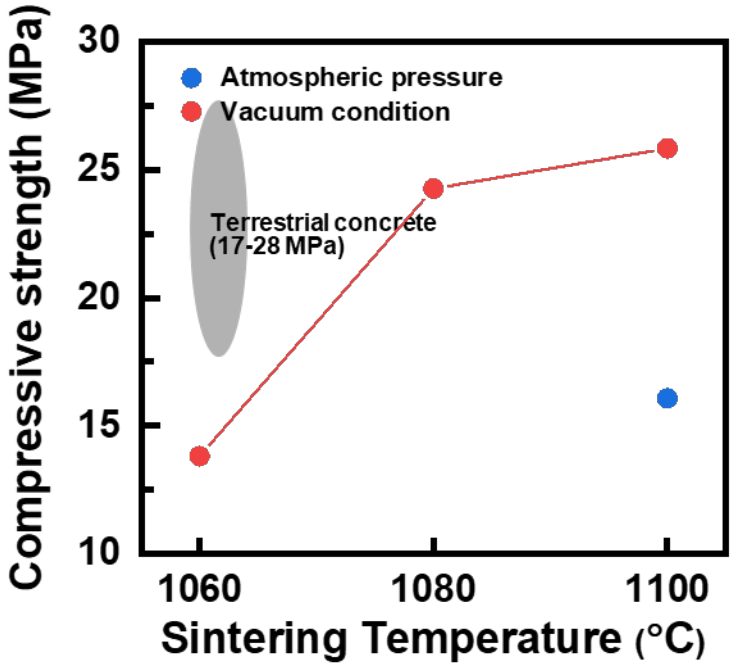
Pressure	Atmospheric pressure	Vacuum condition			
Sintering temperature	1100 ℃	1060 ℃	1080 ℃	1100 ℃	1120 ℃
Color	Brown	Gray			
Sintered KLS-1					
X-Ray transmission image					

Density and mechanical property of the vacuum microwave sintered KLS-1

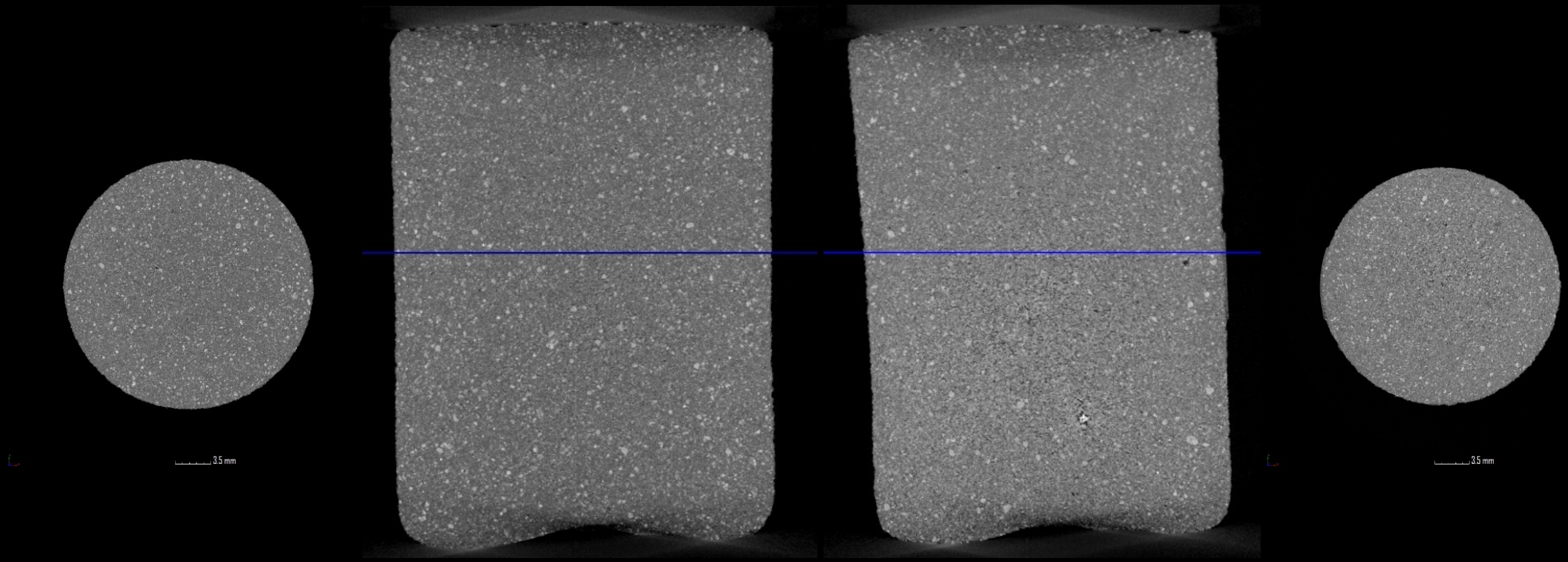
- As the sintering temperature increased, bulk density increased and porosity decreased.
- Samples sintered at 1080°C and 1100°C under vacuum have a mechanical strength similar to that of terrestrial concrete (17–28 MPa).
- At the same temperature, a sample sintered in a vacuum has a higher density and strength than a sample sintered at atmospheric pressure because pores can shrink under vacuum condition.







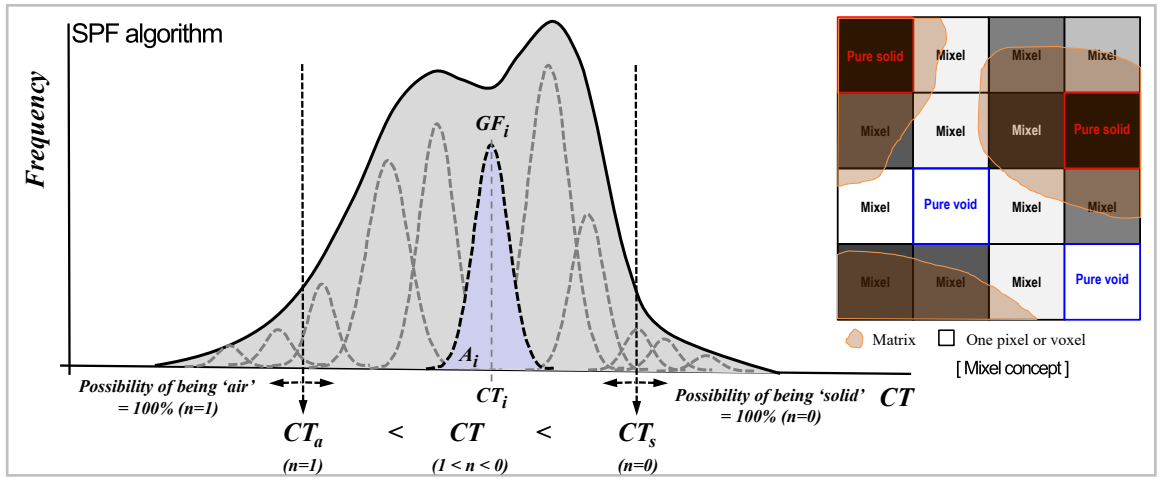
X-ray CT analysis



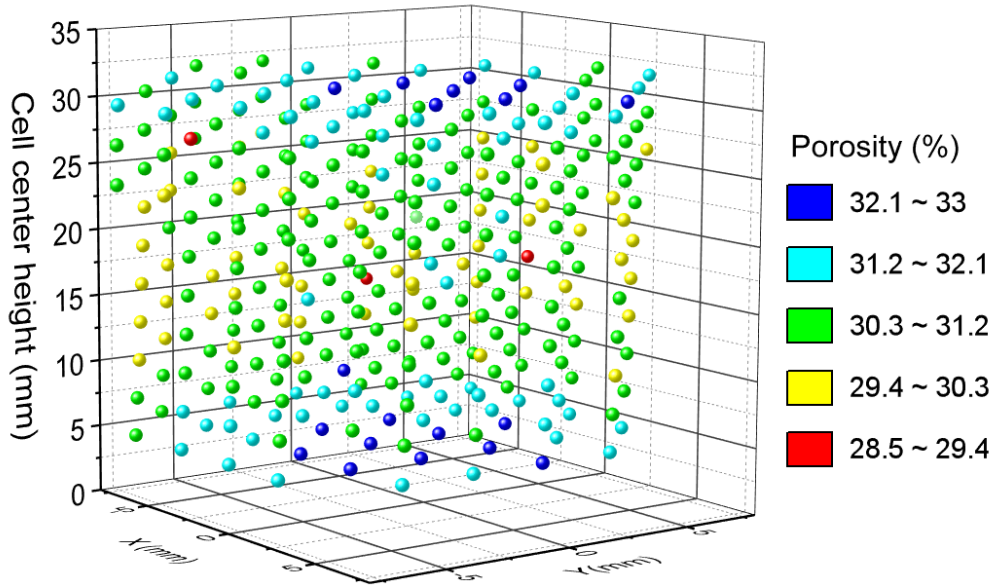
[X-ray CT images of lunar regolith simulant vacuum microwave-sintered at 1080 °C and 1100 °C]

Homogeneity evaluation by X-ray CT analysis

- Statistical phase fraction (SPF) method was developed to estimate the total and local porosity of porous samples
- Based on X-ray CT images, the spatial distribution of local porosities was investigated for homogeneity evaluation.
- For the sintered sample at 1080 °C, the minimum and maximum local porosities are 28.5% and 33 %, respectively. The average porosity is 30.87%.
- Highly uniform sintered samples were produced by vacuum microwave sintering.



Zhuang et al. "A novel method for estimating subresolution porosity from CT images and its application to homogeneity evaluation of porous media." *Scientific Reports* 12.1 (2022): 16229.



[Local porosity of vacuum microwave sintered KLS-1 at 1080 ℃]

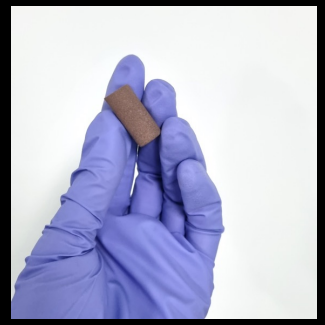
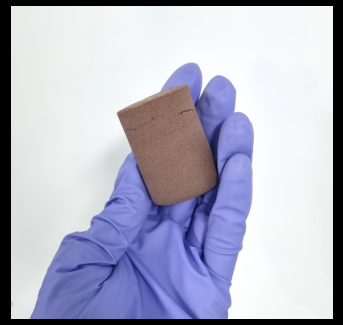
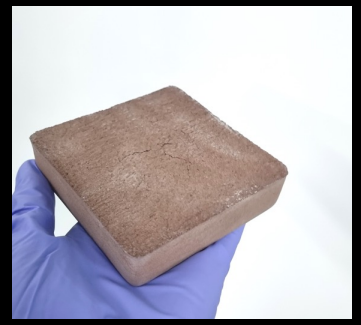
Summary

- A lunar regolith simulant (KLS-1) underwent SiC susceptor-assisted microwave sintering at different temperatures under vacuum.
- As the sintering temperature increased from 1060°C to 1100°C, the density and mechanical strength increased.
- At 1120°C, pores formed inside the sintered body due to evaporation of some molten parts.
- We expect vacuum microwave-sintered lunar regolith to be a promising building material for future infrastructure on the Moon.

Sintering test of lunar regolith simulant

2018 | 2019 | 2020 | 2021 | 2022 | 2023 ~

Scale up


- Development of microwave sintering equipment for operation in vacuum chamber
- Development of additive construction technology based on microwave sintering

Vacuum microwave sintered blocks

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Thank you