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Geopolymer composites and 3D printing technology to create modern solutions for Lunar and Martian habitats

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GEOPOLYMER CAMP

Purpose of the presentation

The main aim of this presentation is to show the possibilities of production and innovative solutions for manufacturing lunar and Martian shelters based on geopolymer composites.

We will discuss possible materials for in-space applications with particular attention to the geopolymers materials.

The last part of the presentation will show the results of the attempt to make a lunar regolith simulant at the Cracow University of Technology

Lunar and Martian regolith

- **Lunar and Martian regoliths** are layers of fine-grained material covering the lunar/Martian surface.
- **Physical properties of Lunar regoliths** are mainly a result of the mechanical disintegration of basaltic and anorthositic rocks that occurred as a result of constant meteorite impacts and bombardment by charged solar and interstellar atomic particles on the surface of the Moon over billions of years.
- Due to the presence of perchlorates, **properties of Martian regolith** can vary considerably from those of terrestrial soil, including its toxicity.
- Moreover, **a Mars sample-return mission's objective has not yet been achieved**, however, Mars rovers and Mars orbiters have been used to study the soil remotely.

Footprint in lunar soil. Few rocks are sitting out on top of mature regolith. NASA photo AS11-40-5877

Human in-space missions

- National Aeronautics and Space Administration (**NASA**) and the European Space Agency (**ESA**) announced that they wanted to ensure the possibility of permanent human residence in the so-called habitats on the Moon or Mars before 2040.
- The first manned mission after Apollo 17, **Artemis III**, is scheduled to take place by 2024 to help implement sustainable lunar exploration.

- **Human in-space missions** (the Moon, Mars, etc.) will require the capability to build structures on site using the local resources as a potentially more energy-efficient and economically viable alternative to transporting all materials needed for the construction of an outpost from Earth
- Nowadays, **one of the most promising materials** for that purpose are **geopolymer composites.**

https://lifestyle.livemint.com/smart-living/innovation/future-of-lunar-habitats-designing-for-life-on-the-moon-111634486770359.html

Why geopolymers composites?

- The geopolymer cement/geopolymer concrete seems to be a reasonable solution for in-space constructions, especially lunar and Martian habitats, because of its advantages, such as:
  - attractive mechanical properties:

  compressive strength: up to 90 MPa, flexural strength: 10–15 MPa at 28 days;
  - high early strength formulation:

  compressive strength: 20 MPa, flexural strength: 10 MPa after 24 h;
  - fire- and heat-resistant;
  - possibilities for applications in different conditions because of their chemical resistance to atmospheric conditions and a variety of acids and salts;
  - simplicity of the application;
  - low shrinkage (<0.05%);
  - good adherence to such materials as concrete, steel, glass, and ceramics,
  - the effectiveness of the manufacturing process and environmental benefits (low CO_2 emission and energy efficiency during the production process).

Why geopolymers composites?

- Additionally, the advantage is the possibility of using local materials instead of transportation, exemplary **lunar regolith is made up of large parts of silicon and aluminum oxides** as shown in Table (geopolymer cement consisting of up to 98% by weight of in-situ regolith could be produced on the lunar surface [Mills et al. 2022]).

Chemical compositions of lunar soils (weight %)	Apollo 11	Apollo 12	Apollo 14	Apollo 15	Apollo 16	Apollo 17
	Landing area: mare	Landing area: mare area	Landing area: highland	Landing area: highland	Landing area: highland – mare contact area	Landing area: highland – mare contact area
SiO_2	42.15	46.30	48.10	46.95	45.26	40.95
TiO_2	7.80	3.20	1.70	1.60	0.66	7.61
Al_2O_3	13.65	13.35	17.40	12.70	25.48	12.78
Cr_2O_3	0.30	0.38	—	0.47	0.25	0.46
Fe_2O_3	—	—	—	—	—	—
FeO	15.55	16.30	10.40	16.29	6.58	15.76
MnO	0.20	0.22	0.14	0.22	0.34	0.21
MgO	7.85	9.70	9.40	10.75	6.19	9.99
CaO	11.95	10.65	10.70	10.49	15.17	11.03
Na_2O	0.49	0.46	0.70	0.33	0.45	0.32
K_2O	0.13	0.24	0.55	0.09	0.13	0.08
P_2O_5	0.08	—	0.51	0.16	0.11	0.06
S	—	—	—	0.07	0.07	0.12
LOI	0.12	—	—	—	0.07	—

Why geopolymers composites?

- A similar situation is in the case of Martial regolith (Table below), however, the number of data in this case, is significantly lower [Zhou et. al. 2021a; Just et al. 2020].

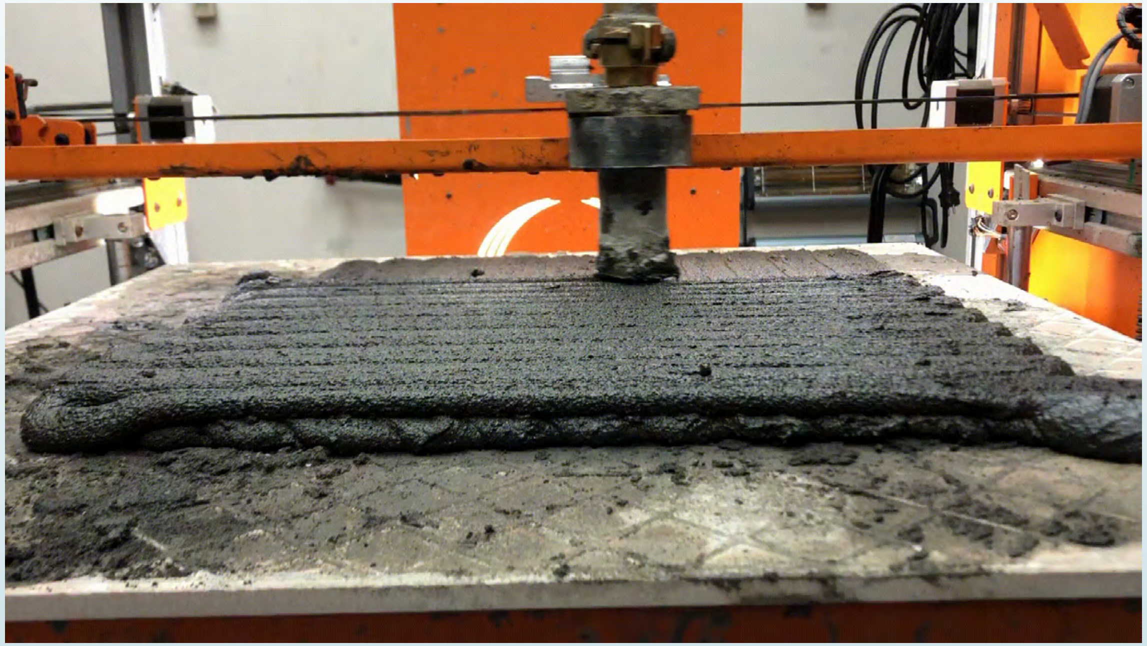
Chemical compositions of martial soils (weight %)	A-2	A-4	A-5	A-8	A-10	A-15
	Target site: After deploy	Target site: Next to Yogi	Target site: Dark next to Yogi	Target site: Scooby Doo	Target site: Next to Lamb	Target site: Mermaid Dune
Na_2O	2.3 ± 0.9	3. 8 ± 1.5	2.8 ± 1.1	2.0 ± 0.8	1.5 ± 0.6	1.3 ± 0.7
MgO	7.9 ± 1..2	8.3 ± 1.2	7.5 ± 1.1	7.1 ± 1.1	7.96 ± 1.2	7.3 ± 1.1
Al_2O_3	7.4 ± 0.7	9.1 ± 0.9	8.7 ± 0.9	9.1 ± 0.9	8.3 ± 0.8	8.4 ± 08
SiO_2	51.0 ± 2.5	48.0 ± 2.4	47.9 ± 2.4	51.6 ± 2.6	48.2 ± 2.4	50.2 ± 2.5
SO_3	4.0 ± 0.8	6.5 ± 1.3	5.6 ± 1.1	5.3 ± 1.1	6.2 ± 1.2	5.2 ± 1.0
Cl	0.5 ± 0.1	0.6 ± 0.2	0.6 ± 0.2	0.7 ± 0.2	0.7 ± 0.2	0.6 ± 0.2
K_2O	0.2 ± 0.1	0.2 ± 0.1	0.3 ± 0.1	0.5 ± 0.1	0.2 ± 0.1	0.5 ± 0.1
CaO	6.9 ± 1.0	5.6 ± 0.8	6.5 ± 1.0	7.3 ± 1.1	6.4 ± 1.0	6.0 ± 0.9
TiO_2	1.2 ± 0.2	1.4 ± 0.2	0.9 ± 0.1	1.1 ± 0.2	1.1 ± 0.2	1.3 ± 0.2
FeO	16.6 ± 1.7	14.4 ± 1.4	17.3 ± 1.7	13.4 ± 1.3	17.4 ± 1.7	17.1 ± 1.7
Org. Sum	68.6	78.2	89.1	99.2	92.9	98.9

Technology

- The other critical point for in-space application is proper technology. In this case, the most promising solutions seem to be 3D printing technologies.

This kind of technology has a lot of advantages, such as:

- energy efficiency,
- the possibility of automation,
- design freedom,
- and reduced manufacturing time.



It seems to be the best option for lunar and Martian habitats production.

Materials possible to use for lunar and Martian shelters

- Building infrastructure on the Moon or Mars is an engineering challenge, but it is a necessary step to develop further space projects.

- The main challenge in building on the Moon or Mars is the different conditions than in the case of Earth:

  - the lack of atmosphere that results in pressures near vacuum,
  - low gravity (the Moon at about 1.6 m/s^2 and Mars at 3.721 m/s^2, respectively),
  - high level of galactic cosmic radiation (GCR) and infrequent but very intense solar particle events (SPEs),
  - limitation to access to liquid water,
  - extreme thermal cycle (the Moon from -173 °C to +117 °C and Mars from -140 °C to +21 °C),
  - higher seismic activity than for Earth,
  - and micrometeoroids.

Materials possible to use for lunar and Martian shelters

Currently, several attempts have been made to construct a technical infrastructure for this kind of facility, especially in the context of lunar shelters, include:

- traditional ordinary Portland cement (OPC)-based concrete with lunar regolith as aggregate,
- sulfur cement,
- solar-sintered regolith (basalt),
- Sorel cement (magnesium chloride-based binder),
- phosphoric acid binder types of cement,
- epoxy/polymer-based cement
- geopolymer type binders.

Materials possible to use for lunar and Martian shelters

- Geopolymer type binders.
  - Geopolymer cement should provide **better radiation protection levels** and **stability** and **require significantly less resources in the production process** than traditional concrete and other presented materials.
  - Moreover, previous works showed that a **shielding thickness of 50 cm** (99 g/cm^2) **with geopolymer cement** should be **sufficient for a prolonged crewed lunar mission**, with the absorbed dose for a 12-month stay being similar to the annual whole-body radiation worker limit
  - **The same amount of material is sufficient according to the strength and durability requirements** for the shielding properties of the geopolymer cement. In general, the geopolymer binder has the following advantages over other concreate-like materials:

Materials possible to use for lunar and Martian shelters

In general, **the geopolymer binder has the following advantages** over other concreate-like materials:

- **Availability of proper raw material:** The regolith is rich in aluminosilicate minerals but poor in calcium; its chemical and mineral characteristics match better with geopolymerization technology than traditional OPC-based concrete. Additionally, while geopolymers may require some solution to dissolve and activate the regolith, the water demand is much lower compared to OPC, and water must be harvested from the polar ice caps for other human sustainability purposes.

- **Geopolymers can be prepared under ambient conditions**, which reduces energy consumption during the construction process. Curing at elevated temperatures is relevant to daytime lunar surface temperatures.

Materials possible to use for lunar and Martian shelters

In general, **the geopolymer binder has the following advantages** over other concreate-like materials:

- **For the geopolymer system where the bulk of the binder is the regolith itself, it allows for the limited usage of terrestrial materials.** The use of lunar regolith and alkali metals as components of geopolymer composites can thereby facilitate lunar construction without the need to bring materials in from the Earth at an extreme cost. Using in situ resource utilization (ISRU) technology allows one to limit the cost of construction.

- **The presence of alkali metals on the moon might be used as a source of the alkaline solution for geopolymerization**. Geopolymerization based on different solutions is a relatively well-known technology.

- **The phosphate-based geopolymers can be developed as a material applicable to Martian inhabitants**. Raw materials, such as phosphoric acid and water, are available in the Martian soil, which means it can be even more effective than in the case of lunar settlers where an activator must be delivered from Earth.

Technology - additive manufacturing

- The most promising solution seems to be the usage of **additive manufacturing techniques**, due to their advantages such as resource-saving and requiring minimal human involvement and others.
- However, the literature shows the possibility to use different techniques for the production of the construction from lunar and Martian regolith:

Method	Material	Compressive strength	Reference
Binder jetting	Regolith, soler cement, binder liquid	20 MPa	Cesaretti et.al. 2014
Extrusion	Regolith (72 wt%), urea, alkaline solution	13 MPa	Pilehvar et.al. 2020
Selective laser melting	Regolith	4 MPa	Goulas et.al. 2019
Solar sintering	Regolith	2 MPa	Meurisse et.al. 2018
Casting: geopolymer	Regolith (76 wt%), liquid silicate, alsaline solution	16 MPa	Montes et.al. 2015
Casting: Sulphur concrete	Regolith (65 wt%), sulphur	31 MPa	Toutanji et.al. 2012
Casting: Thermite reaction	Regolith (67wt%), aluminium powder	18 MPa	Faierson et.al. 2010
Vat polymerization	Regolith (69 wt%)	5 MPa	Altun et.al. 2021

Technology - additive manufacturing

- **NASA experiments confirm that it is possible using additive manufacturing technology in low gravity**, but the tests were made from plastic materials [Leach et. al. 2012].

- **Other tests have been made for cementitious materials** (concretes) by using two methods:

1) **Extrusion deposition,**

   - It obviates the need for any formwork or shuttering. It explored the use of Contour Crafting on the Moon and Mars, employing a lunar rover (ATHLETE) equipped with a robot extruding concrete through a nozzle, though only for the fabrication of infrastructural elements (landing pads, blast walls, etc. [Dini 2012].

Technology - additive manufacturing

2) Powder bed 3D printing.

- Tested by ESA for a large-scale 3D printer called D-shape [Leach et. al. 2012].
- It uses a layer-by-layer printing process with a 'chlorate-based, low viscosity, high superficial tension liquid with extraordinary reticulate properties if added to metallic oxides used as a catalyzer' as an 'ink' to bind lunar dust to create stone-like objects [Leach et. al. 2012; Dini 2012].

Some other trials for 3D printing technologies have been done also for planetary regolith-based concrete such as: sorel-type cement (MgO-based), sulphur cement, polymers / trash composites and Portland cement. All of them confirm the efficiency of this technology in extraterrestrial applications. Despite the existing research, the additive technologies still require improvements, including their efficiency [Ma et. al. 2022, Yuan et al. 2022, Doğan-Sağlamtimur et. al. 2022].

Summary of the theoretical part

- **The design, production and testing** of lunar and Martian soil simulants are an important step on the way to solving both scientific, technical and engineering problems that are barriers to the development of space missions.
- It should be emphasized that **it is not possible to produce lunar or Martian regolith simulants that perfectly reflect the composition and properties of materials found on the lunar and Martian surfaces**. Of great importance here is the fact that lunar and Martian soils show significant differences in composition depending on where they were collected.
- Moreover, **there is still a great need to develop simulants** that could be produced cheaply on an industrial scale.
- Also, **the technology for the production of lunar and Martian concretes requires further work** that can be implemented during planned space exploration missions.

Lunar soil simulants - research conducted at Cracow University of Technology

The aim of the work was to develop ceramic-based materials for fabrication by 3D printing technology.

The developed material (powder) is planned to imitate lunar regolith (ground) in terms of chemical composition.

The scope of the study:

- The **oxide composition of the substrates** used were taken into account during the synthesis.
- the **analysis of the content of individual phases by XRD diffractometry**,
- **the analysis of the particle size distribution**,
- and **the observation on the scanning electron microscope** (SEM) of the individual components used as substrates during the preparation of the mixtures (i.e. fly ash, volcanic tuff, olivine, silica, quartz river sand, granite flour, basalt flour) were carried out.
- The prepared mixtures, differing in the proportion of each component, were observed on a scanning electron microscope, and **the oxide composition was analyzed by energy dispersive spectroscopy** (EDS), which made it possible to select a mixture with an oxide composition most similar to the lunar regolith.

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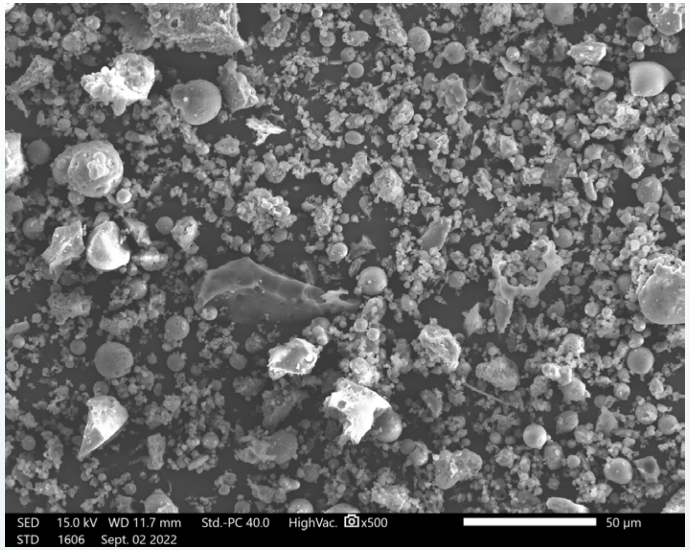
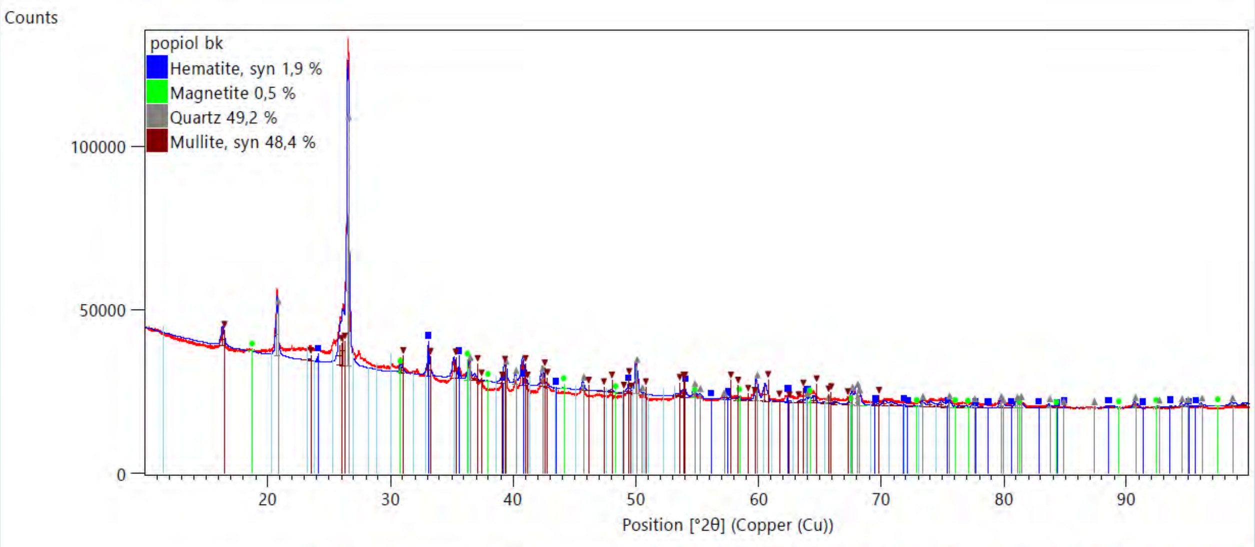
Materials – fly ash

- Pozzolana in the form of **F-grade fly ash obtained from the Skawina Combined Heat and Power Plant** (Skawina, Poland) was used as a base material for the geopolymers tested.
- This ash is mainly composed of quartz and mullite, with a small content of other phases, not exceeding 4%.



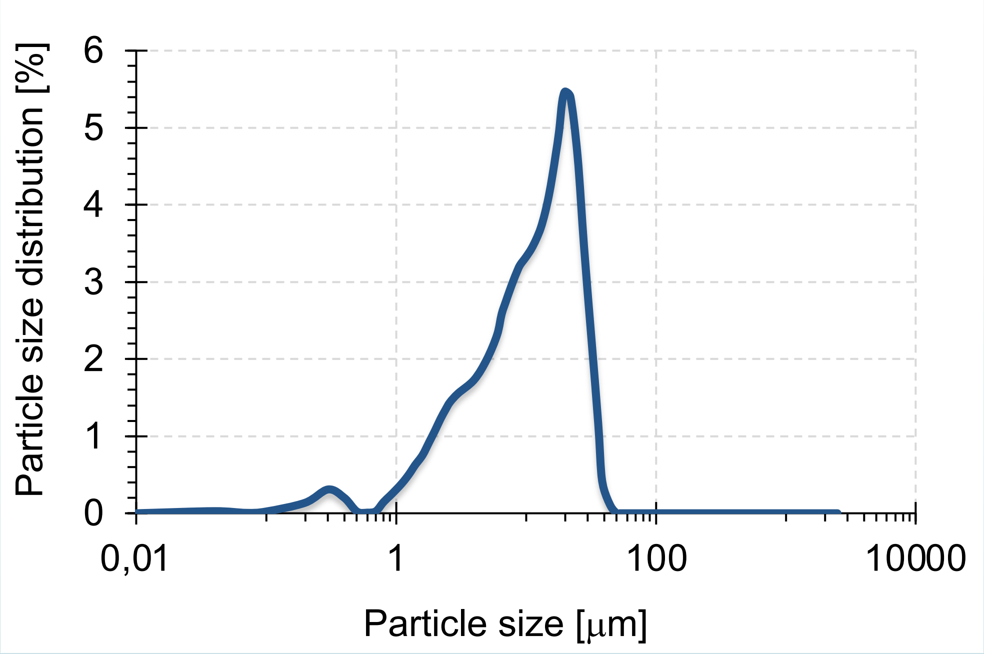
The proportions of the phases that are included in the fly ash studied (results from XRD analysis on Aeris X-ray diffractometer from Panalyticalz)

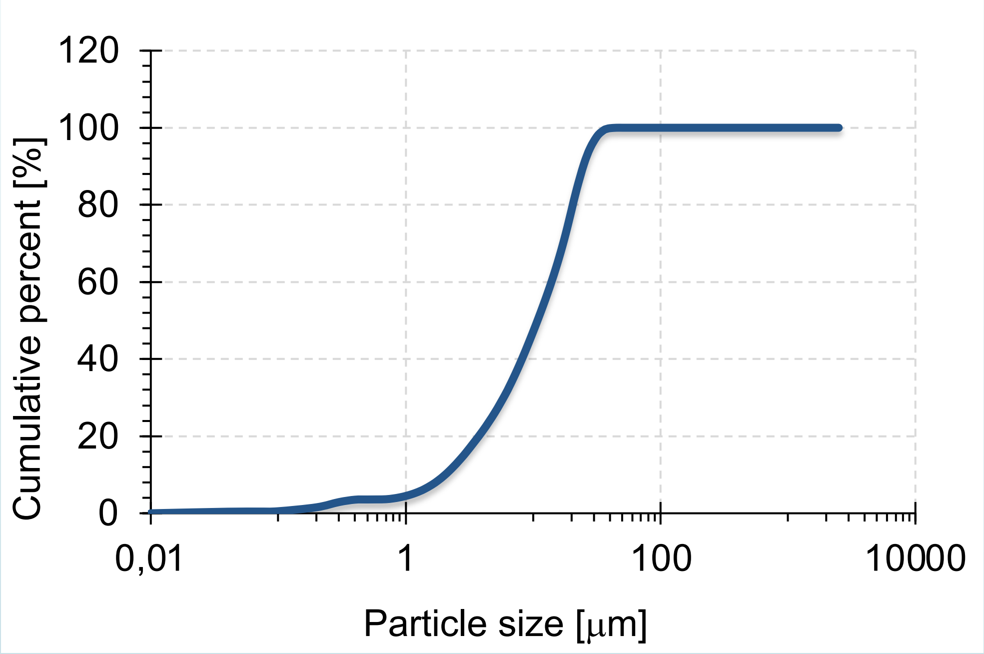
Precursor	Identified phase		Content of identified phase in sample [%]
Fly ash	Name of the phase	Chemical formula	
	Quartz	SiO_2	49.2
	Mulite	$Al_6Si_2O_{13}$	48.4
	Hematite	Fe_2O_3	1.9
	Magnetite	Fe_3O_4	0.5



Materials – fly ash

- The fly ash selected for the study, due to its composition, especially its high content of aluminum and silicon, and physicochemical properties (a mainly fine fraction with a smoothness of 16.7% and density of 2.22 g/cm³), can be successfully used in the geopolymerization process.
- The figures below show the particle size distribution plot and the cumulative curve for the ash used in this study.





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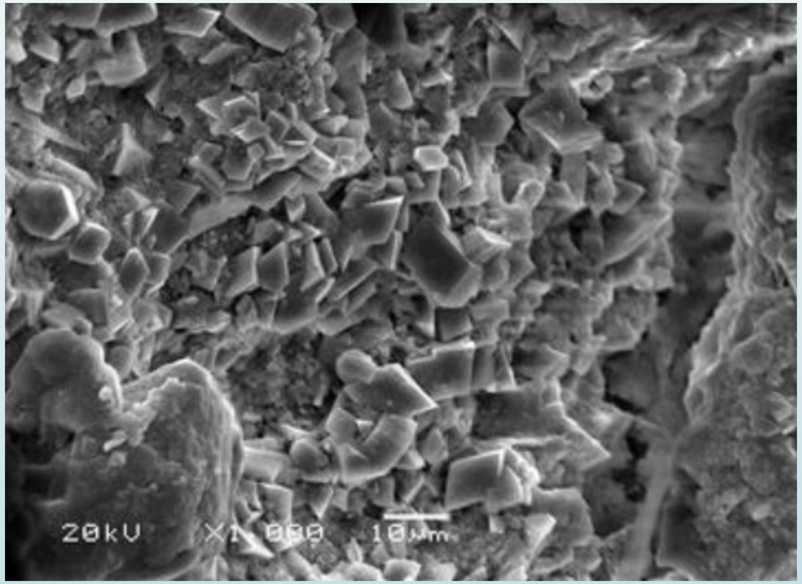
Materials – volcanic tuff

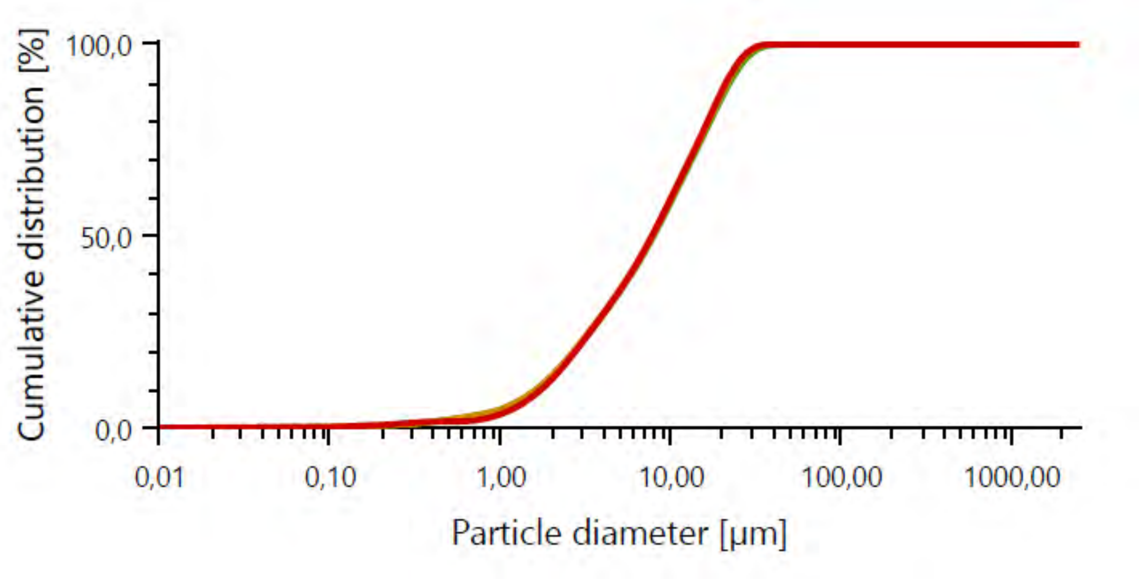
- **Volcanic tuff** is porous rock belonging to the family of clastic rocks, which consist of pyroclastic material, often with admixture of other clastic materials, cemented with e.g. silica or clay binder. The characteristic feature of tuff is high porosity and the associated low specific gravity.
- **Tuff from Filipowice** in Poland was used for the study.
- This tuff from Filipowice **includes the following components**: sanidine, kaolinite, biotite, illite, quartz, heavily modified feldspar, crushed alien rocks, opaque minerals, microcrystalline binder and carbonate binder.

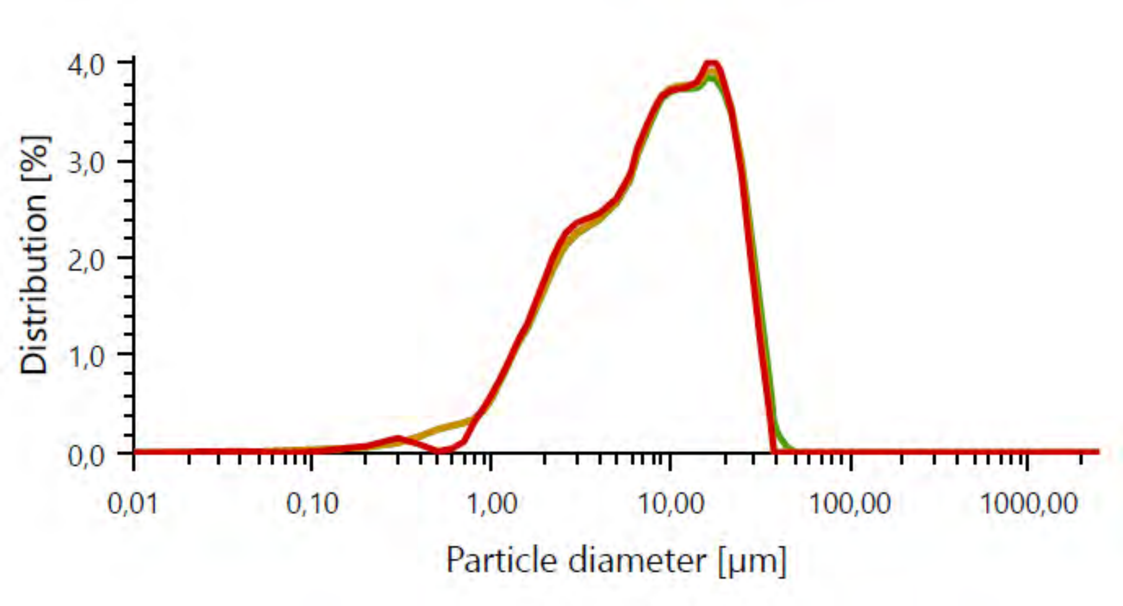
SiO	56.01 %
Fe_2O_3	5.39 %
Al_2O_3	16.72 %
CaO	5.39 %
MgO	0.60 %
TiO_2	0.88 %
K_2O	9.13 %
Na_20	0.40 %
Other	5.48 %

Table 1. *Composition of oxides in a sample of tuff from Filipowice used in the present studies*



Materials – volcanic tuff





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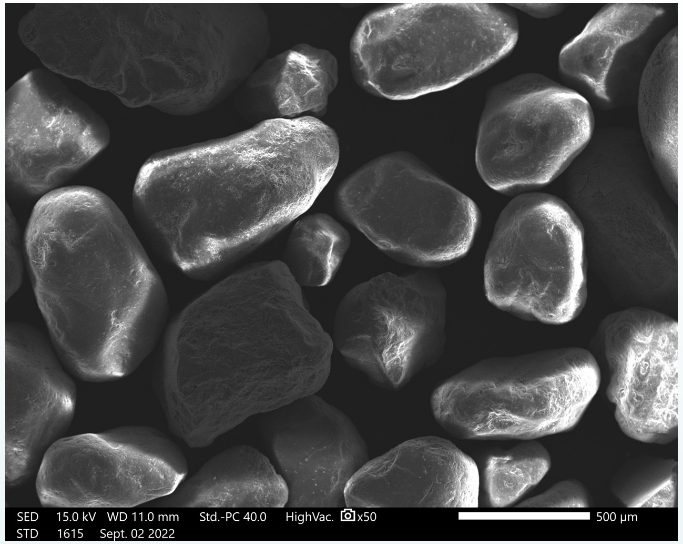
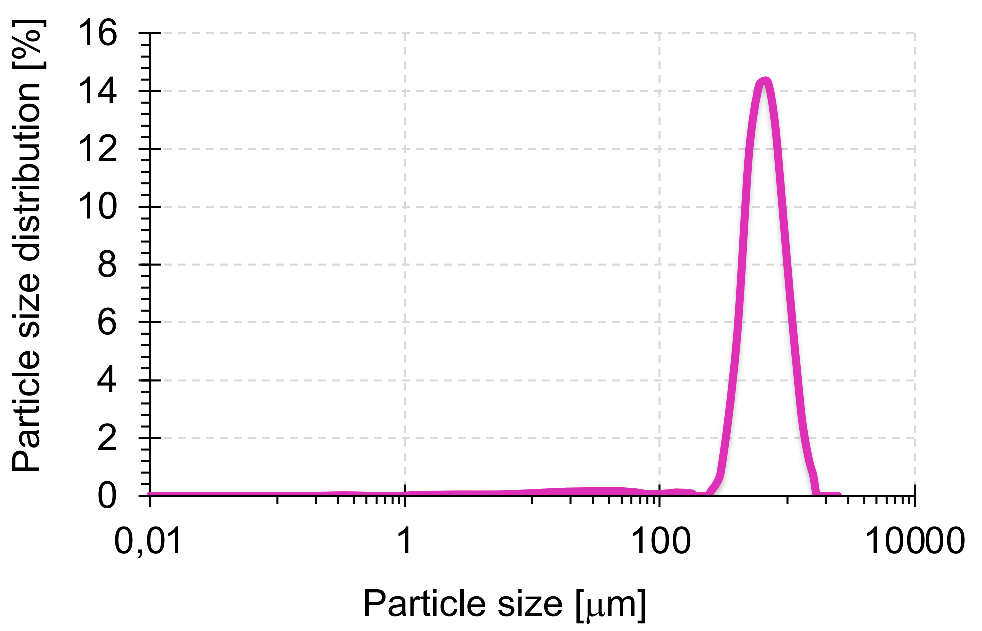
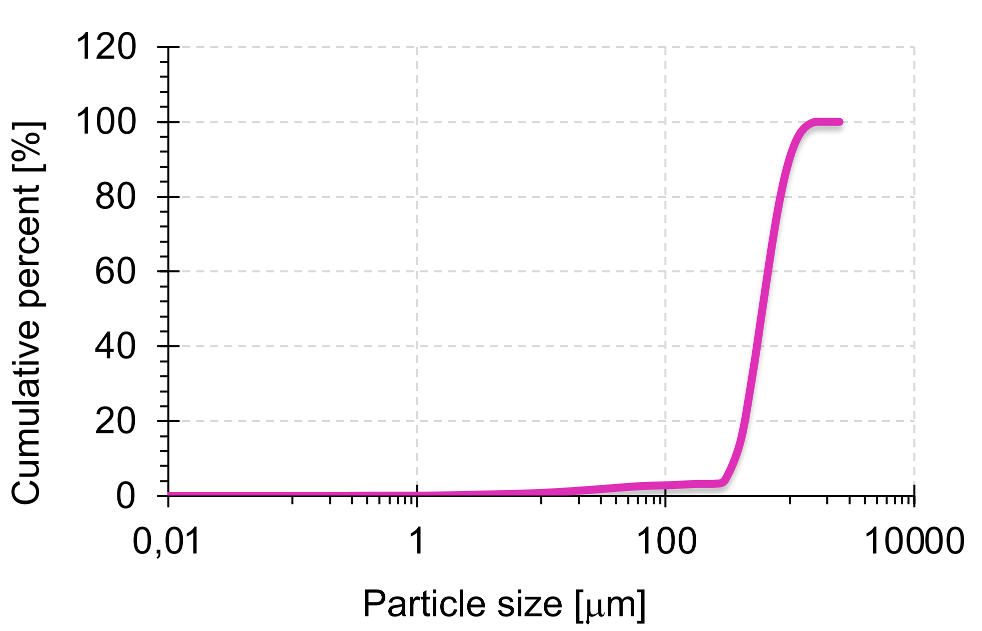
Materials – river sand

- Another raw material was **quartz river sand**, which showed no surface absorption due to the surface saturation of its particles.
- The figures below show the particle size distribution plot and the cumulative curve.







Materials – granite

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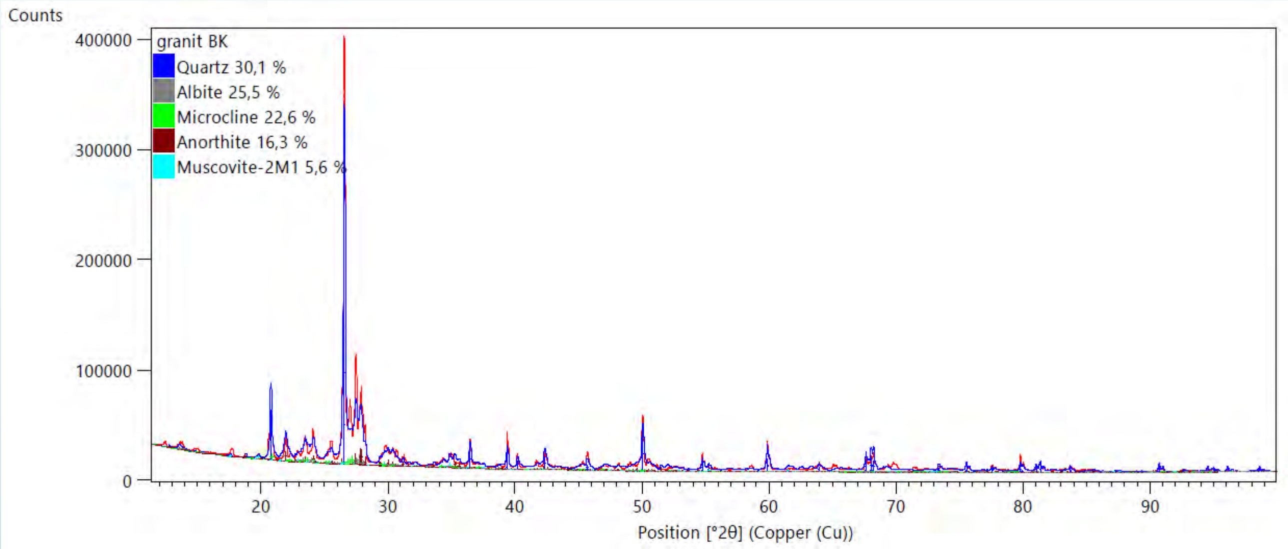
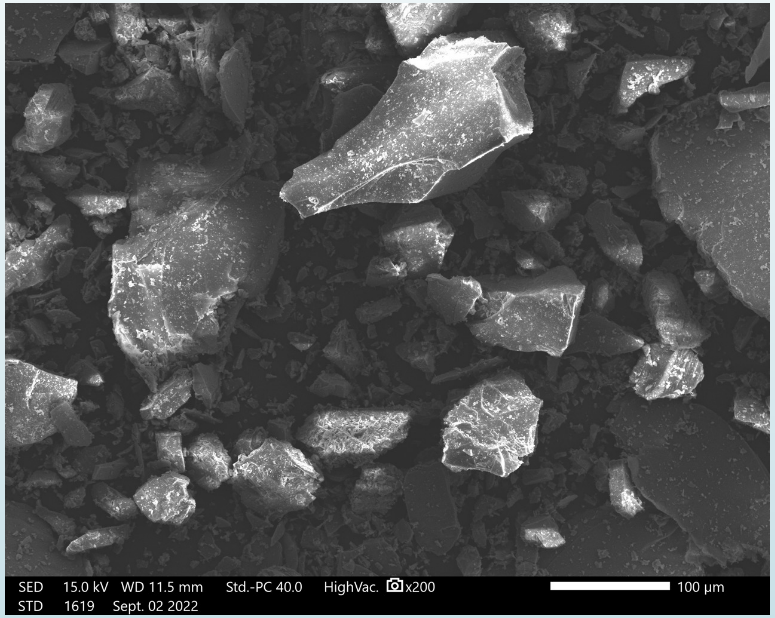
- The last solid raw material used in this study was **granite in the form of flour**.
- **Granite flour** is granite rock artificially crushed in stone mills.
- Its characteristic feature is a high content of quartz and other valuable silicon compounds, including silicates and silicic acid salts.
- Figure below shows the particle size distribution histogram and cumulative curve for the granite.





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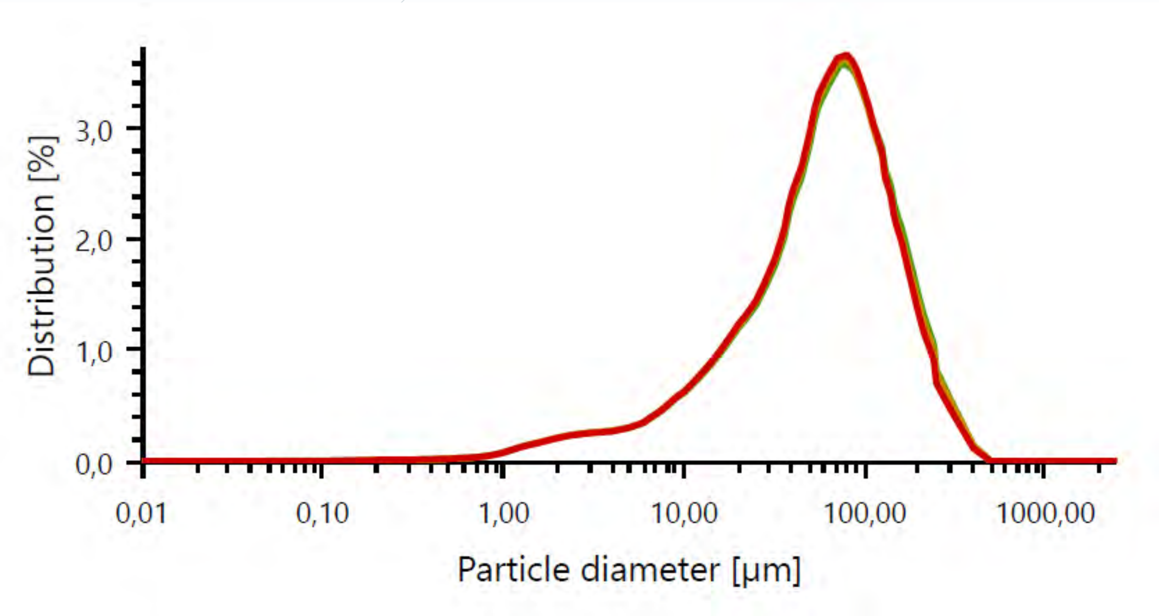
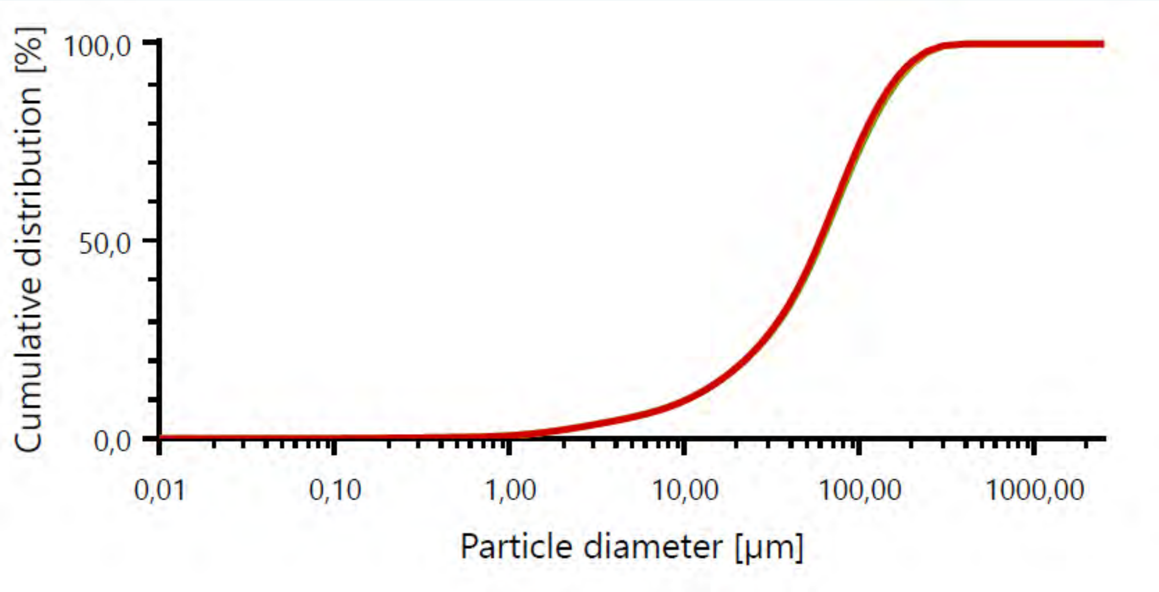
Materials – granite





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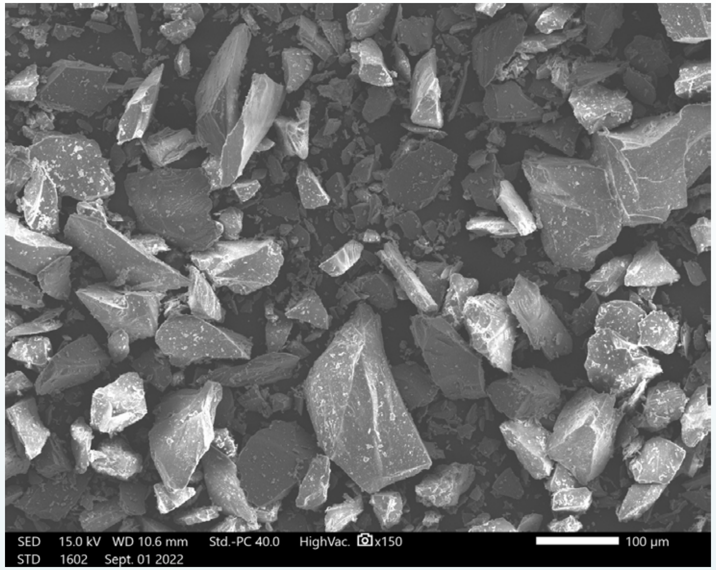
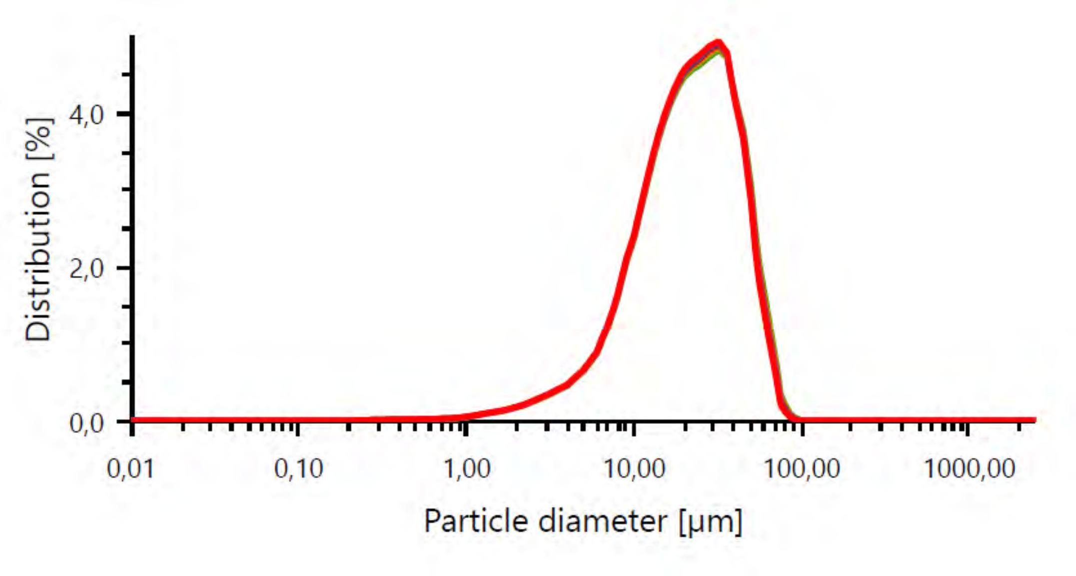
Materials – silica

- A light powder, mineral, made from natural volcanic rock subjected to mechanical and thermal treatment at about 950 °C. Natural product, chemically inert, non-flammable, harmless.



Basic composition:
- SiO_2: 74,86%
- Al_2O_3: 12,58%
- TiO_2: 0,06%
- Fe_2O_3: 0,70%
- CaO : 0,75%
- MgO: 0,26%
- Na_2O_3: 3,40%
- K_2O: 4,78%



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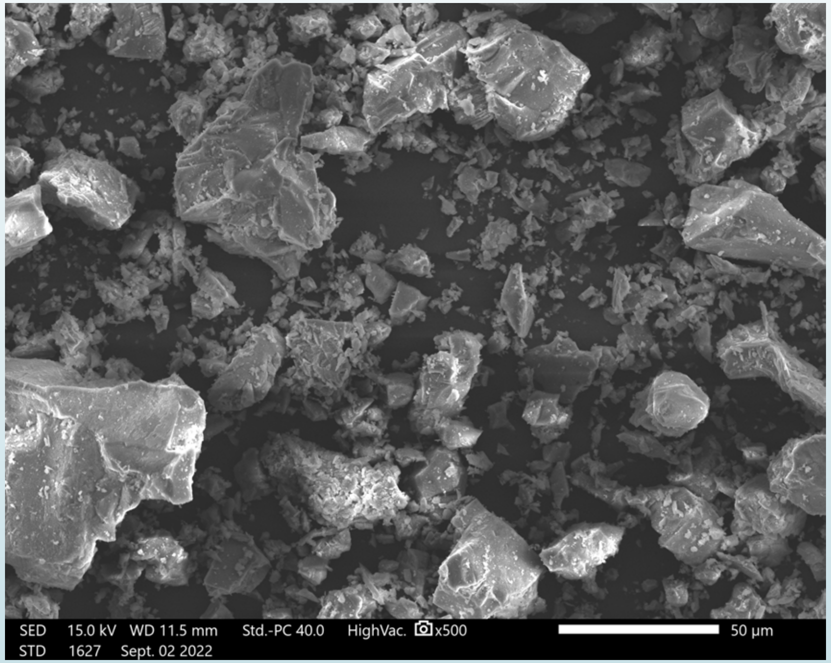
Materials – basalt flour

- Basalt is the most common volcanic rock, formed from magma smelted in the Earth's mantle. In areas of ocean bottoms, it forms the Earth's crust.
- Basalt is also a common rock on the moon. It is characterized by very high mineral content.
- Basalt meal is a natural dust, resulting from processing when mining the raw material.

Elemental composition:

SiO_2 - Silica: 46,6%
Al_2O_3 - Aluminum oxide: 14,3%
Fe_2O_3 - Iron oxide: 11,4%
CaO - Calcium oxide: 9,21%
Na_2O - Sodium oxide: 3,10%
MgO - Magnesium oxide: 7,90%
K_2O - Potassium oxide 0.823%
TiO_2 - Titanium oxide: 1,95%
P_2O_5 - Phosphorus oxide: 0.48%
Mn_2O_3 - Manganese oxide: 0.266%



Materials – basalt flour

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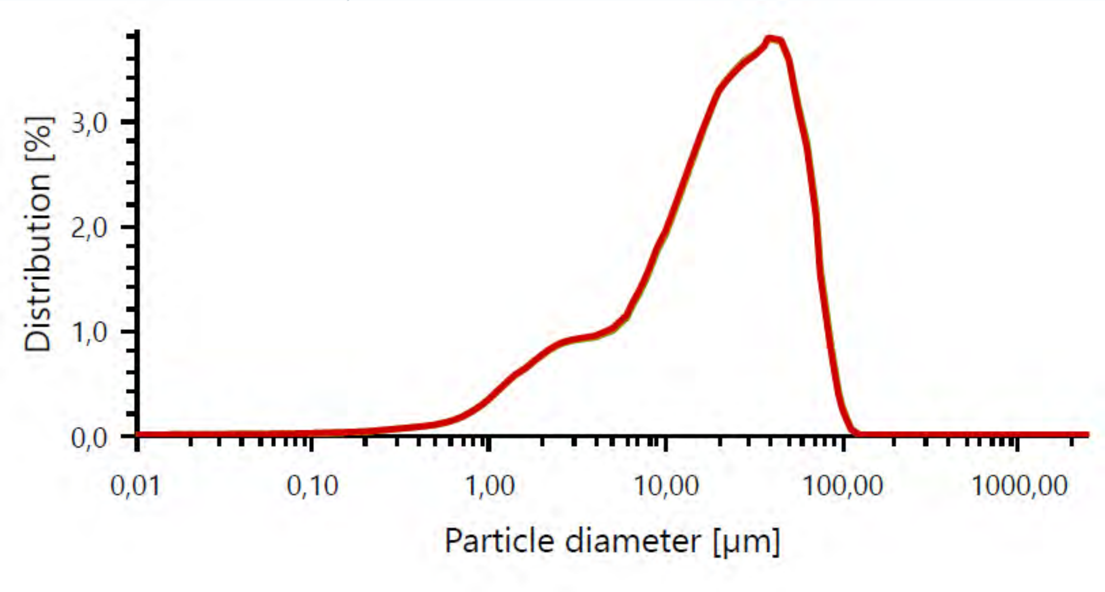
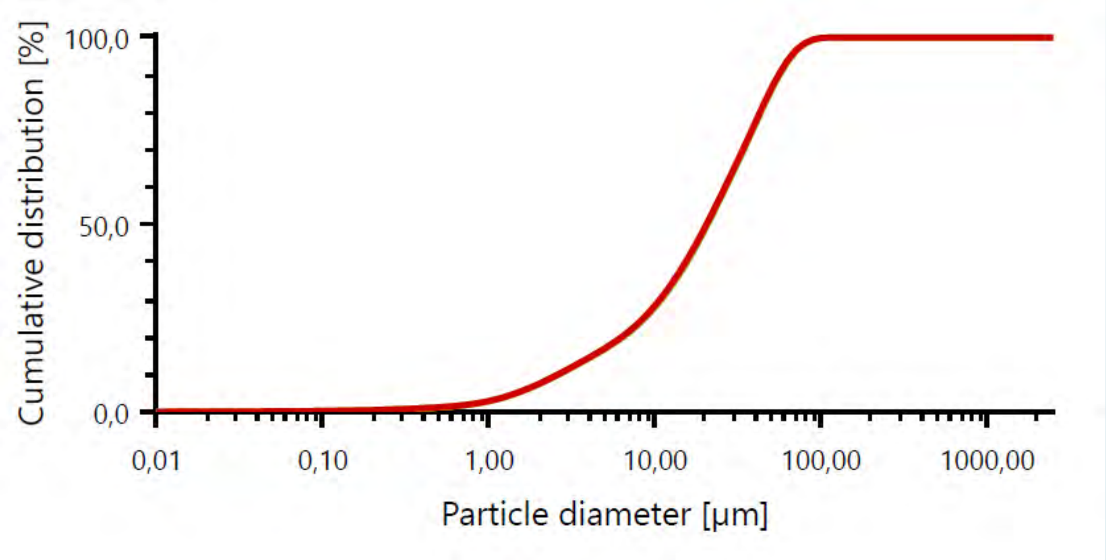
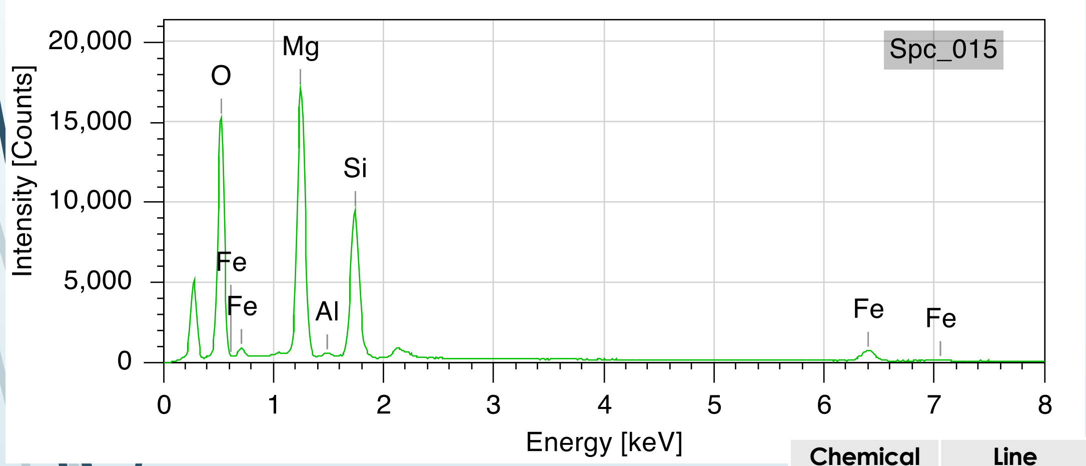


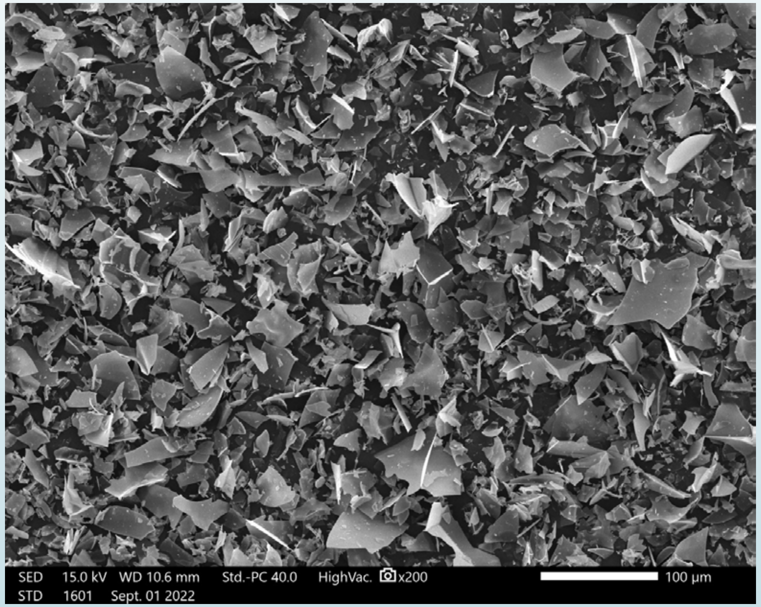


Materials – olivine

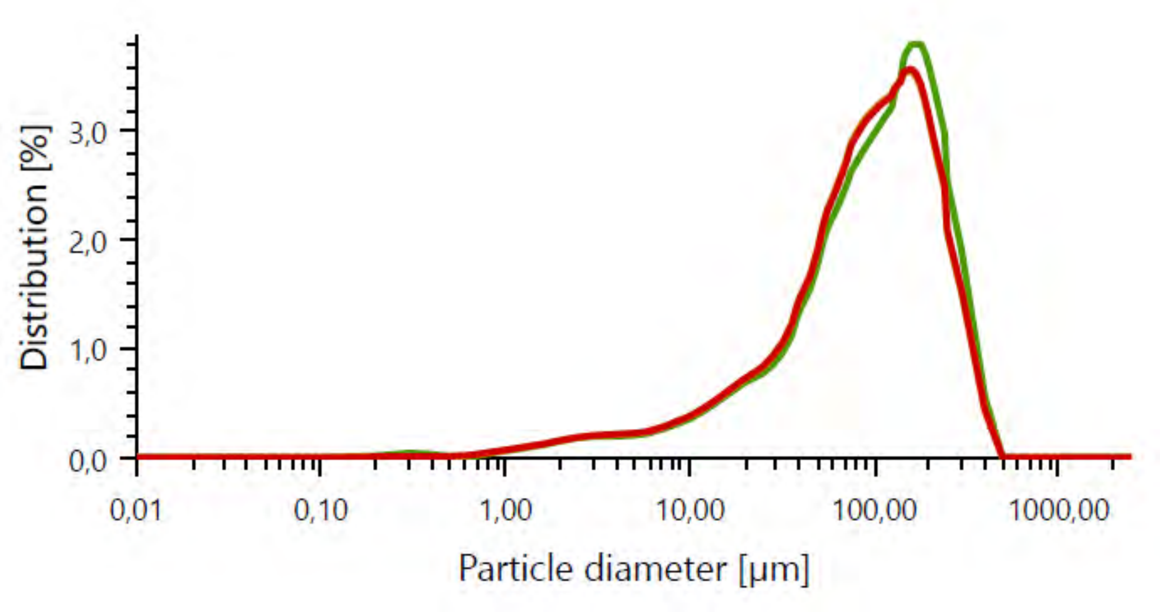
- **Olivines** are a group of minerals classified as silicates, they crystallize in a rhomboid pattern. Their distinguishing feature is their yellow-green color, which is often extremely pure and intense.
- **Ground olivine stones** were used in the mixes.

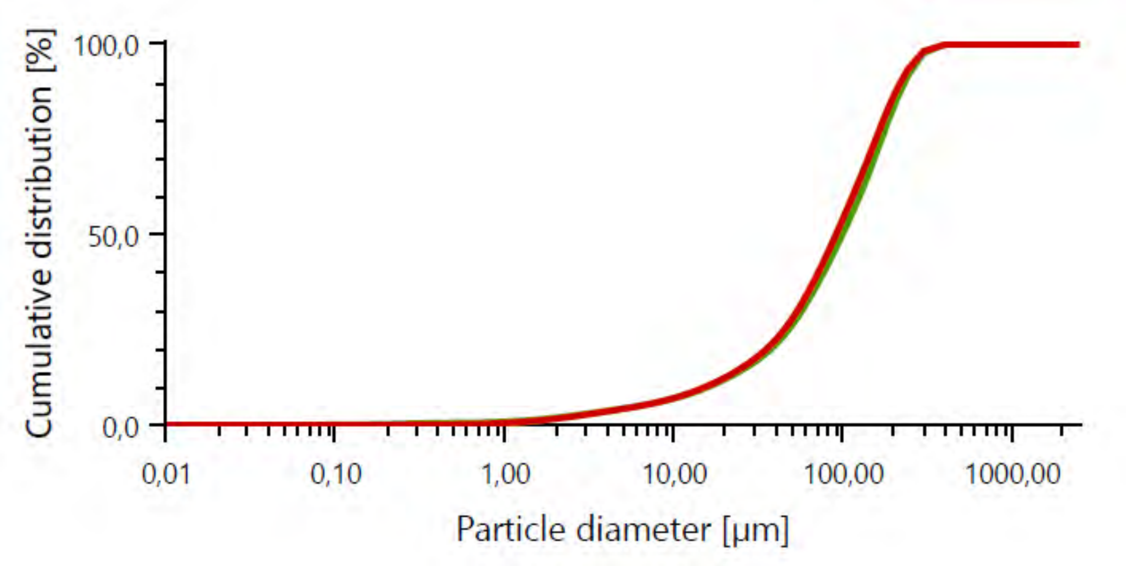


Chemical formula	Line	Mass%	Mol%	Cations
O	K			
MgO	K	45.69±0.26	56.81±0.32	10.12
Al2O3	K	1.08±0.06	0.53±0.03	0.19
SiO2	K	40.41±0.31	33.71±0.26	6.00
FeO	K	12.82±0.27	8.94±0.19	1.59
Total		100.00	100.00	



Materials – olivine





Oxides

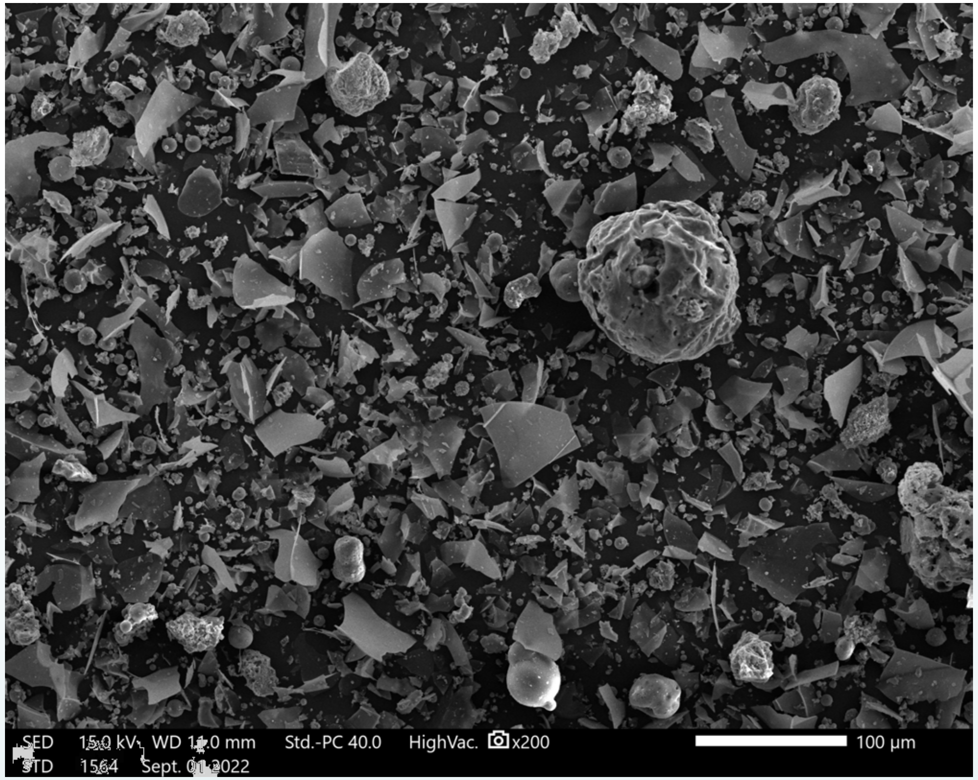
Oxides in pure form were also introduced into the several mixtures:

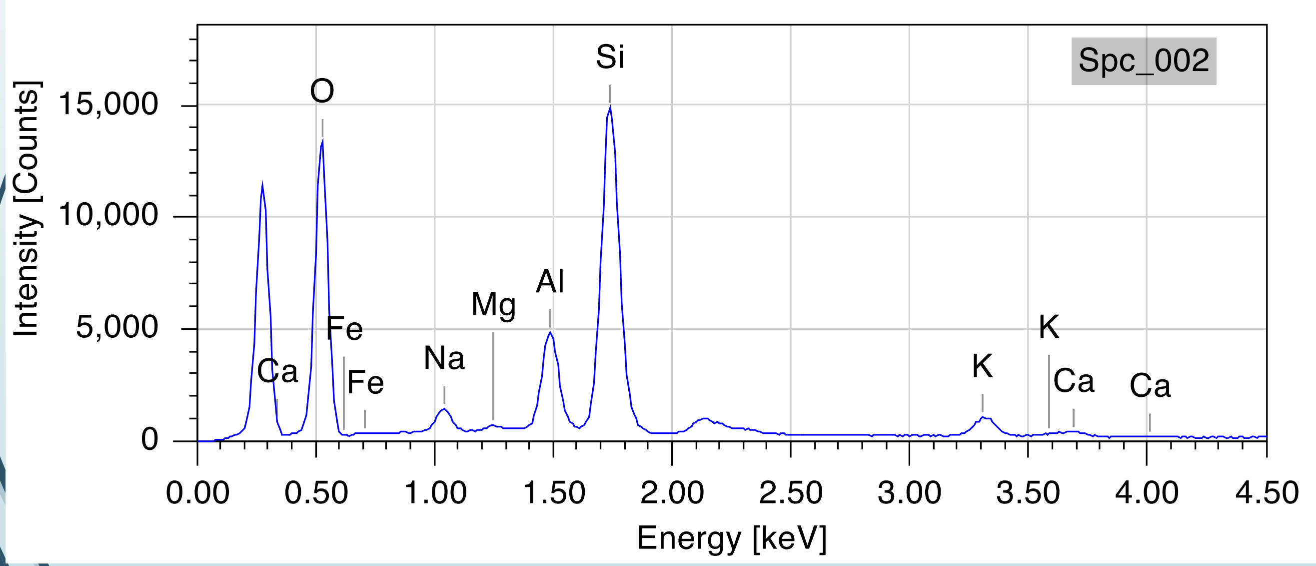
- FeO
- Fe_2O_3
- CaO
- TiO_2
- Al_2O_3
- MgO

http://www.lerncoach.li/tlenki-metali/

Mixture I

Chemical formula	Line	Mass%	Mol%	Cations
O	K			
Na_2O	K	3.56±0.09	3.78±0.09	0.92
MgO	K	0.55±0.04	0.89±0.07	0.11
Al_2O_3	K	16.22±0.19	10.46±0.12	2.53
SiO_2	K	70.51±0.43	77.16±0.47	9.35
K_2O	K	4.99±0.11	3.49±0.08	0.84
CaO	K	1.62±0.08	1.90±0.09	0.23
FeO	K	2.55±0.14	2.34±0.13	0.28
Total		100.00	100.00	

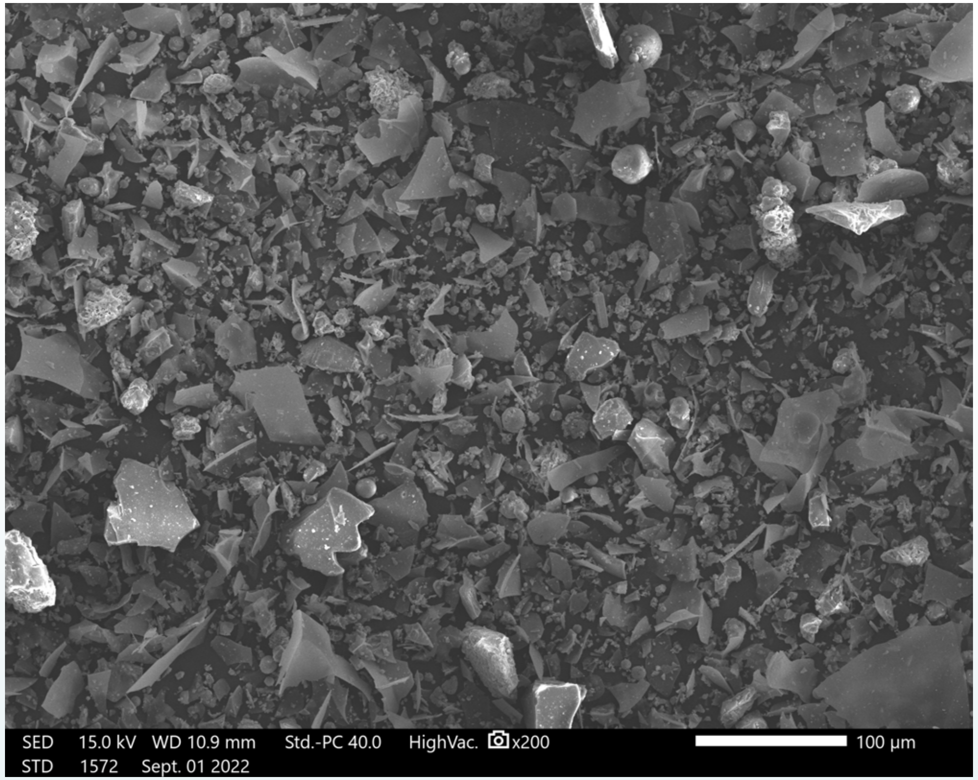


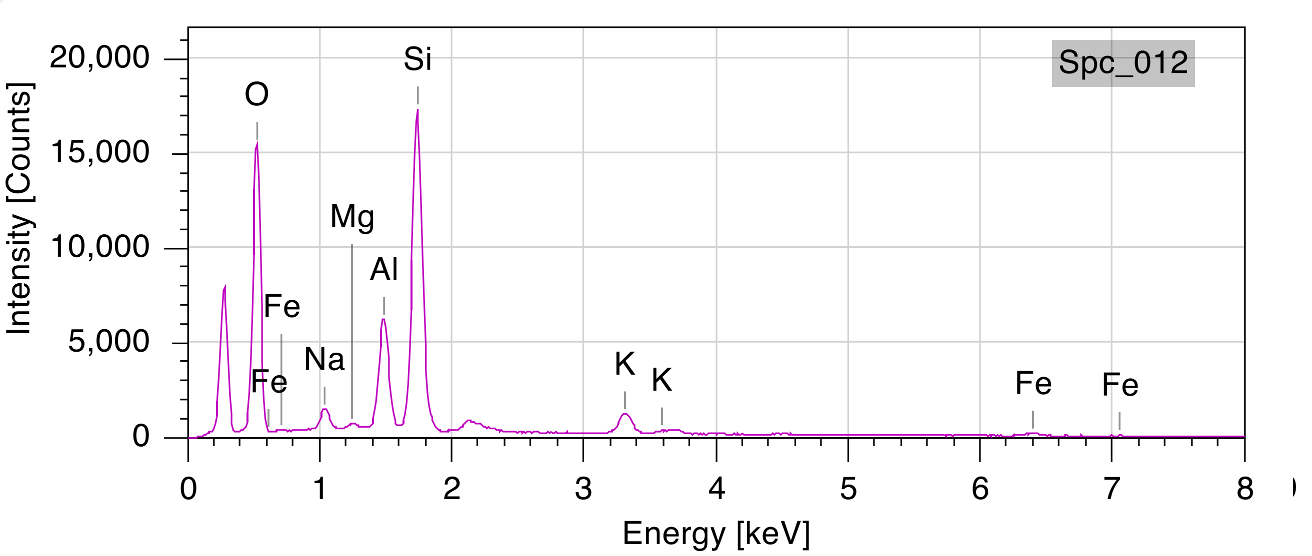


Component	Wt. [%]
fly ash	21.74
quartz sand	65.22
silica	13.04

Mixture II

Chemical formula	Line	Mass%	Mol%	Cations
O	K			
Na_2O	K	3.18±0.07	3.41±0.08	0.81
MgO	K	0.63±0.04	1.04±0.07	0.12
Al_2O_3	K	18.26±0.18	11.90±0.12	2.84
SiO_2	K	70.21±0.39	77.62±0.43	9.25
K_2O	K	4.99±0.10	3.52±0.07	0.84
FeO	K	2.72±0.14	2.51±0.13	0.30
Total		100.00	100.00	

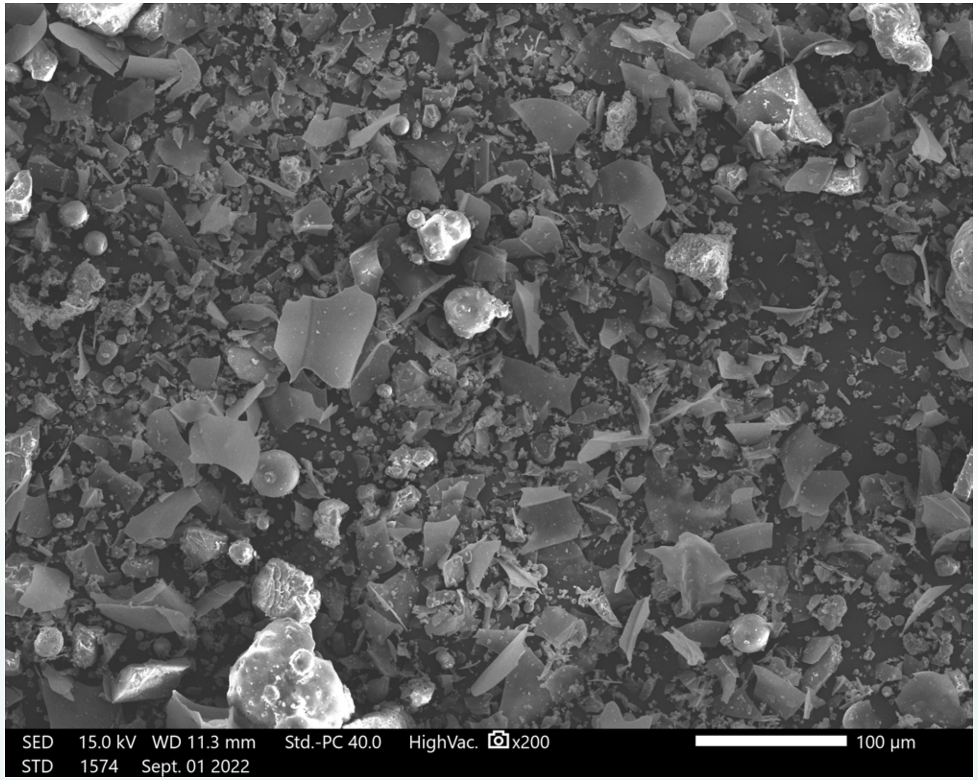


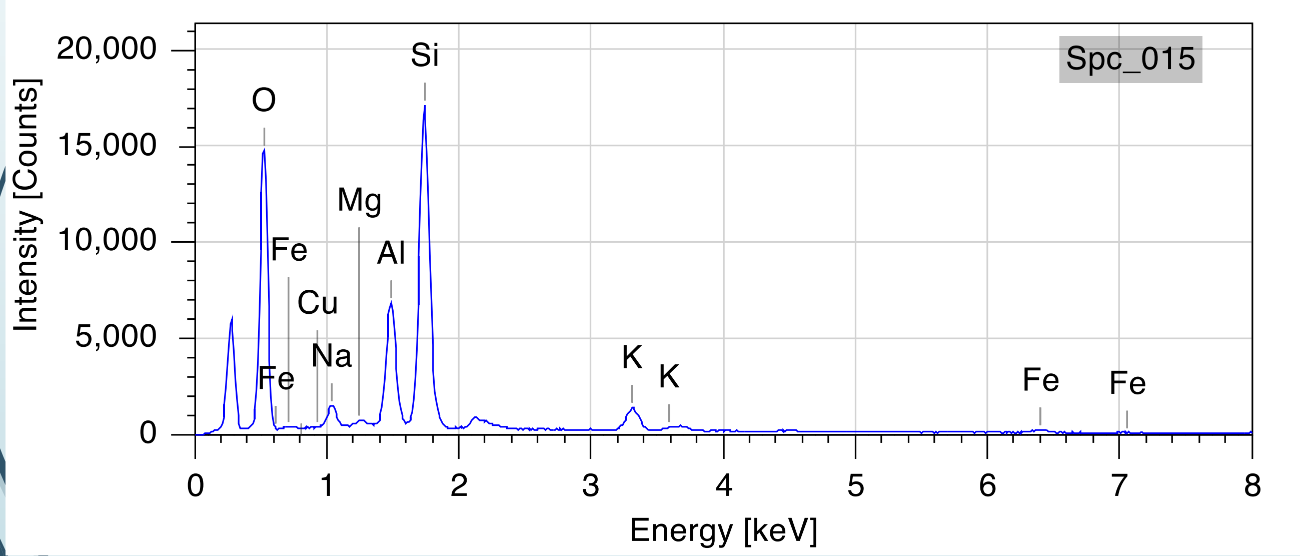


Component	Wt. [%]
fly ash	21.74
granite flour	65.22
silica	13.04

Mixture III

Chemical formula	Line	Mass%	Mol%	Cations
O	K			
Na_2O	K	3.15±0.07	3.41±0.08	0.82
MgO	K	0.69±0.04	1.15±0.07	0.14
Al_2O_3	K	19.38±0.18	12.77±0.12	3.06
SiO_2	K	66.58±0.38	74.45±0.42	8.93
K2O	K	5.18±0.10	3.69±0.07	0.89
FeO	K	3.14±0.14	2.94±0.13	0.35
CuO	K	1.89±0.17	1.59±0.15	0.19
Total		100.00	100.00	

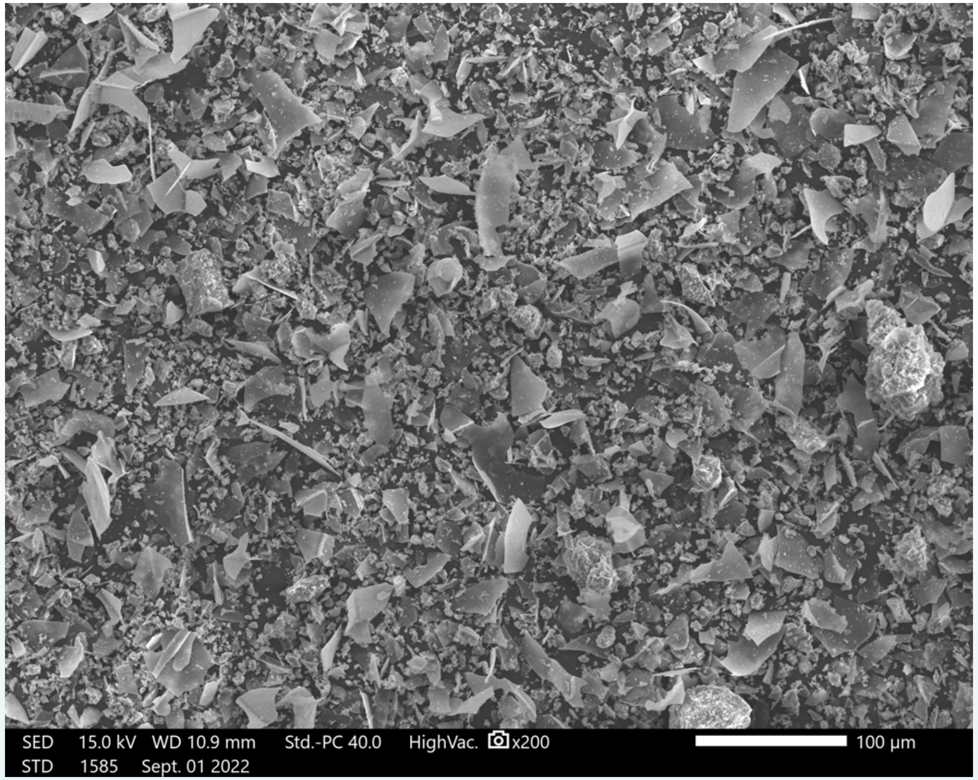


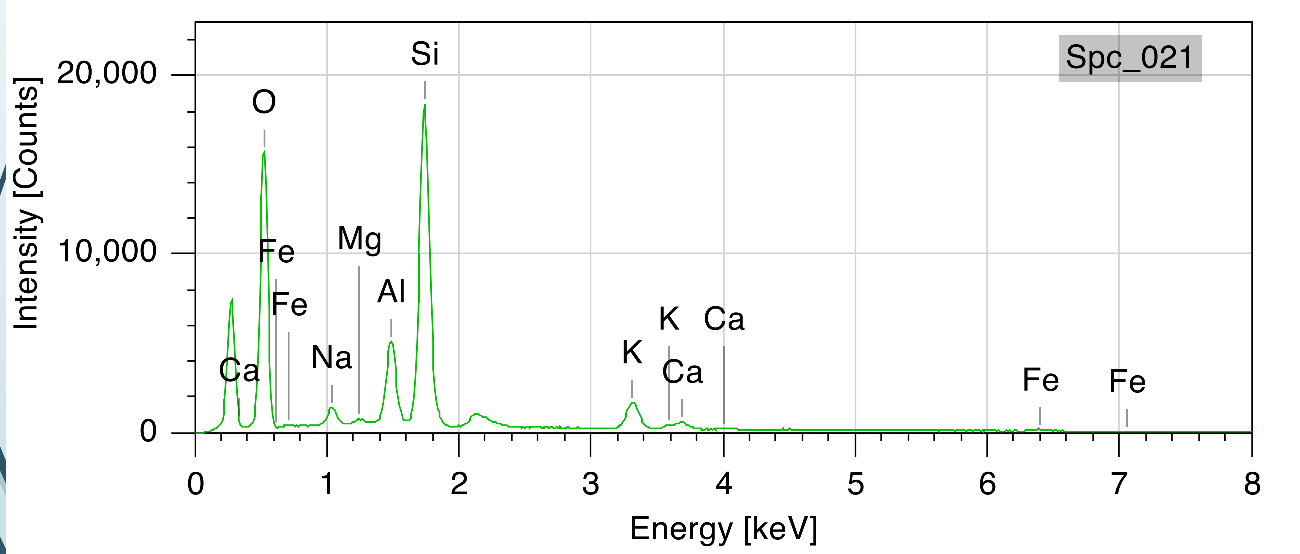


Component	Wt. [%]
fly ash	21.74
granite flour	32.61
silica	13.04
quartz sand	32.61

Mixture IV

Chemical formula	Line	Mass%	Mol%	Cations
O	K			
Na_2O	K	2.65±0.07	2.80±0.07	0.69
MgO	K	0.67±0.04	1.08±0.07	0.13
Al_2O_3	K	13.95±0.16	8.96±0.10	2.20
SiO_2	K	71.07±0.38	77.45±0.42	9.51
K_2O	K	7.06±0.11	4.91±0.08	1.21
CaO	K	2.38±0.08	2.78±0.10	0.34
FeO	K	2.22±0.12	2.02±0.11	0.25
Total		100.00	100.00	

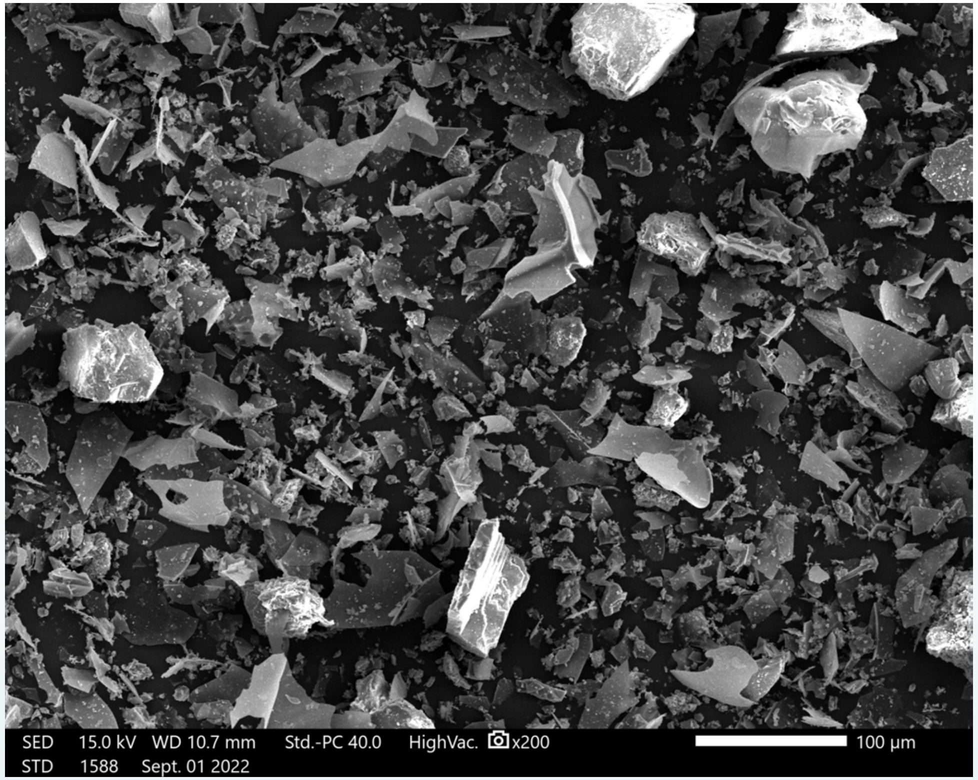


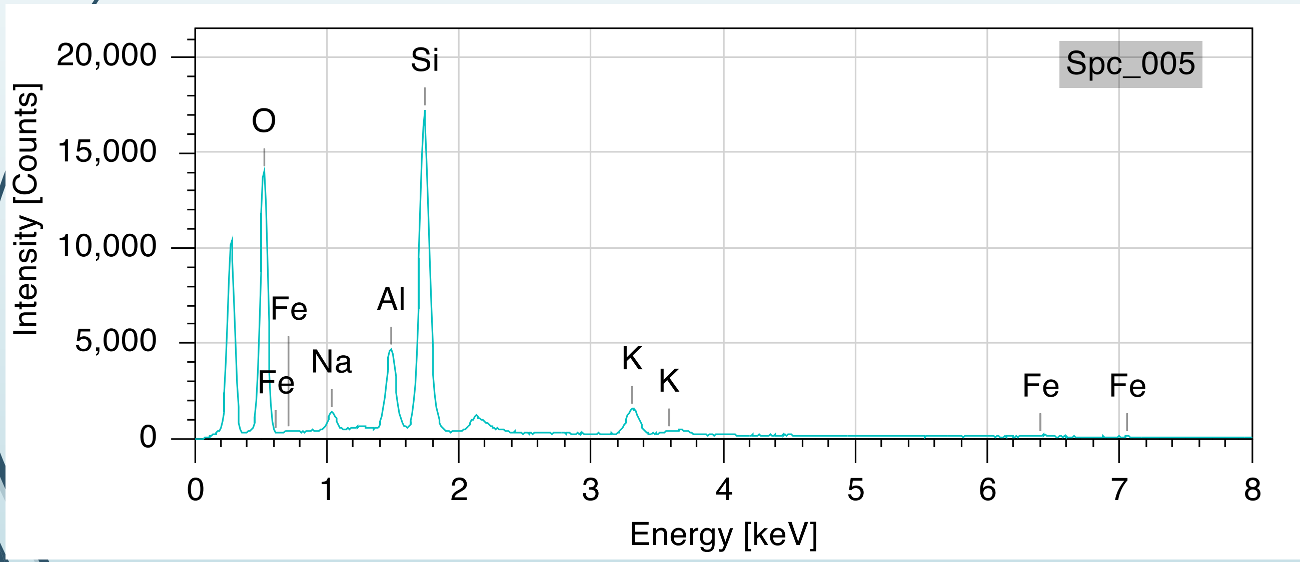


Component	Wt. [%]
volcanic tuff	21.74
quartz sand	65.22
silica	13.04

Mixture V

Chemical formula	Line	Mass%	Mol%	Cations
O	K			
Na2O	K	2.99±0.08	3.18±0.08	0.77
Al2O3	K	14.41±0.17	9.32±0.11	2.24
SiO2	K	73.50±0.41	80.70±0.46	9.72
K2O	K	7.17±0.12	5.02±0.09	1.21
FeO	K	1.94±0.12	1.78±0.11	0.21
Total		100.00	100.00	

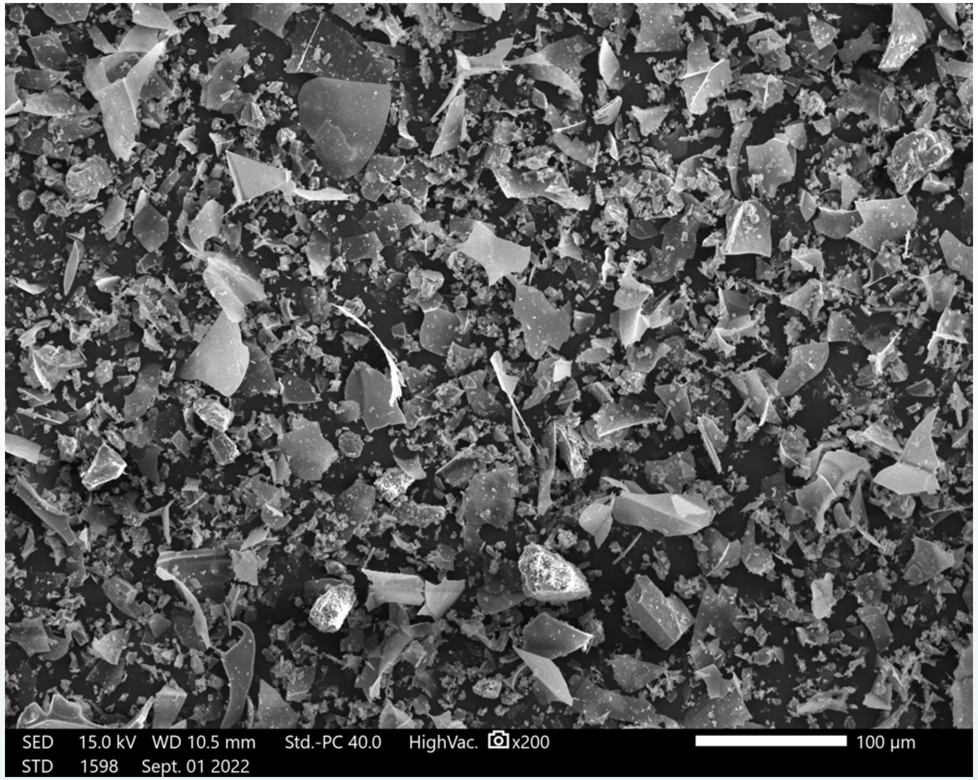


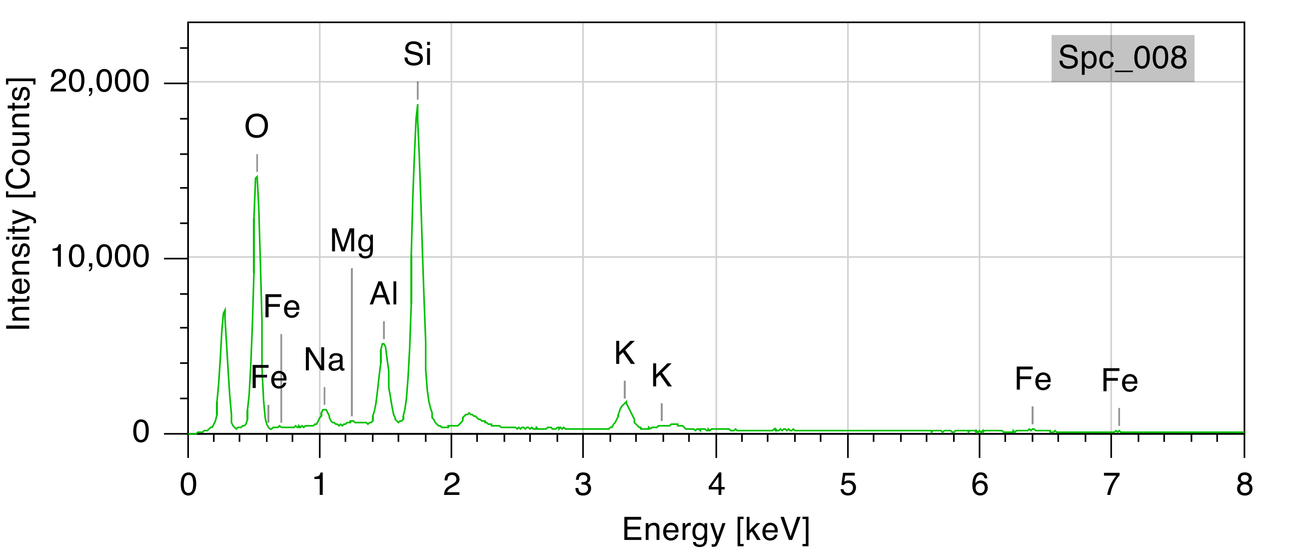


Component	Wt. [%]
volcanic tuff	21.74
granite flour	65.22
silica	13.04

Mixture VI

Chemical formula	Line	Mass%	Mol%	Cations
O	K			
Na_2O	K	2.60±0.07	2.76±0.07	0.67
MgO	K	0.46±0.04	0.75±0.06	0.09
Al_2O_3	K	14.46±0.16	9.34±0.10	2.26
SiO_2	K	72.94±0.39	79.98±0.43	9.66
K_2O	K	7.26±0.12	5.08±0.08	1.23
FeO	K	2.29±0.13	2.10±0.12	0.25
Total		100.00	100.00	

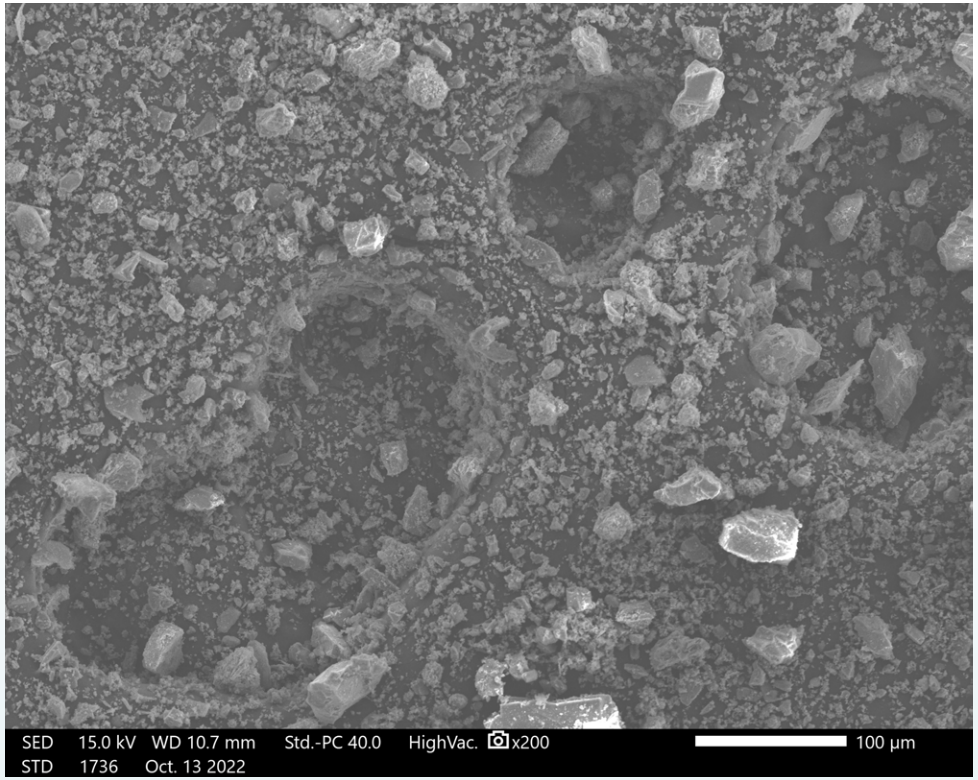


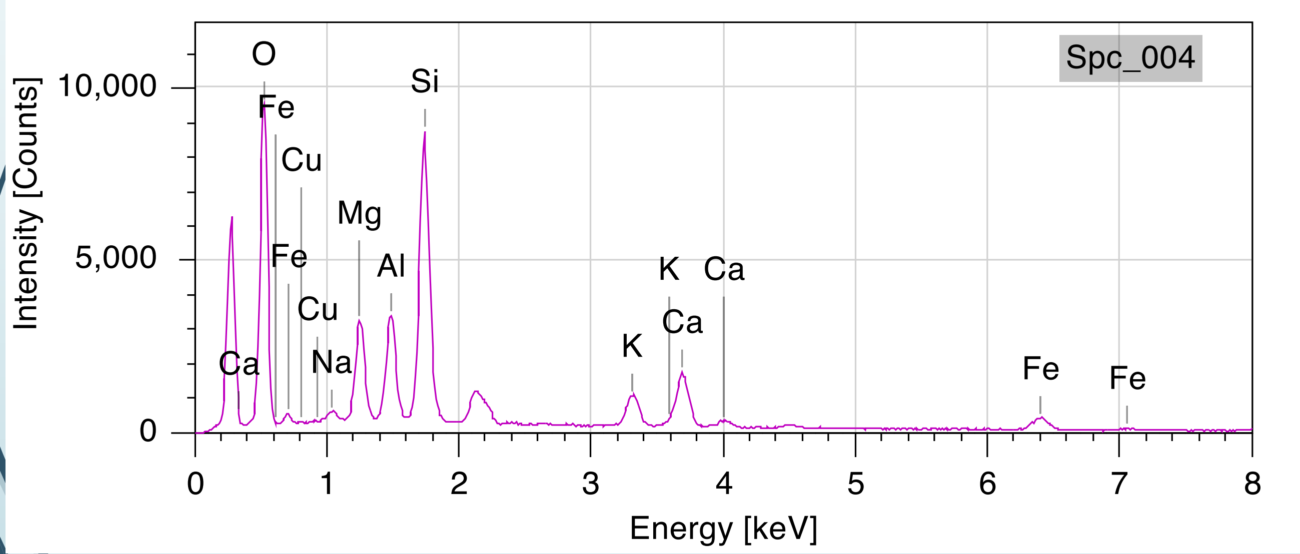


Component	Wt. [%]
volcanic tuff	21.74
granite flour	32.61
silica	13.04
quartz sand	32.61

Mixture VII

Chemical formula	Line	Mass%	Mol%	Cations
O	K			
Na_2O	K	1.09±0.06	1.10±0.06	0.32
MgO	K	10.88±0.15	16.83±0.24	2.48
Al_2O_3	K	13.52±0.18	8.26±0.11	2.44
SiO_2	K	44.37±0.36	46.03±0.37	6.80
K_2O	K	5.32±0.11	3.52±0.07	1.04
CaO	K	12.43±0.19	13.82±0.22	2.04
FeO	K	8.80±0.26	7.63±0.23	1.13
CuO	K	3.60±0.26	2.82±0.20	0.42
Total		100.00	100.00	

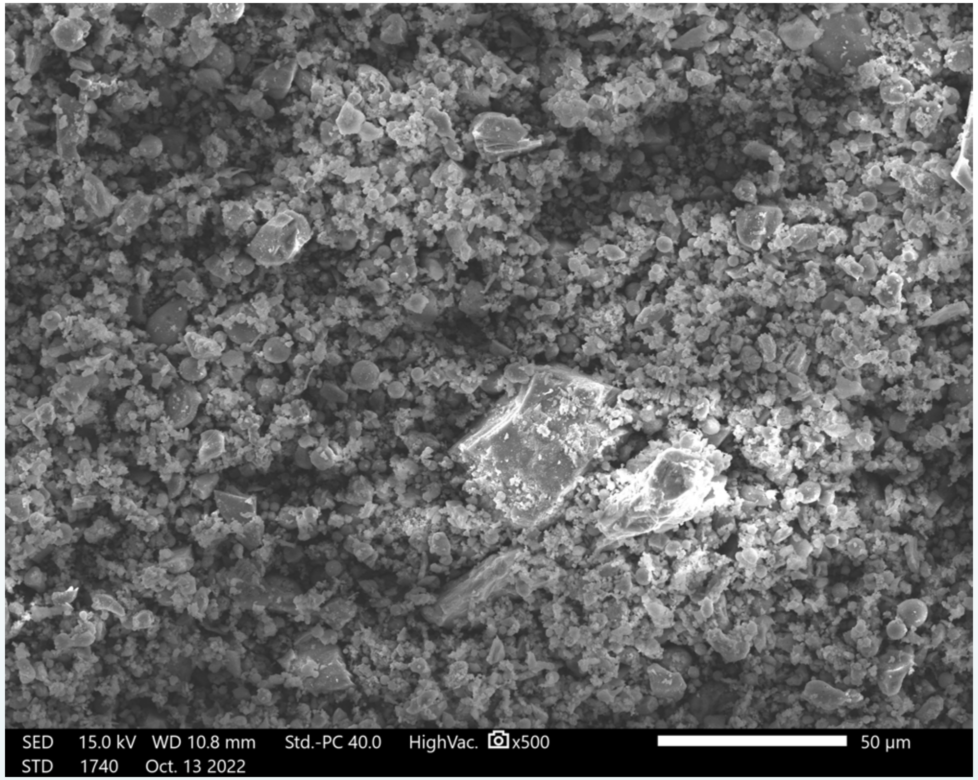


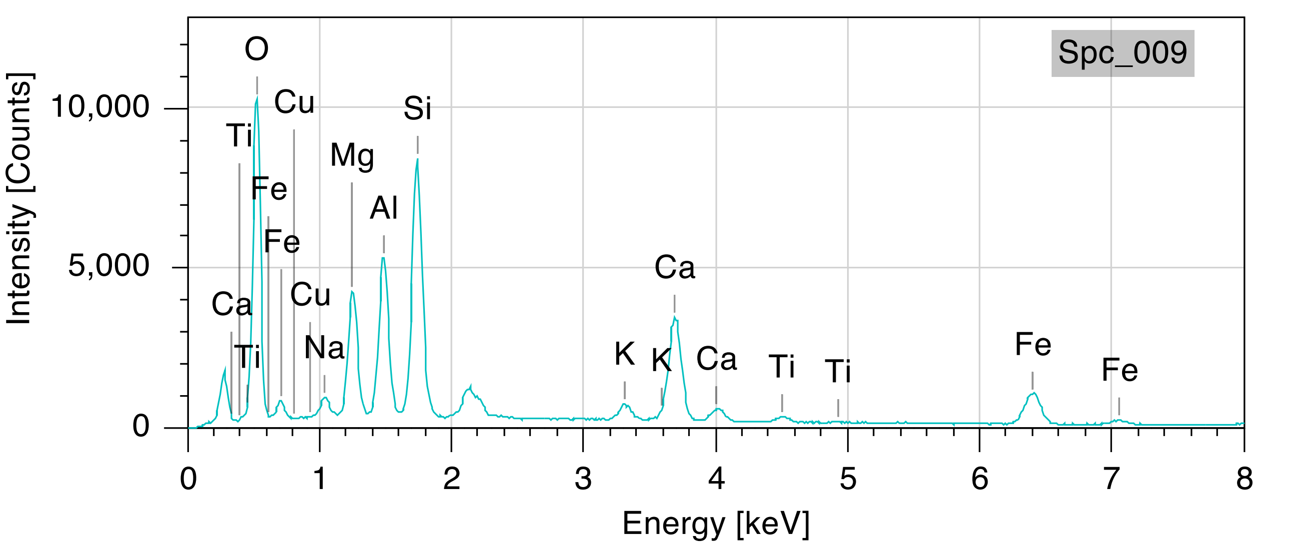


Component	Wt. [%]
volcanic tuff	32.47
basalt flour	32.47
olivin	0.65
oxide mixture	34.42

Mixture VIII

Chemical Formula	Line	Mass%	Mol%	Cations
O	K			
Na_2O	K	1.74±0.06	1.77±0.06	0.56
MgO	K	10.66±0.13	16.65±0.20	2.62
Al_2O_3	K	15.31±0.16	9.45±0.10	2.98
SiO_2	K	30.59±0.25	32.05±0.26	5.05
K_2O	K	1.82±0.06	1.22±0.04	0.38
CaO	K	17.43±0.19	19.57±0.21	3.08
TiO_2	K	1.74±0.08	1.37±0.07	0.22
FeO	K	17.90±0.30	15.69±0.26	2.47
CuO	K	2.81±0.19	2.23±0.15	0.35
Total		100.00	100.00	

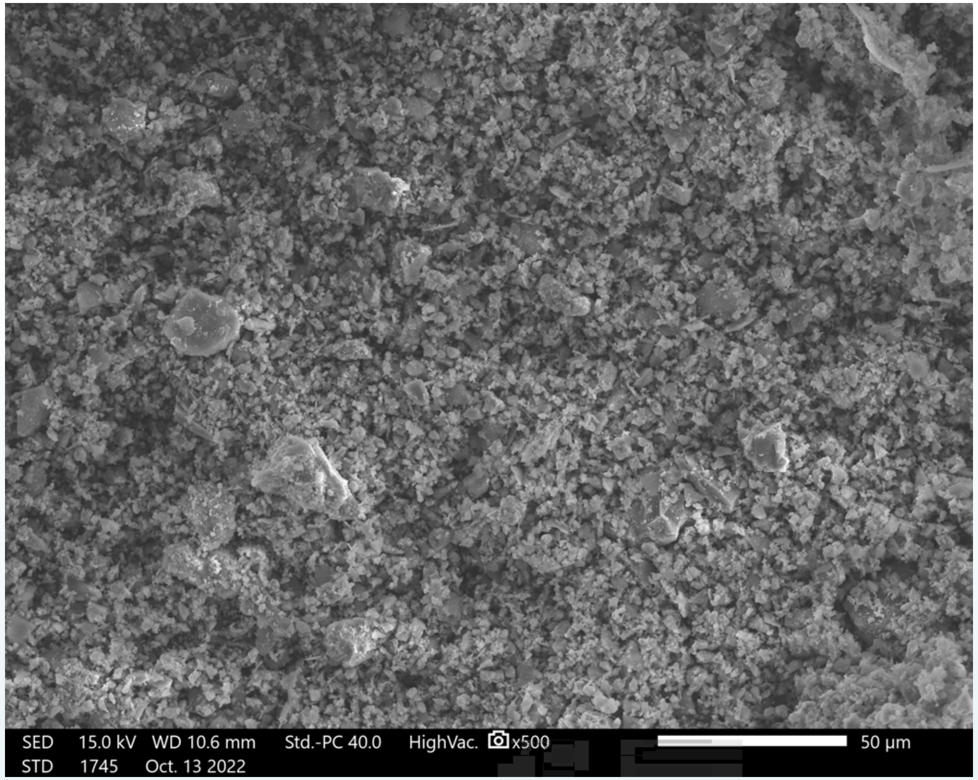


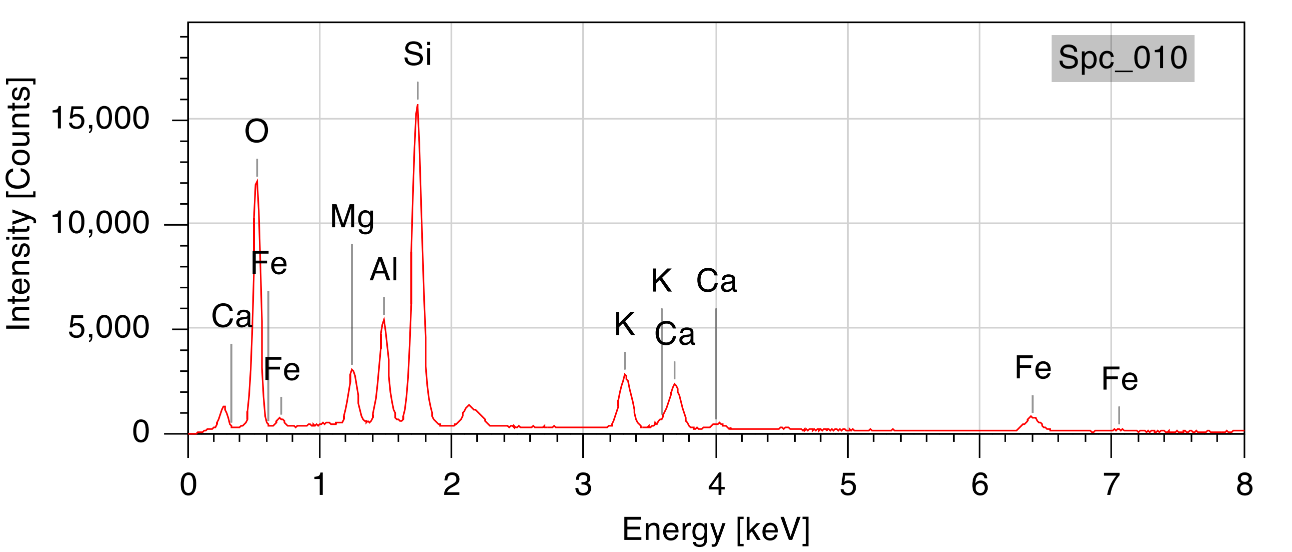


Component	Wt. [%]
fly ash	32.47
basalt flour	32.47
olivin	0.65
oxide mixture	34.42

Mixture IX

Chemical formula	Line	Mass%	Mol%	Cations
O	K			
MgO	K	5.99±0.09	9.56±0.14	1.35
Al_2O_3	K	12.62±0.14	7.96±0.09	2.25
SiO_2	K	50.64±0.30	54.24±0.32	7.65
K_2O	K	9.23±0.11	6.31±0.08	1.78
CaO	K	10.52±0.14	12.07±0.16	1.70
FeO	K	11.00±0.23	9.85±0.21	1.39
Total		100.00	100.00	

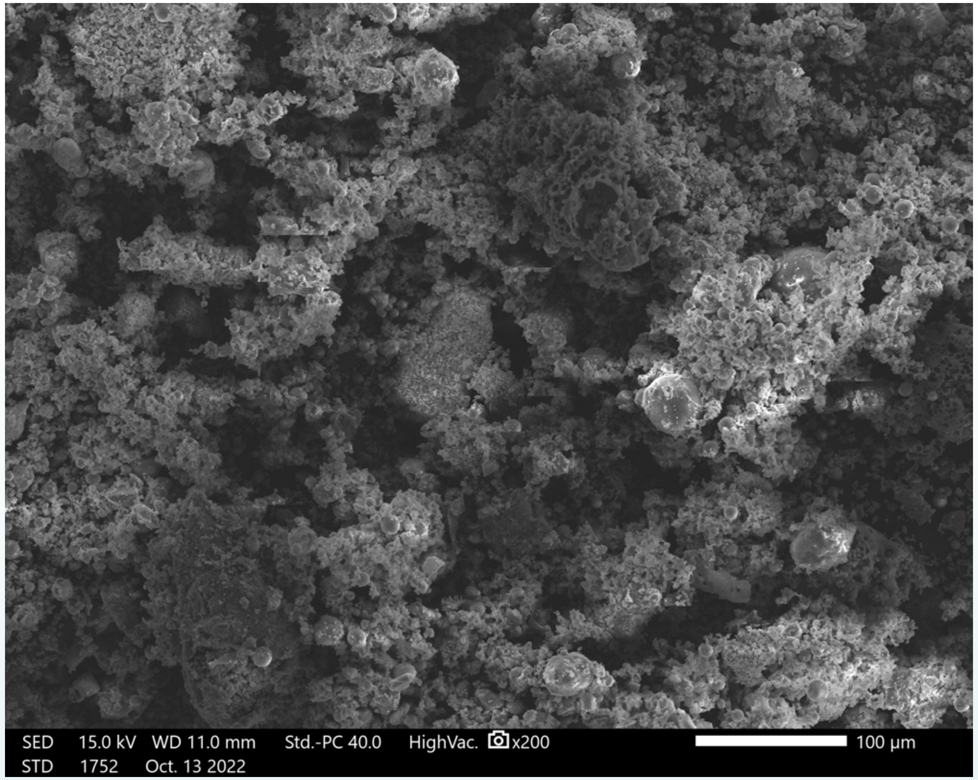


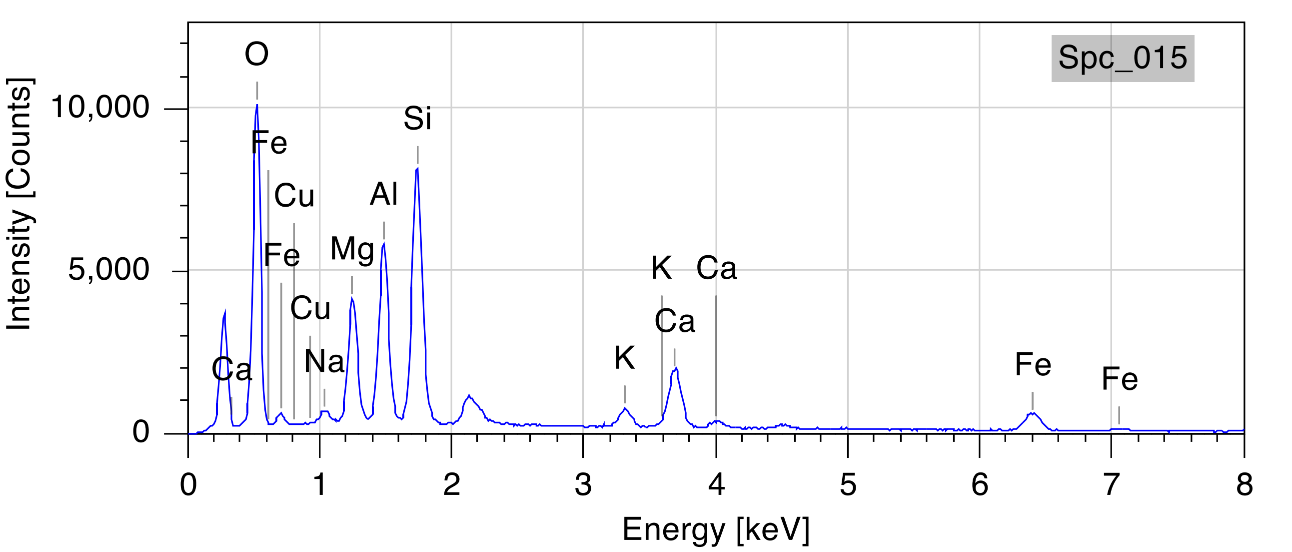


Component	Wt. [%]
volcanic tuff	64.94
olivin	0.65
oxide mixture	34.42

Mixture X

Chemical formula	Line	Mass%	Mol%	Cations
O	K			
Na_2O	K	1.19±0.05	1.22±0.05	0.36
MgO	K	12.00±0.15	18.86±0.23	2.76
Al_2O_3	K	20.14±0.20	12.52±0.13	3.66
SiO_2	K	36.95±0.30	38.99±0.32	5.70
K_2O	K	2.57±0.07	1.73±0.05	0.51
CaO	K	12.06±0.17	13.64±0.20	2.00
FeO	K	11.95±0.28	10.54±0.24	1.54
CuO	K	3.13±0.22	2.50±0.18	0.37
Total		100.00	100.00	





Component	Wt. [%]
fly ash	64.94
olivin	0.65
oxide mixture	34.42

Best composition

- The design, production and testing of lunar soil simulants are an important step on the way to solving both scientific, technical and engineering problems that are barriers to the development of space missions.

- It should be emphasized that it is not possible to produce lunar regolith simulants that perfectly reflect the composition and properties of materials found on the lunar surfaces.

- The closest composition to the lunar regolith was obtained for mix numbers VII and VIII based on:
- **volcanic tuff (mix VII) / fly ash (mix VIII),**
- **basalt flour,**
- **olivin,**
- **oxide mixture.**

Further investigation

The next stage of the research will be an attempt to use the prepared lunar regolith simulants in 3D printing technology with use alkaline solution.

It is also necessary to carry out:

- mechanical properties tests,
- microstructure observation,
- computed tomography studies to check the integrity of 3D printed layers and porosity,
- tests to simulate the effect of environmental conditions on the material using a climate chamber, where the obtained samples were subjected to temperatures in the range of -40°C to +120°C, and then carry out strength properties tests.

Small-Scale concrete 3D printer.

Faculty of Materials Engineering and Physics

Cracow University of Technology

Acknowledgment

NARODOWE CENTRUM NAUKI

MINIATURA

This work was supported by the Polish National Science Centre research project under the title: "Development of lunar regolith simulant for 3D printing in Binder Jetting technology",

no. DEC-2021/05/X/ST5/00903.

The works presented were carried out as part of the project: "Geopolymer foams with low thermal conductivity produced on the basis of industrial waste as an innovative material for the circular economy", which is financed by the National Center for Research and Development under the LIDER X program.

No.: LIDER/31/0168/L-10/18/NCBR/2019.

NCBR Narodowe Centrum Badań i Rozwoju

LIDER

The theoretical part of the presentation developed based on the article:

Korniejenko, K.; Pławecka, K.; Kozub, B.
An Overview for Modern Energy-Efficient Solutions for Lunar and Martian Habitats Made Based on Geopolymers Composites and 3D Printing Technology. *Energies* **2022**, *15*, 9322. https://doi.org/10.3390/en15249322

Thank you
for
your attention