

Materials Possible for Lunar and Martian Habitats

Subjects: [Materials Science](#), [Composites](#)

Contributor: Kinga Korniejenko , Kinga Pławecka , Barbara Kozub

Space missions will require the capability to build structures on site using local resources. Before 2040, NASA and the European Space Agency want to ensure the possibility of a permanent human residence in shelters on the Moon or Mars. Herein, innovative and energy efficient solutions for manufacturing lunar and Martian shelters based on geopolymer composites are shown.

geopolymer

energy efficiency

lunar habitat

Martian habitat

1. Introduction

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 so-called habitats on the Moon or Mars before 2040 ^[1] ^[2]. The first manned mission after Apollo 17, Artemis III, is scheduled to take place by 2024 to help implement sustainable lunar exploration ^[3]. Human in-space missions (the Moon, Mars, etc.) will require the capability to build structures on site using the local (planet) resources as a potentially more energy-efficient and economically viable alternative to transporting all materials needed for the construction of an outpost from Earth (The Space Launch System, NASA's new heavy-lift vehicle, delivering more than 25 tons of cargo to the moon is estimated to cost more than USD 2 billion to launch ^[4]). Nowadays, one of the most promising materials for that purpose are geopolymer composites ^[5].

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 ^[6]^[7] 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 to 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%); and good adherence to such materials as concrete, steel, glass, ceramics, the effectiveness of the manufacturing process, and environmental benefits (low CO₂ emission and energy efficiency during the production process).

2. Materials Possible to Usage 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. Human in-space missions (the Moon, Mars, etc.) will require the capability to build structures on site using local (planet) resources (so-called INRU) as a potentially more economically viable alternative to transporting all materials needed for the construction of an outpost from Earth ^[8]. The cost of transportation of 1 kg of material to the Moon is more than EUR 20,000 ^[9]^[10]. Transportation to other planets is even more expensive, and when scaling to account for the

infrastructure needed to sustain a lunar or Martian presence the cost becomes 'astronomical', not to mention the space required when packing the shuttle [\[11\]\[12\]](#).

The main challenge in building on the Moon or Mars is the different conditions than in the case of Earth. There are limitations with the use of traditional terrestrial methods used for construction [\[11\]\[13\]](#). The basic differences are: the lack of atmosphere that results in pressures near vacuum, low gravity (the Moon at about 1.6 m/s² and Mars at 3.721 m/s², 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 cycling (the Moon from -173 °C to +117 °C and Mars from -140 °C to +21 °C), higher seismic activity for both planets than for Earth, and micrometeoroids [\[7\]\[11\]\[13\]\[14\]](#). The potential building materials should match these difficult conditions.

In order to explore extraterrestrial bodies, it will be necessary to develop a cement-like binder. However, the phenomenon of cement solidification in a microgravity (μg) environment is not yet well understood. Several years ago, as part of the Microgravity Investigation of Cement Solidification (MICS) project on the International Space Station (ISS), scientists conducted research on cement solidification in microgravity. During this research, for the first time in space, scientists mixed tricalcium silicate (C₃S) with water, and then made comparisons between cement samples processed on the ground and in microgravity. In their work, the researchers hypothesized that the minimization of transport phenomena (i.e., buoyancy, sedimentation, and thermosolutal convection) caused by gravity would ensure diffusion-controlled crystal growth, resulting in unique microstructures. As a result of their research, the scientists showed that the main differences in μg of hydrated C₃S paste included reduced aspect ratio of portlandite crystals and increased porosity [\[15\]](#).

Currently, several attempts have been made to construct a technical infrastructure for this kind of facility, especially in the context of lunar shelters [\[8\]\[14\]\[16\]](#). These 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 and alkali-activated regolith or 'geopolymer' type binders—**Table 1**.

Table 1. Types of material possible to use for lunar and Martian shelters.

Material	Advantages	Disadvantages	Source of Information
1 Traditional OPC-based concrete with lunar regolith as aggregate	<ul style="list-style-type: none"> - Well-known technology under Earth conditions. - Good protection against solar wind, radiation, and micrometeorites. 	<ul style="list-style-type: none"> - Chemical and mineral characteristic are not consistent with lunar and Mars regolith, especially lack of calcium. - The water for the production process is required in a huge amount, which is a significant problem, especially in the context of lunar applications. 	[11]
2 Sulfur concrete	<ul style="list-style-type: none"> - Sulfur can be found on the lunar surface in the form of 	<ul style="list-style-type: none"> - The concrete composition (approximately 20% sulfur and 80% 	[11][17][18][19]

Material	Advantages	Disadvantages	Source of Information
	<p>the mineral troilite (FeS). It can be extracted from lunar regolith by heating.</p> <ul style="list-style-type: none"> - To produce sulfur "concrete", water is not required. - Sulfur is abundant on the Martian surface. 	<p>aggregate) has to be prepared and heated between 130–140 °C.</p> <ul style="list-style-type: none"> - The compression strength of sulfur concrete suffers significantly from temperature cycling. On average, it loses 80% of its strength due to cracking. - Producing sulfur concrete would require a power source to bake sulfur out of the lunar soil and melt the concrete mixture, which requires an uncertain amount of energy and equipment. - The material has radiation shielding properties worse than that of plain regolith simulant. - It requires a large amount of consumables and sulfur is not abundant on the lunar surface. 	
<p>3 Sintered basalt/regolith</p>	<ul style="list-style-type: none"> - Microwave or solar power could be used to create the heat necessary to sinter the regolith in bricks or other building elements. - Sintered fine regolith is characterized by good thermal insulation, including the possibility of thermal and dust control and micrometeorite protection. 	<ul style="list-style-type: none"> - Sintered fine regolith has low density, is brittle, has very low resistance to tensile stresses, and the material typically shrinks considerably. - Due to the low density of the material, it would require substantial thicknesses to be used as radiation protection for human habitation. - Low-stress resistance might be an issue for its use for the construction of protective walls or shells for habitats on the surface. 	<p>[20][21]</p>

Material	Advantages	Disadvantages	Source of Information	
4	Magnesium chloride-based binder (Sorel cement)—33% magnesium chloride and 66% water	<ul style="list-style-type: none"> - Solution tested by ESA. - It is a very fast-setting technology with high early compressive strength is around 70 MPa after a few hours. - Technology tested in terrestrial environment shows good results at ambient temperatures. The materials have a better compressive strength (69–83 MPa) than Portland cement (45–55 MPa). 	<ul style="list-style-type: none"> - Due to the low density (about 1.7 t/m³) and high porosity the minimum thickness, 1500 mm is required for extraterrestrial application to protect human habitation against radiation. - For the binder manufacturing in this process, it is necessary a substantial amount of consumables, including chemicals and water. The magnesium-chloride cement requires a huge amount of water in the binder (30%), which must be delivered from Earth. Even if the construction will be optimized, as for example a honeycomb, supplying previously mentioned materials will be expensive. 	[22]
5	Phosphate-based binder	<ul style="list-style-type: none"> - Phosphate-based binders are considered a promising material for use on the Martian surface because of availability in phosphoric acid and water in Martial soil. 	<ul style="list-style-type: none"> - To create adequate strengths of the ratio of the acid-to-regolith in the resulting material would have minimum 0.6:1 by weight, which requires a significant amount of materials (water and phosphoric acid). - Gaining the basic feedstocks, including water, that could be required for additional technologies for Martian applications or it could be transported from Earth for lunar applications. 	[19]
6	Epoxy/polymer-based cement	<ul style="list-style-type: none"> - Possibility of producing relatively light structures. 	<ul style="list-style-type: none"> - Epoxy/polymer-based systems that require additional terrestrial resources to produce the bulk of the binder. 	[11]

Concrete-like materials have the highest potential for use in extra-terrestrial construction due to their inherent mechanical properties, resilience, and durability. Therefore, construction materials that use little of those resources, such as geopolymers, while providing sufficient protection against the harsh lunar environment are of interest. Geopolymer

cement should provide better radiation protection levels and stability and require significantly less resources in the production process than traditional concrete and other materials presented above [\[11\]\[23\]\[24\]](#). Moreover, previous works showed that a shielding thickness of 50 cm (99 g/cm²) 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—5 cSv, 5 rem [\[25\]\[26\]](#). 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 concrete-like materials [\[11\]\[23\]\[24\]\[27\]](#):

- 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 [\[23\]](#), 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.
- 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 [\[24\]\[28\]](#). Using in situ resource utilization (ISRU) technology allows one to limit the cost of construction [\[29\]](#).
- The presence of alkali metals on the moon might be used as a source of the alkaline solution for geopolymerization [\[24\]](#). 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 [\[23\]](#).

It is also worth noticing that the geopolymerization process should be planned by two different methods using alkali and phosphatic acids. The alkali substances are available on the Moon [\[24\]](#), whereas phosphoric acid and water are available on Mars [\[23\]\[28\]](#).

3. Raw Materials Used for Manufacturing Lunar and Martian Habitats

It is rather obvious that it is impossible to have access to the proper amount of materials to prepare samples and building elements from the testing lunar and Martian constructions. Because of that, the preparation of the lunar and Martian regolith simulant is an important part of each piece of research [\[1\]](#). The preparation of the simulant is not a trivial task, due not only to the possible changes in the material in different areas of the moon or Mars and limited access to this data but also because a large number of features have to be considered in this characteristic [\[10\]\[30\]](#). The most important are: chemical and mineralogical composition (**Table 2**), physical properties, mechanical properties, and morphology. However,

there is a possibility to find simulants ready for lunar and Martian soil, but they do not always fulfill all requirements and have a very high price. Because of that, many authors decided to design their own compositions [1].

Table 2. Comparison of chemical and mineralogical composition for the most popular simulants for lunar and Martian regolith.

Oxides (%wt)	DNA-1	JSC-1A (2015)	JSC-1A (2010)	Martian Soil Pathfinder	Martian Soil Simulant JSC Mars-1
Unit	(wt%)	(wt%)	(wt%)	(wt%)	(wt%)
SiO ₂	41.90	42.95	45.70	42.00	43.48
TiO ₂	1.31	1.57	1.90	0.80	3.62
Al ₂ O ₃	16.02	14.53	16.20	10.30	22.09
Fe ₂ O ₃	14.60	11.50	12.40	21.70	16.08
FeO	0.00	7.52	0.00	0.00	0.00
MgO	6.34	8.64	8.70	7.30	4.22
CaO	12.90	9.11	10.0	6.10	6.05
Na ₂ O	2.66	2.60	3.20	2.80	2.34
K ₂ O	2.53	0.71	0.71	0.60	0.70
P ₂ O ₅	0.00	0.65	0.65	0.70	0.78
MnO	0.00	0.17	0.17	0.30	0.26
Source	[31]	[25]	[32]	[33]	[33]

To achieve the proper composition, researchers present different approaches. The most popular is using the ready base, such as fly ash or volcanic tuff or other raw materials, and supplementing it with proper metal oxides [28][30][34]. Currently, the main problem with the chemical composition of regolith simulants is iron. For example, in JSC-1A the total iron content is reported as being made up of 76% Fe₂O₃ (i.e., 9.8% of the total JSC-1A mass); however, in practice, on the extraterrestrial system post this element is expected to be in the form of FeO (the iron on the moon surface is considered to be at the lower oxidation state, since oxidation takes place in the presence of moisture and oxygen, both being scarce on the moon) [8][35].

It is worth noting that some previous investigations show that a small amount of additives can significantly improve material properties, for example, supplementing the simulant with aluminum sources could improve compressive strength by 100.8% and reduce alkali content, resulting in significantly reducing the mass of materials transported from the earth for the construction of lunar infrastructure and saving space transportation costs [7][30].

A second important element is the mineralogical composition. The major components of lunar regolith are glasses; fragments of rocks and minerals, mainly consisting of silicates, such as olivine, pyroxene, and plagioclase; and non-

silicates, such as ilmenite [32][36][37]. This composition is also quite similar to many terrestrial volcanic ashes [38][39]. The expected minerals in the planned composition are plagioclase and pyroxene and a small amount of ilmenite and olivine. The other research suggests that the following minerals could also appear in regolith simulants: anorthite, albite, enstatite, feldspar potassian, alkali basalt, orthopyroxene, orthoclase, wollastonite, estatite, ferrosilite magnesian, fayalite, titanomagnetite, and forsterite [25][38][39]. In the case of the Martian regolith, the olivine and pyroxene and secondary alteration minerals are mainly expected [33]. Moreover, a certain amount of plagioclase and minor Ti magnetite, Carich pyroxene, olivine, glassy, and ferric oxide particles can be present [33].

The physical composition of materials will include properties, such as density, particle size, and particle size distribution. This distribution is not always relevant in commercially available simulants to previous research of lunar and Martian soils. The analysis of samples that came from the moon shows that the particle size distribution generally follows the log-normal curve with mean values in the range of 45–100 μm [40]. The 'Dust' fraction of lunar regolith includes particles smaller than 10 μm , of which approximately 90% (by weight) are particles smaller than 1 μm , although some particles can even be as small as 10 nm [40][41]. Particles with dimensions larger than 0.25 mm (250 μm) constitute only 10% (by weight) of a regolith. Meanwhile, lunar regolith simulant—JSC-1A—is a basaltic powder, JSC-1A has particles <1 mm and ranges in sizes from approximately 10 to 50 μm [42].

The next important issue is the particle's morphology. The lunar and Martian regolith contains morphological forms that do not exist on Earth; these are spherical lunar chondrules (with dimensions from a few microns to 0.5 mm) formed as a result of meteorite falls and the sudden melting of lunar rocks. The particles are predominantly angular with smooth facets [1][41]. The fragmentation of the lunar regolith is the result of mechanical impacts but also thermal stress caused by high daily temperature differences and erosion caused, among others, by ionizing radiation of the solar wind and galactic cosmic radiation [1][43]. Meanwhile, the commercially available regolith simulants have sharp shapes because they are received by crushing and milling [1]. The granulometric composition of most simulants differs from that of the lunar regolith. They mainly correspond to coarser fractions, since obtaining very fine particles is associated with difficult and expensive technology [1].

The design of the regolith and other features should be taken into consideration. One of them is adhesion. There is proof that lunar regolith is characterized by very strong adhesion to various surfaces. This is a negative property in the context of functioning on the surface of the Moon and can cause (together with combination with the high abrasiveness) damages to machinery mechanisms and research equipment, including optics. However, in the context of adhesion of the binder to aggregate in cementitious materials, this feature seems to be very important and desirable [1]. Another important element to design a regolith's simulant is a method of production that could have a significant influence on the material's properties [44][45][46].

Another challenge is to find more effective technologies for production in extraterrestrial conditions. Some investigations show the possibility of obtaining oxygen by reduction techniques from the regolith [47]. The by-product of this process could be used as a raw material for shelters; however, it has been not taken into account in the current investigation, nor has composition for the regolith's simulants.

References

1. Sokołowska, J.J.; Woyciechowski, P.; Kalinowski, M. Rheological Properties of Lunar Mortars. *Appl. Sci.* 2021, 11, 6961.
2. Spedding, C.P.; Lim, S.; Nuttall, W.J. ISRU technology deployment at a lunar outpost in 2040: A Delphi survey. *Acta Astronaut.* 2021, 181, 316–324.
3. NASA ARTEMIS. Available online: <https://www.nasa.gov/specials/artemis/> (accessed on 17 September 2022).
4. Berger, E. The White House Puts a Price on the SLS Rocket—And It's a Lot Again, Congress Is Urged to Allow a Commercial Launch of the Europa Clipper. *Arstechnica*. 6 November 2019. Available online: https://www.lpi.usra.edu/publications/books/lunar_bases/LSBchapter02.pdf#pagemode=bookmarks&page=15 (accessed on 17 September 2022).
5. Ma, S.; Fu, S.; Wang, O.; Xu, L.; He, P.; Sun, C.; Duan, X.; Zhang, Z.; Jia, D.; Zhou, Y. 3D Printing of Damage-tolerant Martian Regolith Simulant-based Geopolymer Composites. *Addit. Manuf.* 2022, 58, 103025.
6. Korniejenko, K.; Łach, M.; Hebdowska-Krupa, M.; Mikula, J. Impact of flax fiber reinforcement on mechanical properties of solid and foamed geopolymer concrete. *Adv. Technol. Innov.* 2021, 6, 11–20.
7. Xiong, G.; Guo, X.; Yuan, S.; Xia, M.; Wang, Z. The mechanical and structural properties of lunar regolith simulant based geopolymer under extreme temperature environment on the moon through experimental and simulation methods. *Constr. Build. Mater.* 2022, 325, 126679.
8. Ferrone, K.L.; Taylor, A.B.; Helvajian, H. In situ resource utilization of structural material from planetary regolith. *Adv. Space Res.* 2022, 69, 2268–2282.
9. Zhang, R.; Zhou, S.; Li, F.; Bi, T.; Zhu, X. Mechanical and Microstructural Characterization of Carbon Nanofiber–Reinforced Geopolymer Nanocomposite Based on Lunar Regolith Simulant. *J. Mater. Civ. Eng.* 2022, 34, 04021387.
10. Zhang, R.; Zhou, S.; Li, F. Preparation of geopolymer based on lunar regolith simulant at in-situ lunar temperature and its durability under lunar high and cryogenic temperature. *Constr. Build. Mater.* 2022, 318, 126033.
11. Mills, J.N.; Katarova, M.; Wagner, N.J. Comparison of lunar and Martian regolith simulant-based geopolymer cements formed by alkali-activation for in-situ resource utilization. *Adv. Space Res.* 2022, 69, 761–777.
12. Taylor, L.A.; Pieters, C.M.; Britt, D. Evaluations of lunar regolith simulants. *Planet. Space Sci.* 2016, 126, 1–7.
13. Hu, Z.; Shi, T.; Cen, M.; Wang, J.; Zhao, X.; Zeng, C.; Zhou, Y.; Fan, Y.; Liu, Y.; Zhao, Z. Research progress on lunar and Martian concrete. *Constr. Build. Mater.* 2022, 343, 128117.

14. Lee, S.; van Riessen, A. A Review on Geopolymer Technology for Lunar Base Construction. *Materials* 2022, 15, 4516.
15. Neves, J.M.; Collins, P.J.; Wilkerson, R.P.; Grugel, R.N.; Radlińska, A. Microgravity Effect on Microstructural Development of Tri-calcium Silicate (C3S) Paste. *Front. Mater.* 2019, 6, 83.
16. Collins, P.J.; Edmunson, J.; Fiske, M.; Radlińska, A. Materials characterization of various lunar regolith simulants for use in geopolymer lunar concrete. *Adv. Space Res.* 2022, 69, 3941–3951.
17. Grugel, R.N.; Toutanji, H.A. Sulfur “concrete” for lunar applications—Sublimation concerns. *Adv. Space Res.* 2008, 41, 103–112.
18. Toutanji, H.A.; Evans, S.; Grugel, R.N. Performance of lunar sulfur concrete in lunar environments. *Construct. Build. Mater.* 2012, 29, 444–448.
19. Buchner, C.; Pawelke, R.H.; Schlauf, T.; Reissner, A.; Makaya, A. A new planetary structure fabrication process using phosphoric acid. *Acta Astronaut.* 2018, 143, 272–284.
20. Cowley, A.; Haefner, T.; Beltzung, J.C.; Meurisse, A. Spaceship EAC—Fostering Activities Relevant to Lunar Exploration and ISRU. In *Proceedings of the Annual Meeting of the Lunar Exploration Analysis Group*, Columbia, MD, USA, 20–22 October 2015; p. 2037.
21. Meurisse, A.; Makaya, A.; Wilsch, C.; Sperl, M. Solar 3D printing of Lunar Regolith. *Acta Astronaut.* 2018, 152, 800–810.
22. Cesaretti, G.; Dini, E.; De Kestelier, X.; Colla, V.; Pambaguian, L. Building components for an outpost on the Lunar soil by means of a novel 3D printing technology. *Acta Astronaut.* 2014, 93, 430–450.
23. Wang, Y.S.; Dai, J.-G.; Ding, Z.; Xu, W.T. Phosphate-based geopolymer: Formation mechanism and thermal stability. *Mater. Lett.* 2017, 190, 209–212.
24. Matta, M.; Smith, S.; Baumgardner, J.; Wilson, J.; Martinis, C.; Mendillo, M. The sodium tail of the Moon. *Icarus* 2009, 204, 409–417.
25. Montes, C.; Broussard, K.; Gongre, M.; Simicevic, N.; Mejia, J.; Tham, J.; Allouche, E.; Davis, G. Evaluation of lunar regolith geopolymer binder as a radioactive shielding material for space exploration applications. *Adv. Space Res.* 2015, 56, 1212–1221.
26. Davis, G.; Montes, C.; Eklund, S. Preparation of lunar regolith based geopolymer cement under heat and vacuum. *Adv. Space Res.* 2017, 59, 1872–1885.
27. Amin, M.; Zeyad, A.M.; Tayeh, B.A.; Agwa, S.A. Effect of high temperatures on mechanical, radiation attenuation and microstructure properties of heavyweight geopolymer concrete. *Struct. Eng. Mech.* 2021, 80, 181–199.
28. Pilehvar, S.; Arnhof, M.; Pamies, R.; Valentini, L.; Kjøniksen, A.L. Utilization of urea as an accessible superplasticizer on the moon for lunar geopolymer mixtures. *J. Clean. Prod.* 2020, 247, 119177.
29. Pilehvar, S.; Arnhof, M.; Erichsen, A.; Valentini, L.; Kjøniksen, A.L. Investigation of severe lunar environmental conditions on the physical and mechanical properties of lunar regolith geopolymers. *J.*

- Mater. Res. Technol. 2021, 11, 1506–1516.
30. Zhou, S.; Lu, C.; Zhu, X.; Li, F. Preparation and characterization of high-strength geopolymer based on BH-1 lunar soil simulant with low alkali content. *Engineering* 2021, 7, 1631–1645.
 31. Haskin, L.A.; Warren, P.H. Lunar Chemistry. In *Lunar Sourcebook*; Heiken, G.H., Vaniman, D.T., French, B.M., Eds.; Cambridge University Press: New York, NY, USA, 1991; pp. 367–474.
 32. Ray, C.S.; Reis, S.T.; Sen, S.; O'Dell, J.S. JSC-1A lunar soil simulant: Characterization, glass formation, and selected glass properties. *J. Non. Cryst. Solids* 2010, 356, 2369–2374.
 33. Zeng, X.; Li, X.; Wang, S.; Li, S.; Spring, N.; Tang, H.; Li, Y.; Feng, J. JMSS-1: A new martian soil simulant. *Earth Planets Space* 2015, 67, 72.
 34. Toklu, Y.C.; Akpınar, P. Lunar soils, simulants and lunar construction materials: An overview. *Adv. Space Res.* 2022, 70, 762–779.
 35. Peys, A.; Douvalis, A.P.; Hallet, V.; Rahier, H.; Blanpain, B.; Pontikes, Y. Inorganic Polymers From CaO-FeOx-SiO₂ Slag: The Start of Oxidation of Fe and the Formation of a Mixed Valence Binder. *Front. Mater.* 2019, 6, 212.
 36. Alexiadis, A.; Alberini, F.; Meyer, M.E. Geopolymers from lunar and Martian soil simulants. *Adv. Space Res.* 2017, 59, 490–495.
 37. Ma, Q.; Wang, H. Analysis of the Direct Shear Test and Microstructure of the Lunar Soil Simulant Solidified by Sodium Silicate. *Adv. Mater. Sci. Eng.* 2022, 2022, 7654781.
 38. Lemougna, P.N.; Wang, K.T.; Tang, Q.; Nzeukou, A.N.; Billong Melo, U.C.; Cui, X.M. Review on the use of volcanic ashes for engineering applications. *Resour. Conserv. Recycl.* 2018, 137, 177–190.
 39. Farries, K.W.; Visintin, P.; Smith, S.T.; van Eyk, P. Sintered or melted regolith for lunar construction: State-of-the-art review and future research directions. *Constr. Build. Mater.* 2021, 296, 123627.
 40. Greenberg, P.S.; Chen, D.; Smith, S.A. Aerosol Measurements of the Fine and Ultrafine Particle Content of Lunar Regolith; NASA/TM—2007-214956; National Aeronautics and Space Administration, Glenn Research Center: Cleveland, OH, USA, 2007.
 41. Naser, M.Z. Extraterrestrial construction materials. *Prog. Mater. Sci.* 2019, 105, 100577.
 42. Neves, J.M.; Ramanathan, S.; Suraneni, P.; Grugel, R.; Radlińska, A. Characterization, mechanical properties, and microstructural development of lunar regolith simulant-portland cement blended mixtures. *Constr. Build. Mater.* 2020, 258, 120315.
 43. Wilson, J.W.; Kim, M.; Schimmerling, W.; Badavi, F.F.; Thibeault, S.A.; Cucinotta, F.A. Issues in space radiation protection: Galactic cosmic rays. *Health Phys.* 1995, 68, 50–58.
 44. Gualtieri, T.; Bandyopadhyay, A. Compressive deformation of porous lunar regolith. *Mater. Lett.* 2015, 143, 276–278.
 45. Lim, S.; Reeve, S.; Lekuona, E.; Garbayo, A.; Le Toux, T.; Morse, A.; Bowen, J.; Anand, M. Challenges in the microwave heating of lunar regolith—Analysis through the design of a microwave heating

Demonstrator (MHD) payload. *Adv. Space Res.* 2022, 69, 751–760.

46. Liao, H.; Zhu, J.; Chang, S.; Xue, G.; Pang, J.; Zhu, H. Lunar regolith—AlSi10Mg composite fabricated by selective laser melting. *Vacuum* 2021, 187, 110122.

47. Rasera, J.N.; Cilliers, J.J.; Lamamy, J.A.; Hadler, K. The beneficiation of lunar regolith for space resource utilisation: A review. *Planet. Space Sci.* 2020, 186, 104879.

Retrieved from <https://encyclopedia.pub/entry/history/show/88834>