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Development of lunar regolith-based geopolymer concrete for lunar base construction

Background: In situ resource utilization is a key priority for the future of lunar exploration. One of the most promising resources is lunar regolith, which is rich in its aluminum and silicon oxide composition, making it suitable for use as a precursor for geopolymer cement. This cement can be employed as a construction material, particularly through 3D printing.
Objective: This paper aims to contribute to the development of an optimized method for producing lunar regolith based geopolymer concrete specifically for lunar base construction using 3D printing, by building on insights from existing research and/or conducting an MD simulation focusing on the effect of a [particular lunar environmental condition] on a [specific property] of lunar regolith-based geopolymer.

How are geopolymers created?

A geopolymer is an amorphous, semi-crystalline cementitious material produced by the polymerization reaction of an aluminosilicate source with an alkaline reagent [1].

Geopolymerization is a fundamental chemical reaction between an aluminosilicate source, often fly ash, metakaolin, or slag, and an alkaline activator, which typically consists of sodium hydroxide and sodium silicate or potassium hydroxide and potassium silicate. Most waste products contain silicon dioxide, which is then mixed with an alkaline activator like sodium hydroxide or potassium hydroxide and sodium silicate or potassium silicate. The silicon-oxygen-silicon bonds break down, allowing aluminum atoms to penetrate and form aluminosilicate gels. With the addition of more alkali, these gels harden into geopolymer cement. This cement is then mixed with aggregate and **water** to form geopolymer concrete (GPC). However, it has recently been found that lunar regolith enables the synthesis of cement materials with minimal to zero water consumption, or if used, mixing water used can be recycled [2], moreover, various additives, such as urea, can reduce the amount of water required to achieve workability [3], [4], [5].

GPC is a promising type of concrete that can be used in place of ordinary portland concrete (OPC) for its superior qualities. GPC for lunar base construction is mostly studied in the context of 3D printing and sintering [6]. However, 3D printing offers a faster alternative to sintering and eliminates the need for molds [7].

Can lunar regolith serve as a precursor for geopolymer binders in construction applications?

Table 2. Composition (wt. %) of lunar soil samples obtained by Apollo missions.

No.	SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	Mission
1	42.1	7.8	13.7	15.8	0.2	7.9	12	0.5	0.1	0.1	11
2	42.2	7.8	13.6	15.3	0.2	7.8	11.9	0.47	0.16	0.05	11
3	42.6	3.6	14.2	15.4	0.22	9.7	10.4	0.43	0.24	-	12
4	46	2.8	12.5	17.2	0.22	9.7	10.9	0.48	0.24	-	12
5	48.2	1.73	17.6	10.41	0.14	9.26	11.25	0.61	0.51	0.53	14
6	47.3	1.6	17.8	10.5	0.1	9.6	11.4	0.7	0.6	-	14
7	48.1	1.7	17.4	10.4	0.14	9.4	10.7	0.7	0.55	0.51	14
8	46.95	1.6	12.7	16.29	0.217	10.75	10.49	0.33	0.092	0.16	15
9	45.35	0.49	28.25	4.55	0.06	5.02	16.21	0.42	0.09	0.1	16
10	45.2	0.58	26.4	5.29	0.7	6.1	15.32	0.52	0.14	0.12	16
11	44.65	0.56	27	5.49	0.7	5.84	15.95	0.44	0.13	0.1	16
12	44.9	0.47	27.7	5.01	-	5.69	15.7	0.51	0.22	0.16	16
13	44.77	0.37	28.99	4.35	0.07	4.2	16.85	0.44	0.06	0.05	16
14	45	0.54	27.3	5.1	0.3	5.7	15.7	0.46	0.17	0.11	16
15	41.67	6.52	13.57	15.37	0.21	10.22	11.18	0.34	0.09	0.06	17
16	39.82	9.52	11.13	17.41	0.25	9.51	10.85	0.32	0.07	0.06	17
17	40.09	9.32	10.7	17.85	0.24	9.92	10.59	0.36	0.08	0.07	17
18	42.2	5.09	15.7	12.4	0.15	10.3	11.5	0.24	0.07	-	17

Lunar regolith is suitable for geopolymer production due to its high aluminum and silicon oxide content in ideal ratios for binder creation [8]. A study used principal component analysis to examine the composition of lunar regolith samples received from the American Apollo and Soviet Luna missions, revealing that, on average, around 40% of the regolith is SiO_2 [9]. Terrestrial geochemists typically express the concentrations of elements such as Si in terms of their oxides because, in silicate-dominated systems, these oxides represent the primary constituents of the rock [10]. The sum of the major and minor metal oxides in a geochemical analysis is expected to approximate 100±1%. This near-total sum is a key quality check in geochemical analyses; if the total deviates significantly from this range, it often indicates a potential error in the analysis. This expectation holds particularly true for lunar samples, as the Moon is known to contain negligible amounts of carbonates, sulfates, or hydrous minerals, which could otherwise account for significant non-oxide components in the rock.

If specific research on lunar regolith simulant geopolymer is unavailable, reviewing studies on fly ash and volcanic ash geopolymers can be advantageous due to their compositional similarities [4]. However, it is essential to account for the unique properties of regolith in any comparative analysis.

Table 1
Chemical composition of DNA-1 lunar regolith simulant and fly ash class F, compared to the composition of lunar regolith samples (the highest and lowest values of each component from 19 analyzed lunar samples is shown).

Chemical	Lunar regolith simulant DNA-1 (wt. %)	Fly ash class F (wt. %)	Lunar regolith soil samples range (wt. %) (McKay et al., 1991)
SiO_2	47.79 ± 0.05	50.83 ± 0.04	40.6–48.1
Al_2O_3	19.16 ± 0.07	23.15 ± 0.06	12.0–28.0
Fe_2O_3	8.75 ± 0.01	6.82 ± 0.01	4.7–19.8
CaO	8.28 ± 0.03	6.87 ± 0.02	10.3–15.8
K_2O	3.52 ± 0.02	2.14 ± 0.01	0.04–0.55
Na_2O	4.38 ± 0.03	1.29 ± 0.01	0.31–0.70
MgO	1.86 ± 0.01	1.70 ± 0.01	5.6–13.0
TiO_2	1.00 ± 0.01	1.01 ± 0.01	0.47–8.4

Environmental conditions on the Moon

Moonquakes

Deep moonquakes range from 0.5 to 1.3 in magnitude on the Richter scale, while the strongest shallow moonquakes reach 4 to 5 [11].
<u>Effect on geopolymer:</u> moonquakes do not directly damage building structures in the low-gravity environment of the Moon, but they can negatively affect the structural performance during the construction phase [12].

Radiation

In 2019, researchers determined that daily radiation on the Moon is 1,369 microsieverts, approximately 2.6 times higher than what the International Space Station crew experiences [13]. Moreover, solar particle events (SPEs) that mainly consist of low- to medium-energy protons [14] pose one of the greatest risks during space missions [15].

<u>Role of geopolymer:</u>

Simulation results indicate that the mechanical and chemical properties of Lunamer and fly-ash based geopolymer provide sufficient radiation shielding for lunar living quarters, ensuring crew safety without the need for additional protective measures [8], [16], [17].

<u>Effect on geopolymer:</u>

Existing research mostly discusses the ability of geopolymer to act as a radiation shield. Research on the effects of radiation on its properties is scarce. Most research tends to examine the cumulative effects of the lunar environment, which includes radiation but isn't isolated to it.

Vacuum

The vacuum conditions on the Moon are advantageous for preparing lunar geopolymers because the absence of carbon dioxide reduces the occurrence of efflorescence [18].

High temperature

The natural temperature conditions on the lunar surface are suitable for curing lunar regolith geopolymer without the need for additional equipment [18]. The impact of temperature on the specific properties and durability of lunar regolith-based geopolymer production is discussed in detail later in the text.

Properties of lunar regolith simulant based geopolymer

Interfacial transition zone:

The high water-to-cement ratio in traditional cement results in the formation of larger crystals, such as calcium hydroxide, ettringite, monosulfate, and calcium silicate hydrate (C-S-H), leading to a more porous and weaker interfacial transition zone (ITZ) [19], [20], [21]. This ITZ is the region between the cement paste and the aggregate [22]. In heat-cured concrete, if delayed ettringite formation (DEF) occurs, ettringite can precipitate at the paste-aggregate interface. This precipitation can cause internal expansion, creating microcracks that weaken the microstructure and lead to long-term durability issues. In contrast, researchers concluded that crystals and porosity are not significant factors affecting the ITZ in geopolymer materials. As geopolymers do not typically form new large crystals during hydration, with any existing crystals mostly originating from the raw material [23]. The potential formation of harmful large-scale crystals is inhibited due to low water content and the presence of soluble silicate.

Compressive strength

<u>Ratios</u>

To study lunar simulant polymer concrete with varying binder percentages, seven values ranging from 12% to 24% were tested. The results showed that 18% epoxy resin increases the force needed for deformation but reduces flexibility [24].

<u>*Temperature*</u>

Research has shown that temperatures of 60°C and 120°C had minimal impact on the compressive strength of lunar regolith simulant-based geopolymer, which remained above 50.0 MPa, with duration having negligible effect [25]. However, another piece of research showed that cryogenic temperatures and subsequent high-temperature exposure significantly weakened the geopolymer, with microcracks expanding and evolving into visible macrocracks, leading to further deterioration over time [26]. Thus, the relationship between temperature and the compressive strength of lunar regolith-based geopolymer has not been clearly established yet.

Rate of strength development

<u>*Ratios*</u>

The source of material and alkaline activators are the key factors influencing the rate of strength development [27]. Increasing slag content in geopolymer concrete improves strength development, including compressive strength development up to a point, but excessive slag can lead to diminished gains and cracking, highlighting the need for an optimal slag ratio.

Young's modulus

<u>*Temperature*</u>

Young's modulus is a measure of a material's stiffness or rigidity. It quantifies the relationship between tensile stress and tensile strain in the elastic (reversible) deformation region of the material. It describes how much a material will stretch or compress under a given load within its elastic limit. In the same study, simulations showed that Young's modulus decreased as the temperature increased from 25°C to 825°C, then slightly increased above 825°C [25]. This trend is consistent with previous experimental findings, where the compressive strength of geopolymer specimens decreased and then increased as the temperature rose from 300°C to 900°C .

Flowability

One study explored the combined use of steel slag (SS), ground granulated blast furnace slag (GGBS), and fly ash (FA) to enhance the mechanical properties of high-strength, high-toughness alkali-activated composites. It was found that a high proportion of GGBS (>45%) in the mix reduces flowability, but adding SS improves it. The optimal flowability (around 82%) was achieved by using 0.10-0.15 SS, 0.35-0.40 GGBS, and 0.60-0.65 FA in the mix [28]. However, this information might not be entirely relevant to lunar applications, as only fly ash closely resembles lunar regolith in terms of composition and particle size.

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