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Basalt fibre reinforced geopolymer made from lunar regolith simulant

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Abstract

In-situ resource utilization (ISRU) is a key element for increasing sustainability of extended human exploration missions to the Moon. Such missions might require the capability to build structures like radiation shields, habitat walls or shells, and infrastructure like landing pads, surface paving and dust-shield walls on site using local resources as a potentially more economical alternative to bringing all materials needed for the construction from Earth to the lunar surface.

Previous studies have shown that geopolymer might be a promising material for construction on the Moon, since lunar regolith can be used as the main part of the geopolymer matrix. All other necessary ingredients for the geopolymerisation of the regolith - water and alkaline activator - could potentially be sourced on the lunar surface as well. However, curing in vacuum seems to be detrimental to the strength of material formulations that have been explored so far.

The objective of the current study is to investigate the structural properties, shielding abilities, construction process and economic efficiency of an optimized geopolymer recipe made from lunar regolith simulant, when cured under simulated environmental conditions (temperature and vacuum) of the lunar surface, evaluating the effects of adding locally sourced basalt reinforcement fibres and superplasticizers. Furthermore we aim at examining the combination of material and construction technique towards its resource efficiency and applicability for lunar surface applications.

In this paper we discuss the current status of the study and the results of the ongoing experiments. Furthermore, we present a preliminary evaluation of the newly developed material compared to other potential lunar construction materials with regard to its structural performance, shielding properties and degree of *in-situ* resource utilization and offer recommendations for future studies.

1. Introduction, Background and Study Motivation[1]

Human missions to the lunar surface might require the capability to build structures on site using the moon's natural resources as a potentially more economically viable alternative to transporting all materials needed for the construction of an outpost from Earth to the lunar surface.

Concrete and ceramic materials can be (mostly) made from lunar regolith, which would be able to improve protection of the crew from harsh environmental conditions like solar wind, radiation and micrometeorites. The materials need either a chemical binder containing water (consumable resources) or comparatively larger amounts of energy. Construction materials that use little of these resources while providing sufficient protection against the harsh lunar environment are therefore of interest.

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1.1 Construction in the lunar environment

The designs of structures on the lunar surface are driven by hard vacuum, partial gravity, radiation, micrometeoroids, extreme thermal cycling (between -173°C and +117°C) and other specific considerations. Although gravity and pressure are different on the lunar surface, the same loading patterns as on Earth exist: compression, tension, bending and torsion. The seismic energy released by the Moon is 7 orders of magnitude lower than the Earth's. It might increase to 4 orders of magnitude less than on Earth should rare, large moonquakes occur. Strengthening of structures against seismic activity on the Moon is therefore likely not needed [2]. However, it should nevertheless be considered when building mission critical elements, taking into account the type of structure and materials used. Sufficient care has to be put into providing low radiation levels within the habitat. These radiation levels could be determined, e.g., by the annual radiation worker full-body dose equivalent limit (5 cSv, 5 rem) [3] and the 30-day blood forming organ (BFO) dose limit in low Earth orbit (25 cSv, 25 rem) [4].

1.1.1 Lunar surface base structures

The following general requirements apply for materials used for lunar habitation [5]:

- Sufficient life cycle
- Resistance to space environment (UV and ionizing radiation, extreme temperatures, abrasion, vacuum, meteorites)
- Resistance to fatigue (vibration, pressurization, deployment, thermal)
- Resistance to stresses (compression, shear, bending loads)
- Resistance to penetration (micrometeoroids, mechanical impacts)
- Biological/chemical inertness
- Reparability (process/materials)
- Further, concerning safety, the following issues have to be considered:
- Process operations (chemical, heat)
- Outgassing
- Toxicity
- Flammability, smoke, explosive potential
- Operational suitability and economy
- Availability through lunar sources (*in-situ* resource utilization)
- Ease of production and use
- Versatility (materials and related processes and equipment)
- Radiation/thermal shielding characteristics
- Meteoroid/debris shielding characteristics
- Acoustic properties
- Launch mass/compatibility (resources from Earth)
- Thermal and electrical properties (conductivity/specific heat)

1.2 Lunar construction materials

Potential lunar construction materials that *do not require binders* include:

1.2.1 Sulphur concrete

Sulphur is a volatile element and can be found on the lunar surface in the form of the mineral troilite (FeS). It can be extracted from lunar regolith by heating [6]. To produce sulphur "concrete" - though technically not a concrete, as no, or very little, chemical reaction between the constituents is involved – water is not required. This is particularly advantageous on the lunar surface, where water is scarce. Yet, sulphur has a melting point around 115°C and "stiffens" above 148°C. This means, the concrete composition (12-22 wt. % sulphur with 78-88 wt. % aggregate) has to be prepared and heated between 130-140°C – a narrow and not practical temperature range to work with on the lunar surface. The produced concrete elements cannot be used where ambient temperatures exceed 115°C. Furthermore, the compression strength of sulphur concrete suffers significantly from temperature cycling. It loses on average 80% of its strength due to cracking [7].

While sulphur concrete theoretically doesn't need any other resources than those that can be found on the moon, producing sulphur concrete would require a power source to bake sulphur out of the lunar soil, and melt the concrete mixture, which requires an uncertain amount of energy and equipment. Additionally, it is not yet clear whether the sulphur content that can be found on the lunar surface is high enough to make exploitation worthwhile and

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environmentally responsible. Another downside of the material is that its radiation shielding properties are worse than that of plain regolith simulant [8].

1.2.2 Sintered basalt/regolith

Sintering is the compaction and formation of a solid mass of material from bulk basalt or a particular mineral or set of minerals in powder form by heat or pressure without melting and liquid casting processes. Within the Materials Processes section at the European Research and Technology Centre, this technology was followed up into a General Support Technology Program (GSTP) project with the German Aerospace Center (DLR) looking at using directed solar energy to sinter regolith into building elements (i.e. a brick) [9, 10].

On the lunar surface microwave or solar power could be used to create the heat necessary to sinter regolith into bricks or other building elements – microwave heating being the process that allows quicker uniform heating. The precursor used for sintering is fine grained regolith. Sintered regolith is brittle and characterized by low density, good thermal insulation, yet low resistance to tensile stresses. Additionally, the material typically shrinks considerably. Sintered regolith has been proposed as an in-situ construction material for the lunar surface for thermal and dust control and micrometeorite protection. Due to the low density of the material, it would require substantial thicknesses to be used as radiation protection for human habitation. In addition, low stress resistance might be an issue for its use for the construction of protective walls or shells for habitats on the lunar surface.

Potential lunar construction materials that *require binders* include:

1.2.3 Magnesium chloride based binder (Sorel cement)

This construction method was proposed in a recent ESA study that tested the D-shape 3D printing process with Sorel cement for construction on the lunar surface [11]. The binder (the “ink” for the 3D printer in the study) consists of 33% magnesium chloride and 66% water which – when combined with a precursor containing magnesium oxide - is very fast-setting and produces a stone-like material (Sorel cement) that reaches very high compressive-strength (around 70 MPa) within hours. Produced in a terrestrial environment at ambient temperatures it has a higher resistance to compressive forces (69-83 MPa) than normal Portland cement (45-55 MPa). The resulting material is a porous, artificial sandstone with a density of about 1.7 t/m^3. Due to the low density of the material a thickness of at least 1500 mm would be required to make use of the material as radiation protection for human habitation. The process also requires a substantial amount of consumables (chemicals and water) to produce the binder.

1.2.4 Phosphate based binder

This rock-like material developed by FOTEC in collaboration with ESA is created by using phosphoric acid as a liquid binder [12]. To create acceptable strengths of the resulting material, the acid to regolith simulant mixture ratio should be at least 0.6:1 by weight. For lunar applications, considerable amounts of water and phosphoric acid would have to be transported to the lunar surface. This material seems to be promising for use on the Martian surface, as phosphoric acid and water are available in the Martian soil.

1.2.5 Geopolymers

This fire- and heat resistant inorganic polymeric material develops, when a polymeric reaction between an alkaline solution (often sodium silicate and sodium hydroxide) and an aluminosilica rich precursor takes place [13].

Lunar regolith is made up in large parts of silicon and aluminium oxides. Fly ash, which is a precursor that is used on Earth to produce geopolymers, closely resembles the oxide and phase composition of lunar regolith (Table 1).

Table 1: Contents of the main oxides of the lunar regolith simulants DNA-1, EAC-1A and JSC-1A, and of lunar soil samples from Apollo missions and typical Class F fly ash [14, 15, 16].

Oxide	**DNA-1**	**EAC-1A**	**JSC-1A**	**Lunar soil 14163 (mean of Apollo mission samples)**	**Typical Class F Fly Ash**
Unit	**(wt%)**	**(wt%)**	**(wt%)**	**(wt%)**	**(wt%)**
SiO_2	50.75	43.70	41.00	47.30	48.20
TiO_2	1.16	2.40	1.60	1.60	1.00
Al_2O_3	18.77	12.60	15.90	17.80	21.00
Fe_2O_3	8.81	12.00	18.10	0.00	4.90
FeO	0.00	0.00	0.00	10.50	0.00
MgO	2.78	11.90	4.73	9.60	3.40

CaO	7.63	10.80	13.20	11.40	12.80
Na_2O	4.90	2.90	2.50	0.70	1.50
K_2O	5.21	1.30	1.05	0.60	1.20
LOI	0.00	0.00	0.00	0.00	0.80

Depending on the Si-Al ratio in the precursor, the geopolymers can take on different structures. Ratios greater than 3:1 create polymers that can be characterized as 2D networks, 3D polymeric networks develop when the ratio is between 1:1 and 3:1. Lunar regolith exhibits the specific Si-Al ratio (1:1 – 3:1) that is necessary to produce geopolymer, with Mare regolith exhibiting a Si-Al ratio of 2.6:1, and Highland regolith exhibiting a Si-Al ratio of 1.6:1. [17].

Geopolymers are able to create strong chemical bonds with silicate rock-based aggregates such as lunar regolith. This material could be used to construct protective habitat walls or shells. Geopolymers, when produced under terrestrial conditions, show highly advantageous properties such as [18]:

- Shrinkage during setting: < 0.05%
- Uniaxial compressive strength: > 90 MPa at 28 days
- High early strength formulation (uniaxial compressive strength): 20 MPa after 4 hours
- Flexural strength: 10–15 MPa at 28 days
- High early strength formulation (flexural strength): 10 MPa after 24 hours
- Young Modulus: > 2 GPa
- Freeze-thaw: mass loss < 0.1% (ASTM D4842), strength loss <5% after 180 cycles
- Safe long-term durability

According to Montes et al. [19], geopolymer consisting of up to 98% by weight of in-situ regolith could be produced on the lunar surface, greatly reducing the up-mass necessary to build structures, especially effective radiation shielding habitat walls or shells. The alkaline solution would be transported from Earth (yet, the water as well as sodium silicate in the solution might also be sourced locally on the lunar surface, further increasing the percentage of *in-situ* resources in the final material). Furthermore, they showed that a shielding thickness of 50 cm (99 g/cm^2) with geopolymer is sufficient for a prolonged crewed lunar mission, with the absorbed dose for a 12 months stay being similar to the annual whole-body radiation worker limit (5 cSv, 5 rem) [19].

The advantageous strength and durability as well as favourable shielding properties of geopolymers lead to comparatively little amounts of construction material being necessary to shield and protect crews. This in turn reduces necessary up-mass and energy for construction even further.

Davis et al. have demonstrated the principal interest of geopolymer for production on the moon [17]. The aim of this study is to investigate this material by testing formulations with a newly available lunar regolith simulant (DNA-1) and with basalt fibre reinforcement.

1.2.6 Reinforcement – Basalt fibres

Basalt fibres are a material that could be produced in situ at the lunar surface [20] and could increase the structural properties of geopolymer. They have advantageous physiomechanical properties: excellent stability, high strength and elastic modulus, high temperature resistance and reduced thermal and electrical conductivity. They have good chemical resistance, especially in the presence of strong alkalis. Additionally, they are non-toxic and compared to other reinforcement fibres easy to process. The fibres are produced by washing crushed basalt and melting the rock at about 1500 °C, extruding the molten material through nozzles to manufacture filaments of basalt fibre. For concrete reinforcement, usually chopped strands of the basalt fibres should be used. Basalt in the form of fibres has been used as a reinforcement phase to geopolymers used in terrestrial applications, exhibiting enhancements in mechanical strength compared with pure geopolymers.

1.3 Additive Manufacturing

Technologies that require minimal human involvement in the building/assembly process are a necessity when habitats and infrastructure are situated where environmental conditions are harsh, such as the lunar surface. Using additive manufacturing techniques, habitats and infrastructure for humans could be produced *in situ* from lunar regolith. The following two methods appear based on current knowledge to present the most relevant processes for additive manufacturing on the lunar or Martian surface:

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1.3.1 Extrusion deposition

In extrusion deposition, a 3D structure is created by a printer nozzle on a movable extrusion head. This head traces a shape, layer by layer, ejecting melted or binding agent containing feedstock, creating the desired structures in a 3D printing process. Contour Crafting is a form of extrusion deposition. The digitally controlled construction process was developed by Behrokh Khoshnevis and successfully obviates the need for any formwork or shuttering. Leach et al. [21] have explored the use of Contour Crafting on the Moon and Mars, employing a lunar rover (ATHLETE) equipped with a Contour Crafting robot extruding concrete through a nozzle, though only for the fabrication of infrastructural elements (landing pads, blast walls, etc.) [21].

1.3.2 Powder bed 3D printing

Cesaretti et al. have used in the previously mentioned ESA study a large-scale 3D printer called D-shape [11]. 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 catalyser’ as an ‘ink’ to bind lunar dust to create stone-like objects [22]. The construction process with the D-shape printer consists of the following steps:

- deposition of fine regolith for a single layer
- densification of the layered material using a heavy roller
- applying the ‘ink’ on the layered material, tracing pre-defined printing paths
- curing the bonded layer
- repeating the process until the final layer is reached

The main advantage of the D-shape process is that the structure is printed in a bed of lunar dust, which supports the structure that is being printed until it sets, allowing even very shallow arches to be constructed. The cement used in the experiments however necessitates a large quantity of water in the binder (66%), a valuable consumable on the lunar surface that either has to be transported from Earth or - if sufficiently available - mined *in situ*. The Magnesium Chloride that makes up the other 33% of the binder will have to be transported from Earth as well. Even if the structure uses honeycomb construction, supplying those materials will be costly [23].

2. Materials and Methods

2.1 Objective

The first objective of the study was to define a wet-cast geopolymer formulation with lunar regolith simulants used in previous ESA studies for lunar construction, namely DNA-1 and JSC-1A. Due to the unavailability of JSC-1A and JSC-2A since the beginning of the study, the decision was made to substitute this regolith simulant with EAC-1A. The contents of the main oxides in those simulants can be found in table 1. The goal of formulating a new recipe was to minimize the amount of water and alkaline reactant (sodium silicate and/or sodium hydroxide) used and to investigate the role that urea might play as a superplasticizer in reducing water content and increasing workability for geopolymer made from lunar regolith simulant, particularly regarding additive manufacturing with extrusion printing. Furthermore, the suitability assessment of basalt fibres as reinforcement fibres in lunar geopolymer and finding the best performing recipe of the composite are an important step of the study, as previous results from dry-cast geopolymer [17] have shown that curing the material under simulated environmental condition of the lunar surface might be detrimental to the strength of the geopolymer. It is hoped that the use of locally sourceable reinforcement fibres can increase the mechanical strength of the geopolymer significantly. The samples cured both in Earth ambient atmosphere and temperature as well as under simulated lunar conditions (vacuum, extreme temperature oscillations) are tested for radiation shielding capacities and the following structural properties: shrinkage during setting, uniaxial compressive strength, flexural strength, Young’s modulus, density, FTIR analysis, SEM and X-ray tomography.

2.2 Experimental investigation

Due to issues with the provider of JSC-2A, the first stage of the study has been conducted with DNA-1 only. Samples of interest will be produced with EAC-1A as well, using the same recipe and curing conditions, to investigate potential effects caused by the difference in simulant.One of the main goals of the recipe optimization was minimizing the amount of water necessary for the recipe. Water is not only a limited resource and not readily available on the moon, but also increasing the solid content of geopolymers facilitates greater compressive and tensile strength [24].

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For the formation of the 3D geopolymer network and to promote ideal flow properties however, water is an important ingredient. How much water is adsorbed onto the surface of the other ingredients depends on water affinity area of the particle's surface [25]. To minimize the water demand of geopolymer recipes, superplasticizers can be beneficial.
Due to urea's ability to break hydrogen bonds and reduce the viscosity of aqueous mixtures [26] the potential of using urea as a superplasticizer for lunar geopolymers has been investigated. After water, urea is the second most abundant component in human urine and should therefore be readily available from the wastewater of astronauts.
Admixing urea to the geopolymer recipe has been contrasted with adding polycarboxylate and naphthalene based superplasticizers, and with a control recipe without superplasticizer [27].

All lunar geopolymer mixtures were prepared with a sodium hydroxide 12M (480 g/L) as alkaline solution By considering the water limitation and payload cost, laboratory trials of mixture design were repeated several times to gain the minimum amounts of alkaline solution and superplasticizer, while keeping the workability and strength of samples at reasonable levels. Accordingly, while about 64 wt.% of the alkaline solution is water, the ratio of water to the total mass of geopolymer solids (lunar regolith simulant, NaOH pellets and chemical admixture) is 0.19. Experiments investigating the flow properties of different mixtures showed that the recipes in Table 2 brought the best results [27].

Table 2. Mixture design for Lunar Geopolymer. The percentage of chemical admixtures is given relative to the mass of the lunar regolith simulant. Ca. 64 wt.% of the alkaline solution is water [27].

Name of mixture	**NaOH(aq) / Regolith**	**Chemical admixture**
W/O	0.35	-
U	0.35	Urea – 3%
C	0.35	polycarboxylate based (SUPLA PDP 2 SA) - 3%
N	0.35	naphthalene based (FLUBE CR 100 F) - 3%

The first stage of the study investigated curing under Earth ambient pressure and freeze-thaw tests between -80°C and +80°C. With regard to setting time, the recipe containing urea showed the most favourable results for 3D printing. The prolonged initial setting time exhibited by the U samples indicates that the "open time" until the material loses its workability is extended as well. The final setting time fits shape retention requirements for layer-by-layer buildability. With respect to shape deformation and layer-by-layer-buildability, again, the urea sample exhibited the best results. Fresh samples were able to retain their shape with little deformation (ca. 11%) under heavy external loads (5-10 times their own weight), showing no fractures. The urea samples showed higher initial compressive strength than the C and N samples, with the compressive strength increasing continuously even at 8 freeze-thaw cycles. FTIR conducted indicates a continuing formation of geopolymeric products after the 8 conducted freeze-thaw cycles. However, X-ray tomography revealed that the addition of superplasticizer to the geopolymer recipe might promote air void formation and microcracks [27].

2.3 Further steps

The next step of the study aims at investigating the effects of simulated lunar environmental conditions (extreme temperature cycling and vacuum) on geopolymer samples with varying urea contents. It is expected that curing the samples in vacuum could lead to foaming and decreased strength. Therefore, the suitability of basalt fibres as reinforcement to counteract expected detrimental effects of the lunar environment on the curing of the geopolymer will be assessed. Once the best performing samples have been determined, the material's radiation protection properties will be tested at the ISIS Neutron facility (UK). Results will be compared to previous Monte Carlo simulations of the shielding capacity of geopolymer made from lunar regolith simulant [19].

Follow-up experimental procedures aim to determine which reinforcement is better suited for extrusion printing of the new geopolymer recipe specifically. Samples will be additive manufactured with three types of basalt fibre at different ratios. The purpose is to analyse if the fibre addition and distribution has the same effect on the mechanical strength in the cast samples and in the additive manufactured ones. Prior to mechanical testing the samples will again be cured in vacuum and lunar environmental temperatures.

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Challenges correlated with the workability of the geopolymer are forecasted in the additive manufacturing process. There are high chances for a diminished flow rate with increased fibre ratio. This might impose constraints, both on the fibre type and ratio in the fabrication method. Another estimation is lower compressive strength, due to poor bonding between the fibre and the geopolymer matrix. However, several studies also suggest that fibre addition assures crack prevention, and improve the residual strength and flexural toughness. If the reinforcement/matrix interface is carefully controlled it should contribute to improved ductility and failure behaviour under mechanical loading.

Ultimately, it is planned to structurally optimize a prospective habitat protection shell for the specific material and, if previous studies have been successful, to operate the printing process in a representative environment and print samples of said structure.

2.4 Availability of geopolymer constituents on the lunar surface

Geopolymer presents an interesting potential material for infrastructure and habitation construction on the lunar (and Martian) surface, since resources that are readily available *in-situ* (regolith) can be used as the main part of the geopolymer matrix, minimizing the amount of materials brought in from Earth. The other constituents of the geopolymer – water, sodium silcate (Na_2SiO_3) and/or sodium hydroxide (NaOH) to prepare the alkaline solution for the geopolymerization of the lunar regolith – are available on the moon as well.

2.4.1 Availability of silicon dioxide vs. sodium oxide on the lunar surface

Silicon dioxide (SiO_2) as well as sodium oxide (Na_2O) are available compounds on the lunar surface (table 1) and can be used to make sodium silicate ($Na_2O + SiO_2 \rightarrow Na_2SiO_3$), while Na_2O and water can be used to make NaOH ($Na_2O + H_2O \rightarrow 2NaOH$). Na_2O makes up only about 1% of lunar soil sample 14163 [14], and extracting it from lunar regolith would likely be technologically and energetically challenging. Silica (SiO_2) is the most abundant compound in the chemical composition of the lunar surface (45.4% in the Maria, 45.5% in the Highlands). The silica minerals present on the lunar surface are quartz, cristobalite and tridymite. Contrary to terrestrial basalts, where silica minerals generally do not occur, cristobalite, which is the most abundant silica mineral in mare basalt lavas, accounts for up to 5 vol. % of some basalts. Common contaminants are Al_2O_3, TiO_2, CaO, FeO, and Na_2O, yet silica minerals on the moon are almost pure SiO_2. In small quantities, also other silicate minerals like tranquillityite, pyroferroite, zircon and potassium feldspar occur in lunar rocks [28].

However, the lunar regolith is a random matrix of minerals and silicates. It is therefore of considerable interest to develop and mature grain size and mineral sorting techniques. By improving the efficiency of beneficiation processes for gaining the desired compounds in acceptable purity on the lunar surface, we can avoid having to bring them from Earth.

2.4.2 Urea availability on the lunar surface

In currently used water recovery systems for space applications various chemicals are added to the urine and flushwater in the toilet to stabilise the wastewater and lower the urea content to avoid hydrolysis of urea due to microbial contamination. Hydrolysis of urea releases ammonia and causes an increase in pH to about 9.2, leading to more volatile NH_3 and precipitation of compounds with low solubility [29]. Favourably, human urine contains not only water and urea, but also several minerals, particularly calcium, which are beneficial to start geopolymerization. For this study the assumption is made that if astronaut urine should be collected for making lunar geopolymer, the toilet would be unplugged from the water recovery system and connected to a separate tank, where the urea content is not a problem, as long as the liquid is frozen and stabilised [30].

3. Conclusion

Compared to the other lunar material examples using binder in section 1.2, the geopolymer uses local resources very efficiently. At this stage of the study, the material requires about 2,2 wt.% urea and 25.3 wt.% of alkaline solution (NaOH) with the alkaline solution containing 64 wt.% water. Reinforcement fibres might lower that content even further. Given technological development in beneficiation methods, potentially all materials, even the fibres, can be sourced on the moon. In comparison, the magnesium chloride binder relies on the transportation of about 2 wt.% in dry salts, assuming all other ingredients like water and MgO can be found in sufficient amount and beneficiated on the lunar surface. However the total content of water and beneficiated material in this material is far higher than in geopolymer. The phosphoric acid binder requires about 37.5 wt.% of phosphoric acid to be transported from Earth [12].

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Concerning compressive strength, the magnesium chloride binder had exceptional results of about 70-80 MPa when cured at ambient temperatures and atmosphere. However, the effects of thermal cycling have not been studied. For the lunar geopolymer without reinforcement, the sample without superplasticizer exhibits a compressive strength of 32 MPa after 8 freeze-thaw cycles, the one containing 3% urea has a compressive strength of about 16 MPa. Due to the lower gravity on the moon of about 1/6 g, this is well above the limit for structural safety of about >7 MPa. No compressive strength values were published about the phosphoric acid binder.

Cesaretti et al. [11] assume a 150 cm protective shell is necessary to protect sufficiently against ionizing radiation using the magnesium chloride binder structure. Previous simulations of the radiation protection properties of geopolymer show a more favourable behaviour: a shielding thickness of 50 cm (99 g/cm^2) with geopolymer is sufficient for a prolonged crewed lunar mission, with the absorbed dose for a 12 months stay being similar to the annual whole-body radiation worker limit (5 cSv, 5 rem) [19]. There are no results available about the phosphoric acid binder.

In addition to the positive results for lunar applications, valuable results for geopolyer use on Earth have been achieved, as admixing urea as an easily accessible, cheap superplasticizer reduces the amount of required water and improves workability.

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