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Abstract

Future manned missions to the moon will require the ability to build structures using the moon's natural resources. The geopolymer binder described in this paper (Lunamer) is a construction material that consists of up to 98% lunar regolith, drastically reducing the amount of material that must be carried from Earth in the event of lunar construction. This material could be used to fabricate structural panels and interlocking blocks that have radiation shielding and thermal insulation characteristics. These panels and blocks could be used to construct living quarters and storage facilities on the lunar surface, or as shielding panels to be installed on crafts launched from the moon surface to deep-space destinations. Lunamer specimens were manufactured in the laboratory and compressive strength results of up to 16 MPa when cast with conventional methods and 37 MPa when cast using uniaxial pressing were obtained. Simulation results have shown that the mechanical and chemical properties of Lunamer allow for adequate radiation shielding for a crew inside the lunar living quarters without additional requirements.

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Keywords: moon construction, geopolymer, lunar regolith, radiation protection, concrete, inorganic polymer

1. Introduction

Cosmic radiation is a critical obstacle preventing manned space exploration missions. NASAs Human Exploration Destination Systems Roadmap (Technology Area 07) mentions among its top technical challenges for 2017-2022 the development of technologies for shielding radiation from astronauts in missions to the lunar surface and Mars (NASA, 2010). The roadmap suggests the testing of technologies such as sandbagging of regolith, among others, to protect crew compartments. While there are many challenges to overcome to obtain this goal, cosmic radiation is a critical obstacle preventing manned space exploration missions of that length. There is currently no practical technology that can fully reproduce the radiation shielding effect produced by Earths strong magnetic field and dense atmosphere. Since extended missions to the moon and Mars are high priority goals, development of materials and technologies that reduce radiation exposure both in transit, and at the final destination, are of prime interest. An innovative solution is to take advantage of the native shielding properties of the lunar regolith itself, and create habitation structures with it. Due to the extreme cost of up-mass (payload from Earth to space), implementation of construction materials readily available here on Earth is unviable. To address the need for lunar habitation structures, it is proposed to utilize materials that provide durable structural support with increased radiation shielding properties that can be created in-situ, almost entirely from materials that can be readily obtained from the surface of the moon. A similar approach could be followed to investigate the potential of the Mars regolith to be used as source material for geopolymerization, and a separate study should be conducted for that matter.

If successful, the results will help reduce mission risk to the moon, Mars, and other deep space destinations. The lunar regolith-based geopolymer panels (or, Lunamer panels) can be used to erect structures on the face of the moon, utilizing their structural and thermal insulating characteristics, as well as provide radiation shielding to occupants of lunar posts and astronauts on deep space missions launched from the moons surface. With this technology, it could be possible in the future for stripped-down spacecraft to be delivered from Earth to the moon, equipped with Lunamer panels, and re-launched from the lunar surface to reach a final destination in deep space. The purpose of this research is to prove the hypothesis of the possibility to manufacture geopolymer from lunar regolith, but future feasibility studies are required to enable the technology.

Geopolymers are cementitious binders produced through a polymeric reaction between an aluminosilica rich precursor and an alkaline activator solution, which is in many cases a combination of sodium silicate and sodium hydroxide(Davidovits, 2011). Geopolymer concrete—which is the combination of geopolymer binder with fine and coarse aggregate materials such as sand and gravel— has been reported to have exceptional properties compared to Portland cement concrete in terms of mechanical and thermal resistance (Van Deventer, Provis, and Duxon, 2012). Since lunar regolith contains high amounts of aluminum and silicon oxides in ratios similar to those needed to manufacture geopolymer binder, the authors thereby propose the manufacture of Lunamer to be used as a construction material on the moon.

Lunar regolith has been proposed in the past as a construction material by committees such as the American Concrete Institute's Committee 125 on the topic of lunar concrete. Matsumoto, Yoshida, Takagi (1991) detailed the extraction of lunar regolith and other materials needed for he formation of lunar concrete, including a rock breaking system. Swint and Schmidt (1991) discussed the optimization of the procuction of lunar concrete, taking into consideration different mixing and testing conditions and different concrete variables like the cementing agent, plasticizers, and reinforcements. Kanamori, Matsumoto, Ishikawa (1991) studied the long-term effect of mortar exposed to vacuum conditions, concluding that water loss was a major concern, although some vacuum-exposed samples had higher strength than the water-cured samples. Unfortunately, this committee operated on the idea that concrete brought up from earth would be the main building material, mentioning lunar regolith used as an aggregate. The committee met once in 1990, published proceedings in 1991, and never met again. With the advent of geopolymer technology, we may bring the idea of lunar cement back to life.

Sulfur concrete is a waterless technology proposed for lunar construction that involves melting down sulfur and mixing it with aggregates. Although using sulfur concrete has a number of advantages, like being able to use sulfur mined on the moon, it has several drawbacks- the most critical of which being the limited working temperature of sulfur(Toutanji, Evans, and Grugel, 2010). Another disadvantage for sulfur concrete is its poor durability in relation to thermal cycles (Casanova, 1997). The resistance of geopolymer to freeze-thaw has been reported as better than that of traditional Portland cement concrete. However, it is worth noting that the porosity and pore size of the materials have a significant effect in the resistance to frost, and tests at higher heat-cold thermal cycles should be conducted. Sulfur cement melts at 119 °C and undergoes a phase transformation at 96 °C, making it unviable to use without a risk of failure as surface temperatures on the moon can reach 125 °C (Casanova, 1997). To compare, geopolymer binder melts above 1250 °C and is dimensionally stable at temperatures up to 800 °C, both of which are significantly higher than temperatures that can be experienced on the surface of the moon (Rickard, Temuujin, van Riessen, 2012). Another difficulty of sulfur concrete technology is the scarcity of sulfur in the lunar regolith. Mining for iron sulfide, the main source of sulfur on the moon, would be necessary, and subsequent heating at temperatures close to 1100 °C would be required to extract it. Lunamer manufacture could utilize unaltered lunar regolith, which, combined with minimal amounts of activator solution, could produce thermally stable, high performance concrete which can be produced using techniques already employed by NASA, like 3D printing European Space Committee (2013). To utilize sulfur concrete in lunar construction, all the surfaces that the cement would be poured into would need to be pre-heated to prevent early solidification, which presents a challenge while working on the moon. Additionally, sulfur cement's setting time is short (around 60 minutes) giving workers limited time to form and pour the material. Geopolymer setting time, on the other hand, can be controlled to meet specific construction needs. Currently all other construction options, such as epoxy binders, require a significantly larger up-mass with little to no added benefit, making Lunamer the most cost effective and realistic option for lunar construction.

The most critical aspect of a manned lunar mission is the safety and the health of the crew (Simonsen and Nealy, 1991). Since the chemical composition and mechanical properties of Lunamer are similar to that of traditional concrete, its radiation shielding properties are also similar. Simulations show that a lunar outpost built from Lunamer provides adequate radiation shielding to its occupants without extra requirements needed in the structural design. The lack of geomagnetic field shielding in space directly exposes the astronauts on the moon to galactic cosmic rays (GCRs), which is galactic background radiation, and solar energetic particles (SEPs), which are mostly associated with solar flares. For a typical manned space mission, the effects of GCRs are neglected and the effort is focused on the avoidance of SEPs. However, in a prolonged space mission, the accumulation of radiation due to GCRs can be significant(NCRP, 1989). The design of a lunar base thus requires enough shielding from all sources of radiation in order to keep the radiation doses within specified exposure limits for a possible stay of 1 to 12 months. Table 1 summarizes the requirements of concrete for moon construction.

Specification	Requirements
Compressive strength	1/6 of the requirement of a similar structure on earth (usually 35 MPa for a simple one-floor structure)
Density	Based on radiation reduction requirements
Temperature range	Min: -203.15 °C (85 °N) Max: 116.85 °C (equator)
Shielding abilities:	
Annual radiation worker full-body dose equivalent limit	5 cSv, 5 rem
30-day blood forming organ (BFO) dose limit in low Earth orbit	25 cSv, 25 rem

Table 1: Requirements for cement-based construction on the moon.

One of the most pressing constraints in the shielding design is that the construction material must consist mostly of materials naturally found on the planet due to up-mass costs. Additionally, the size of the base should be large enough to provide enough habitation space for the crew. Examples of common designs of early lunar habitats are shown in Figure 1 (Alred, Bufkin, Graf, et al., 1988; Nealy, Wilson, Townsend, 1989).

2. Experimental Plan

2.1. Materials

Lunar regolith simulant JSC-1A was used as the geopolymer precursor for Lunamer. Major oxide composition of the simulant is listed in Table 2.

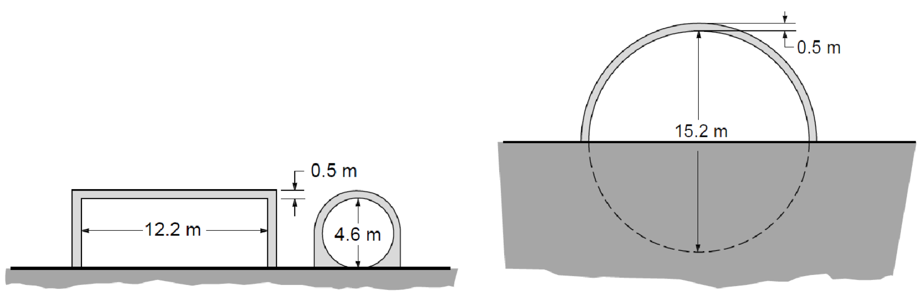


Figure 1: Examples of early lunar habitats. Dimensions from the left habitat are used in the simulation of Lunamer shielding properties.

Oxide	Weight % (Average)
SiO_2	42.95
TiO_2	1.57
Al_2O_3	14.53
Fe_2O_3	11.50
FeO	7.52
MnO	0.17
MgO	8.64
CaO	9.11
Na_2O	2.60
K_2O	0.71
P_2O_5	0.65
LOI	0.01
Total	100

Table 2: JSC-1A Major Oxide Composition

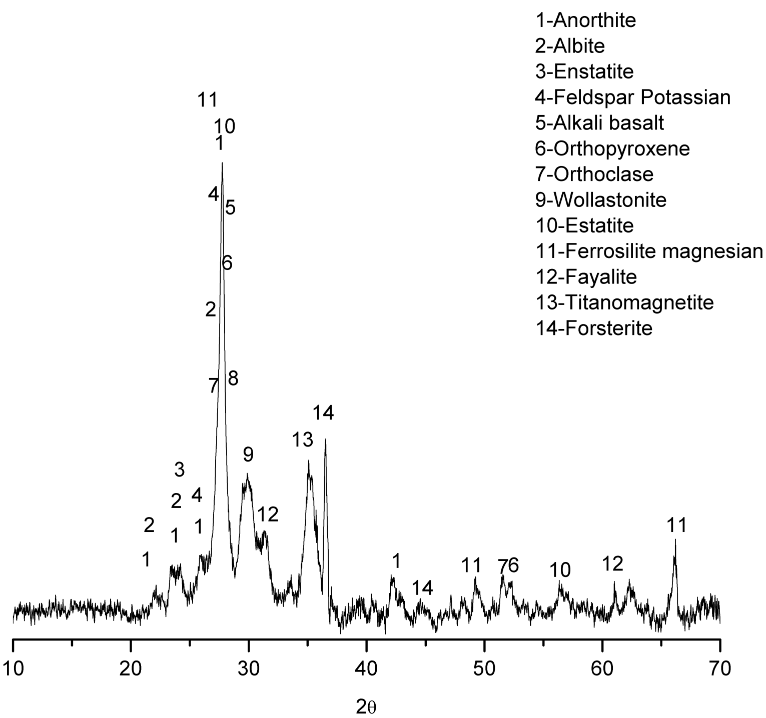


Figure 2: Phase composition of simulated lunar regolith.

The oxide and phase composition of the lunar regolith is similar to that of fly ash currently used to produce Earth-based geopolymers. Compositional requirements include a particular silica to alumina ratio (1:1 to 3:1) which was readily found in the regolith. At least 60% of these fine particles are in the basaltic glassy phase, which will enable them to be activated and form a geopolymer binder when in contact with the activator. The X-Ray Diffraction (XRD) composition of the lunar regolith can be found in Figure 2.

At least 30% by weight of the particles in the simulated lunar regolith are finer than 45 μm. This counts as cement grade fineness, meaning the particles can contribute to binder formation. The remaining 70% of the regolith is not cement grade fineness and is used as filler and aggregate. A dry-cast geopolymer formulation which utilizes minimum amounts of activator was used as a basis for the mix design. A commercial liquid silicate with a SiO_2/Na_2O ratio of 3.22 in a 37.2% by weight solution in water was utilized

System	Activator Solution to Regolith Ratio	Isostatic Pressure Applied (MPa)	Curing
Lun-Cast-3D	0.32	0	3 days at 60 °C
Lun-Iso-3D	0.2	14	3 days at 60 °C
Lun-Iso-Amb	0.2	14	7 days at 23 °C

Table 3: Properties of tested Lunamer systems.

together with a 10 M sodium hydroxide solution to produce three Lunamer concrete systems seen in Table 3.

2.2. Methods

For this research, three Lunamer formulations were produced. The activation system used for all Lunamer formulations consisted of a mixture of 1 part of hydroxide by 1.5 parts of silicate by weight. The first of these formulations (Lun-Cast-3D) was produced by mixing the regolith with the activator solution in the above mentioned proportions using a 0.32 ratio of the activator solution to the cementing fraction of the regolith. The samples were cast normally, without any external pressure added, according to ASTM C-109. Test specimens were cured at 60 °C for 72 hours.

The second and third formulations (Luna-Iso-3D and Luna-Iso-Amb) consisted of dry cast lunar regolith formulations created using a 0.20 ratio of the activator solution to the cementing fraction of the regolith. This mix was compressed to 14 MPa and pelletized into cylinders of 2.5 cm height by 1 cm radius by a 20 ton ICL E-Z Press machine. Half of the samples were cured at 23 °C for 7 days, while the others were cured at 60 °C for 72 hours. The percentage of activator solution used was 0.20 by weight of the 30% of the fine particles present in the regolith, which results in 6% in addition to 100% regolith. However, the activator solution used contained about 66% water, which means that only 2% of the activator solution are chemicals that should be transported from Earth, if water from the Moon could be used as a solvent. This represents significant savings since the estimated launch price per pound of material to orbit is estimated to be at least $10,000 USD, plus an unknown additional cost to transport it to the Moons surface (Futron, 2002). All specimens were then tested for compres-

sive strength using a universal testing machine. The resulting Lunamer was also characterized via Fourier-Transform Infrared Spectroscopy (FTIR) and Scanning Electron Microscopy (SEM). FTIR analysis was conducted with a spectrometer in transmittance mode from 3500 to 600 cm^{-1}. Samples were analyzed via the KBr pellet technique. SEM samples were covered with gold particles and analyzed with a Hitachi S-4800 Field Emission Scanning Electron Microscope.
Two criteria have been used to evaluate the shielding abilities of the final product: the annual radiation worker full-body dose equivalent limit (5 cSv, 5 rem)(USNRC, 2014), and the 30-day blood forming organ (BFO) dose limit in low Earth orbit (25 cSv, 25 rem)(NCRP, 1989).

To speed up the computation, the shape of the habitat was set as sphere with a 460 cmdiameter. Shield thicknesses of 50 cmand 100 cmwere used. Lunamer density of 1.98 g/cm^3 corresponds to shielding thicknesses of 99 g/cm^2 and 198 g/cm^2, respectively. Dose inside the habitat was estimated using the mean and worst solar flare as parameterized by Adams, Silverberg, and Tsao (1981), the flare of October 1989 as parameterized by the ECSS (2000), GCRs at solar minimum (Papini, Grimani, and Stephens, 1996). The differential fluences are shown in Figure 3.

Propagation of protons through the shielding material, their penetration range in human tissue, the associated production of secondary particles, energy, and dose deposition were simulated using techniques based on the Monte Carlo method. The results reported in this paper were obtained using a simulation tool called FLUKA, which is a fully integrated particle physics Monte Carlo simulation package with many applications in high energy experimental physics and engineering(Battistoni, Muraro, Sala, et al., 2007; Ferrari, Sala, Fasso, and Ranft, 2005). This tool is used in shielding, detector, and telescope design, as well as cosmic ray studies, dosimetry, medical physics and radiobiology. Once the incoming particles are generated according to proper type and proper probability density function— in this case, a measured cosmic ray energy spectrum— the properties of the material are determined.

3. Results and Discussion

3.1. Compressive Strength

The control sample (Lun-Cast-3D, Figure 4) showed an average strength of 16.62 MPa. The dry cast samples which were cured for 72 hours at 60 °C

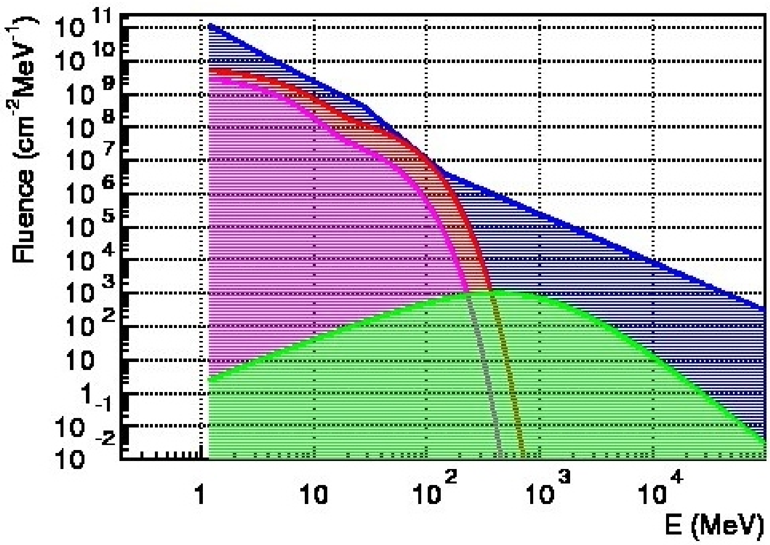


Figure 3: Differential fluences for protons. From top to bottom: flare of October 1989 (blue)(the ECSS, 2000), the worst and mean solar flares(red, pink)(Adams, Silverberg, and Tsao, 1981) and the fluence of the Galactic Cosmic Rays at solar minimum (green)(Papini, Grimani, and Stephens, 1996) over a one month time period.

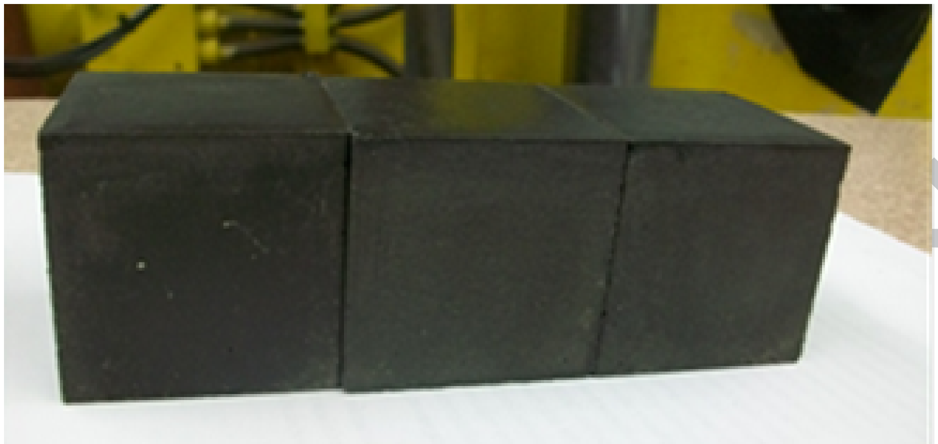


Figure 4: Control Lunamer geopolymer sample (Lun-cast-3D).

System	Compressive strength (MPa)
Lun-Cast-3D	16.62
Lun-Iso-3D	37.63
Lun-Iso-Amb	33.07

Table 4: Compressive strength results.

(Lun-Iso-3D) showed an average strength of 37.63 MPa. The ambient cured dry cast cylinder samples (Lun-Iso-Amb) showed an average compressive strength of 33.07 MPa. In general, the Lunamer samples that were isostatically pressed had a higher compressive strength, despite using less alkaline activator, meaning that part of the strength was gained through a physical mechanism rather than a chemical one. Results are shown in Table 4.

3.2. FTIR

FTIR results are summarized in Figure 5. The band at 1000 cm^{-1} corresponds to the Si-O-Al bonds of the sodium aluminum silicate hydrated geopolymer gel. The Lunacast-3D sample shows a larger amount of geopolymer gel formation resulting in a broader and deeper peak. The samples that were present isostatically (Lun-Iso-3D and Lun-Iso-Amb) showed a smaller amount of gel, primarily because of the lower solution-regolith ratio utilized in the dry cast process. Although these samples have a lower amount of gel, they showed higher compressive strength, likely due to the mechanical compression that was applied to the sample. Bands placed at 1450 cm^{-1}

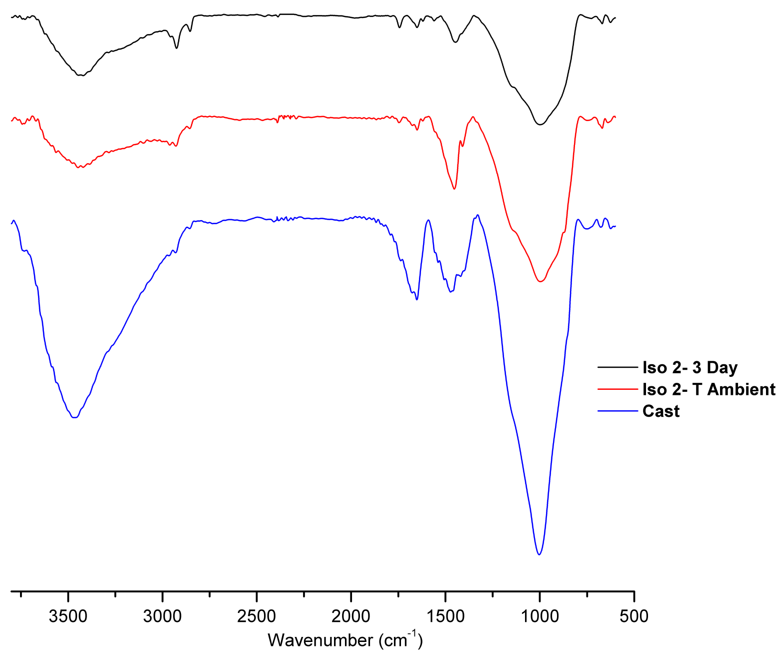


Figure 5: FTIR of lunamer under different manufacturing conditions (top, Lun-Iso-3D; middle, Lun-Iso-Amb; bottom, Luncast-3D).

are assigned to asymmetric vibration mode of O-C-O bonds which means the geopolymer made by regolith was carbonated due to the atmosphere. This is more noticeable on the Lunacast-3D sample than in the isostatically pressed samples due to the amount of water and alkali ions present in the solution that react with the CO2 from the air. Bands present around 1650 and 3460 cm^{-1} are associated with –OH bonds, which, again, are deeper in the Lunacast-3D sample than in the isostatically pressed samples due to the smaller amount of hydration and lower gel formation.

3.3. SEM

The SEM results in Figure 6 show that sample preparation conditions can influence the microstructural development as well as the morphology of the reaction products. The microstructure of Lunacast-3D is similar to that of a typical geopolymer gel phase (left), which shows a uniform matrix and the absence of pores, while the isostatic press Lunamer shows a less dense microstructure (center) and formations similar to dendrites, due to

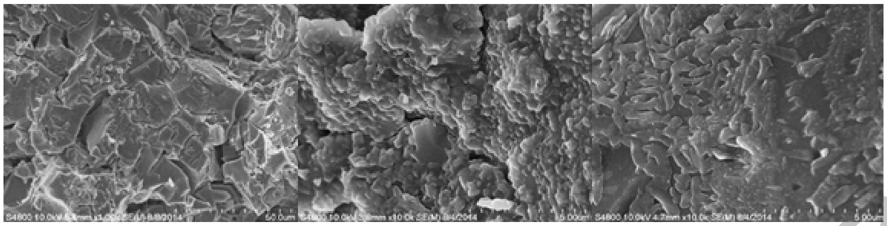


Figure 6: SEM image of Lunamer under different manufacturing conditions, cast (left), isostatic press heat cured (center), isostatic press ambient cured (right)

less liquid in the sample not being available to cover all the particles (right). The morphology differences are attributed to the mechanical treatment of the samples.

3.4. Radiation Shielding Simulation

The first step in quantifying shielding properties consisted of simulating monochromatic protons with kinetic energies of 4, 10, 40, and 100 MeV, as well as 1, 10, and 100 GeV, uniformly impinging on the shielding of a lunar habitat. The effects of the shielding could be seen by plotting the distribution of absorbed energy in different parts of a lunar habitat for particular cosmic proton energy. For example, in Figure 7, where energy deposition for 40, 100, and 400 MeV is shown, one notices that the 50 cm shielding becomes transparent for 400 MeV protons. Figure 8 shows that the shielding thickness is of little importance for proton energies above 1 GeV. In both figures the boxes represent two possible positions of a crew member. In our simulation, the boxes material was chosen to emulate human tissue. While at the beginning of the simulation the volume representing a human was ellipsoidal, to avoid geometry complications in the dosimetry calculations, and to account for possible motion, the shape was changed to a square.

In the second step the absorbed dose and dose equivalent quantities in human tissue were computed. The equivalent dose coefficients are based on coefficients suggested by the ICRP (1991, 1996) and values calculated by Pelliccioni (1998, 2000). Examples of the absorbed dose and dose equivalent as a function of the tissue depth are shown in Figure 9 for proton energies of 100 and 400 MeV for 50 cm thick Lunamer shielding. For proton energies above 400 MeV it was found that the absorbed dose becomes almost position independent.

For high-energy radiation the absorbed dose and dose equivalent, being

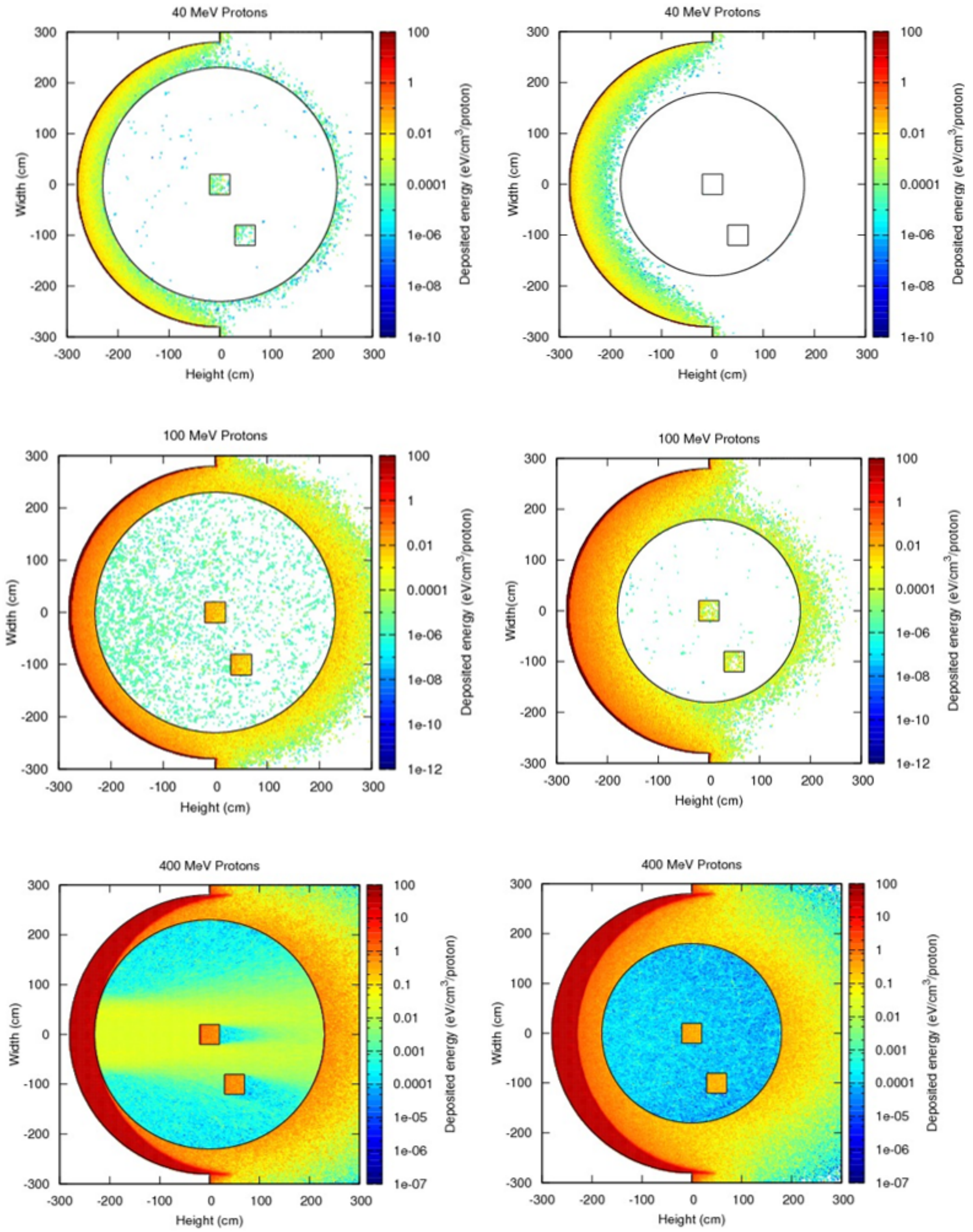


Figure 7: Energy deposited by, from top to the bottom, 40, 100, and 400 MeV protons for 50 cm (left) and 100 cm (right) thicknesses of the Lunamer shielding. The boxes represent two possible positions of a crew member.

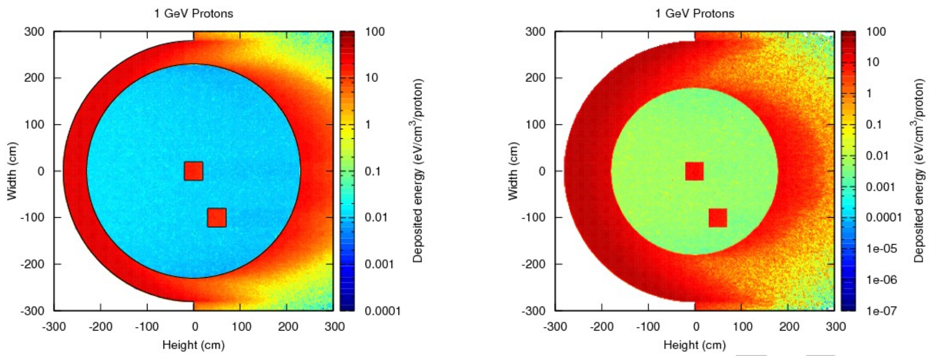
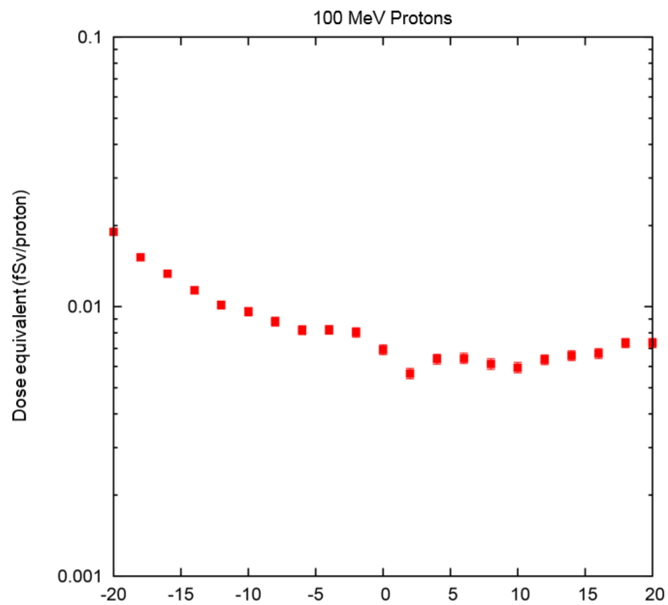


Figure 8: Energy deposited by 1 GeV protons for the case of 50 cm (left) and 100 cm (right) thickness of the Lunamer shielding. The boxes represent two possible positions of a crew member.

almost position independent, are equally delivered to vital organs. It is therefore assumed that the whole-body exposure is equal to the computed BFO dose as the dose had a 5 cm penetration depth. The high-energy dose is shown in Figure 10 and its dose equivalent is shown in Figure 11.

From the differential fluences for protons, shown in Figure 3, and the average dose and dose equivalent of a single proton, shown in Figures 10 and 11, one can calculate total absorbed dose for a particular solar flare or over prolonged period of time. Figure 12 shows the absorbed dose in the energy range of up to 100 GeV for both shielding thicknesses, and Figure 13 shows the dose equivalent for the same situation.

Integration over the curves in Figures 12 and 13 over the cosmic proton's kinetic energy gives the total absorbed dose and dose equivalent for a particular cosmic event. The results are shown in Table 5. The results show that the Lunamer shielding thickness of 50 cm is sufficient to shield against solar flares as parameterized by Adams et al. (Adams, Silverberg, and Tsao, 1981). There is no difference in shielding properties against GCRs between the two shielding arrangements. The rate of accumulation corresponds to an annual whole-body dose equivalent limit for a radiation worker or slightly higher, but is well below the 30-day dose limit for astronauts in low Earth orbit (NCRP, 1989). The problem arises with rare solar flares with high energy proton components, like the one in October 1989. As shown in Table 5, the shielding is not only insufficient to protect against such radiation, but increasing the thickness may actually increase the absorbed dose. The absorbed dose may be an order of magnitude larger (in this particular study,



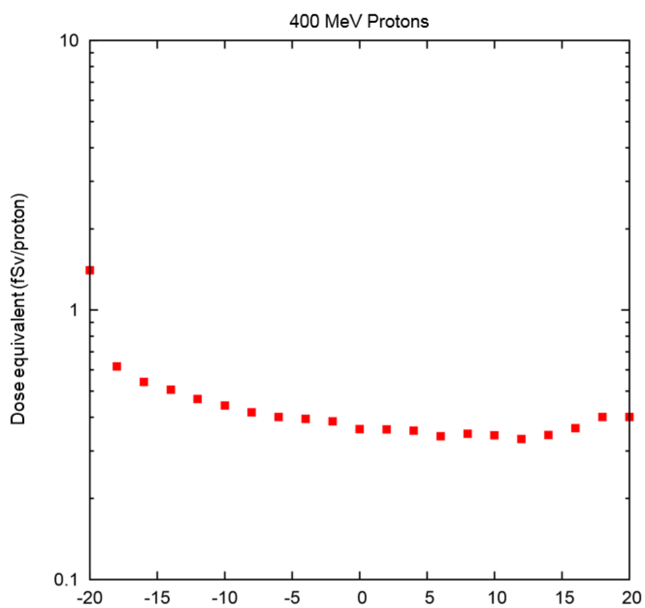


Figure 9: Absorbed dose (top) and dose equivalent (bottom) per proton in human tissue as a function of depth for 100 and 400 MeVprotons in the case of 50 cm thick shielding.

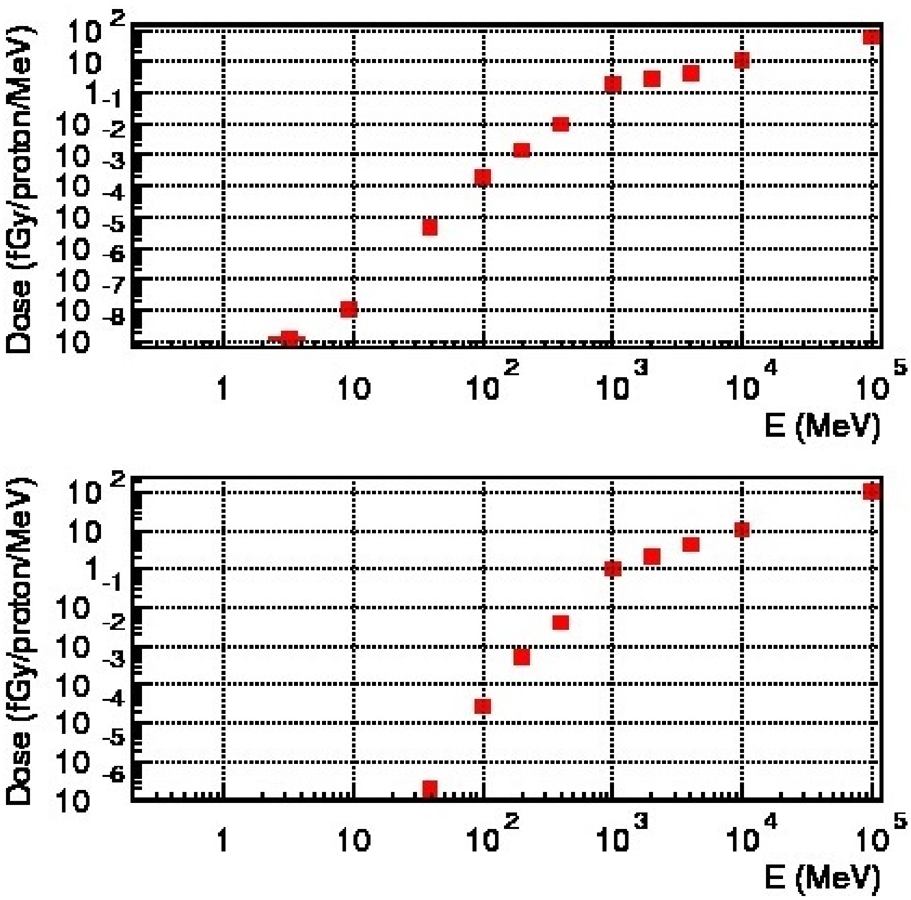


Figure 10: Whole body absorbed dose per proton as a function of proton kinetic energy for a 50 cm (top) and 100 cm (bottom) thick lunamer shielding.

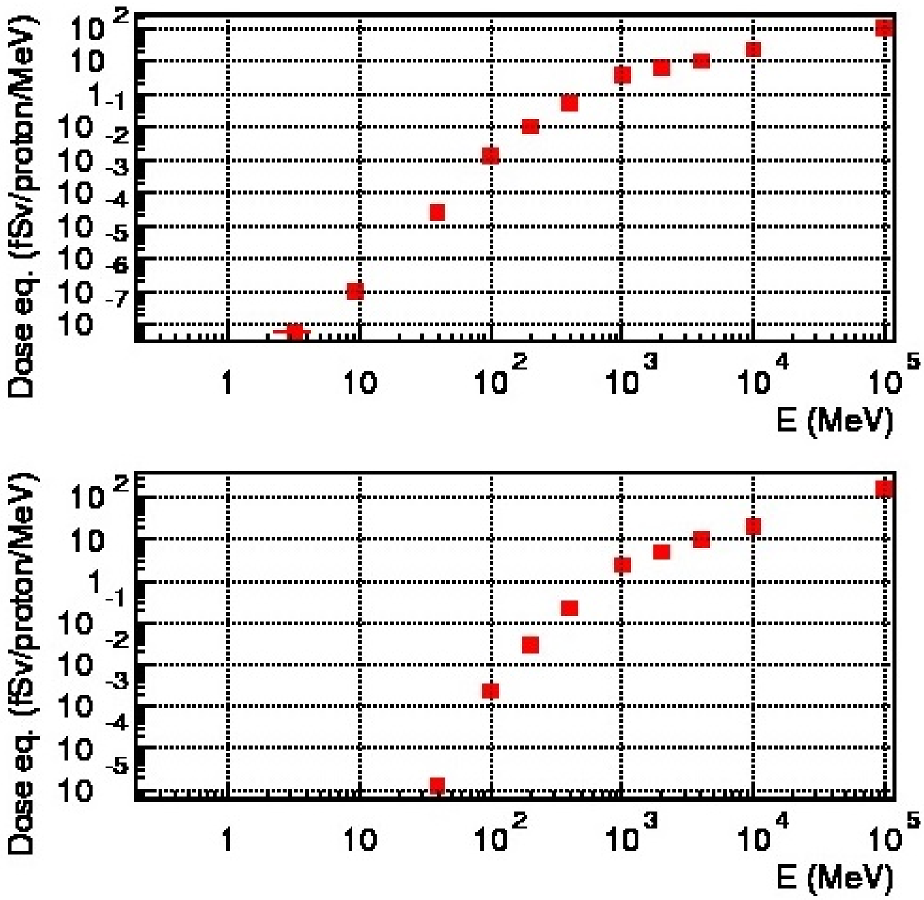


Figure 11: Whole body absorbed dose equivalent per proton as a function of proton kinetic energy for 50 cm (top) and 100 cm (bottom) thick Lunamer shielding.

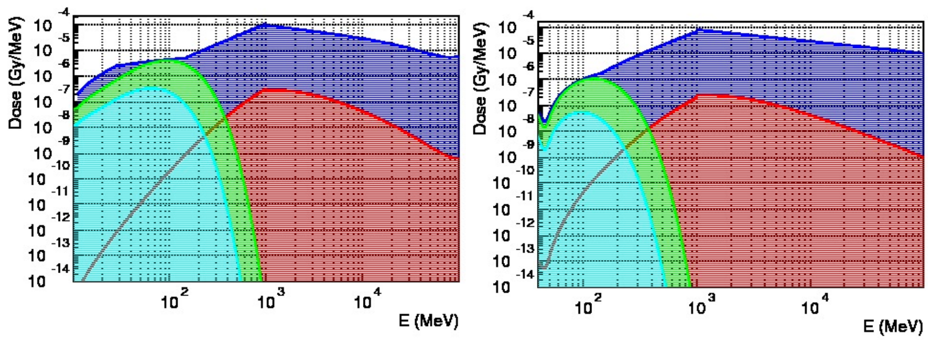


Figure 12: Whole body absorbed dose as a function of proton kinetic energy for a 50 cm(left) and 100 cm (right) thick lunamer shielding. From top to the bottom curves represent the doses for the Flare of 1989 (blue), the worst fluence (green), the mean fluence (light blue), and the GCR for a 30 day period (red).

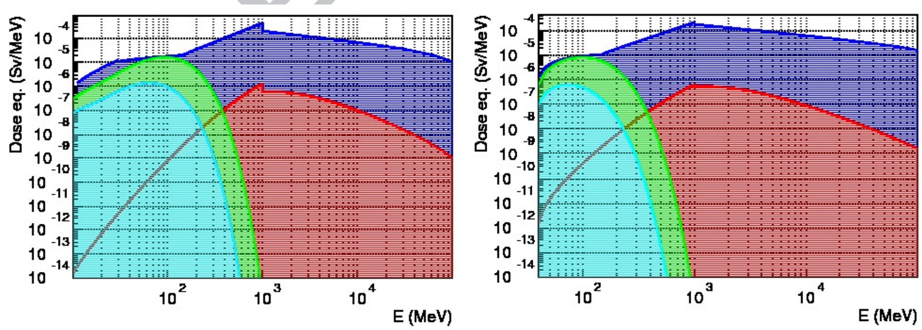


Figure 13: Whole body absorbed dose equivalent as a function of proton kinetic energy for a 50 cm (left) and 100 cm (right) thick Lunamer shielding. From top to the bottom curves represent the doses for the Flare of 1989 (blue), the worst fluence (green), the mean fluence (light blue), and the GCR for a 30 day period (red).

by a factor of 68) than the annual dose limit for a radiation worker, so special protections have to be designed for such cases.

Event	Dose (cGy)		Dose Equivalent (cSv)	
	50 cm	100 cm	50 cm	100 cm
Flare 1989	131	171	341	344
Mean Fluence	0.003	0.0009	0.012	0.005
Worst Fluence	0.055	0.02	0.21	0.11
30 day GCR	0.17-0.48	0.16-0.45	0.40-1.13	0.36-1.02

Table 5: Whole body absorbed dose and dose equivalent for a particular cosmic event for two different shielding thicknesses. The variation in the 30 day GCR dose is a result of a variation in a possible solid angle. For reference the results should be compared to the radiation ground worker exposure limit of 5 cSv (5 rem) per year and NASA recommended exposure limit of 25 cSv (25 rem) per 30 days (NCRP, 1989).

3.5. Conclusions

The research presented in this paper proved that it is possible to create a geopolymer binder from lunar regolith with compressive strength that would enable the construction of structures on the moon. The Lunamer binder showed a microstructure typical of geopolymers when cast, and a less dense microstructure and dendritic formations when pressed isostatically. FTIR analysis showed that the largest amount of geopolymer gel is obtained with the regular cast method, mainly because of the higher amount of activator solution. It was found that during the manufacture of the dry press samples, two strengthening processes occur: a chemical reaction that dissolves the particles to create a new network structure, and a mechanical process that compacts the matrix. Isostatic pressing could be a possibility for the manufacture of building bricks made of Lunamer in the moon, possibly by means of 3D printing. Using the isostatically pressed Lunamer is not a requirement, but if used, its density of 2.29 g/cm^3 will improve the shielding properties. Simulations using FLUKA showed that the radiation protection inside the lunar base built out of lunar regolith based geopolymer cement, the Lunamer, will be sufficient for a prolonged manned lunar mission. The absorbed dose for a 12 month stay is on the order same order of magnitude of the annual whole-body radiation worker limit (5 cSv, 5 rem). Only in the case of rare large solar flares containing high energy protons, the shielding will not protect the crew and the absorbed dose may exceed the dose limit for a radiation worker by an order of magnitude in a short time period. It was suggested that special protections should be designed for this scenario. Further research is necessary to prove the feasibility of this approach in terms of manufacturing and to produce the polymerization reaction under vacuum conditions.

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