

Performance of “Waterless Concrete”

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ABSTRACT: The development of permanent lunar bases is constrained by performance of construction materials and availability of in-situ resources. Concrete seems a suitable construction material for the lunar environment, but water, one of its major components, is an extremely scarce resource on the Moon. This study explores an alternative to hydraulic concrete by replacing the binding mix of concrete (cement and water) with sulfur. Sulfur is a volatile element on the lunar surface that can be extracted from lunar soils by heating. Sulfur concrete mixes were prepared to investigate the effect of extreme environmental conditions on the properties of sulfur concrete. A hypervelocity impact test was conducted, having as its target a 5-cm cubic sample of sulfur concrete. This item consisted of JSC-1 lunar regolith simulant (65%) and sulfur (35%). The sample was placed in the MSFC Impact Test Facility’s Micro Light Gas Gun’ target chamber, and was struck by a 1-mm diameter ($\sim 1.4 \times 10^{-3}$ g) aluminum projectile at 5.85 km/s. In addition, HZTERN code, provided by NASA was used to study the effectiveness of sulfur concrete when subjected to space radiation.

1. INTRODUCTION

In building permanent structures on the moon, such as a human habitat, an indigenous construction material is preferred. The most probable material that has the possibility of being composed entirely of lunar materials is concrete. Concrete is composed of about 70% aggregate and about 30% binder. Aggregate is fine and coarse regolith and the binder is what binds the aggregate together to make concrete. The aggregate used in a lunar environment would be the lunar regolith resulting in $\sim 70\%$ of the materials needed for construction already present. The more indigenous lunar materials used the cheaper construction will be.

2. SULFUR CONCRETE

Sulfur “concrete” is an established construction material (Toutanji et al 2005). Here the sulfur serves as a thermoplastic material that effectively binds with a non-reactive aggregate. Though truly not concrete in a strict sense as no, or very little, chemical reaction occurs between the constituents it has gained wide acceptance, particularly for use in environments subjected to acids and salts. Other properties include good mechanical properties (generally better than Portland cement), low water permeability, and rapid setup times. The composition generally consists of 12 – 22 wt. % sulfur and 78 – 88 wt. % of aggregate. The sulfur might contain 5% plasticizers and the aggregate can consist of any number of materials including rock sands, minerals, and glasses, both coarse and fine. The sulfur melts at $\sim 119^\circ\text{C}$ and the liquid goes through a phase change and “stiffens” above 148°C . Consequently the sulfur and aggregate

are mixed and heated between 130°C and 140°C, a rather narrow working range. Obviously, the concrete product cannot be used in an environment that exceeds the melting point of sulfur.

Sulfur has been found on the moon in the form of the mineral troilite, FeS (Grugel and Toutanji 2008). This raises the interesting possibility of reducing the ore to obtain sulfur for construction purposes, an attractive alternative to conventional concrete as water, an undoubtedly precious resource, is not required. Troilite reduction to elemental sulfur has been previously discussed as well as using sulfur concrete on the moon (Grugel and Toutanji 2006). For the purpose of this paper it is initially assumed that elemental sulfur is available on the lunar surface and a means of using it to make concrete exists.

2.1 Experimental Procedure

Sulfur powder and JSC-1 lunar regolith simulant were used to cast 50.8 mm (2 in.) cubes. The sulfur concrete mixes consisted of 35% sulfur and 65% JSC-1 aggregate by mass. Silica-sulfur binder and JSC-1 aggregate mixes were also prepared to study the effect of silica on the properties of sulfur concrete. Silica is the main element of the lunar regolith composition. The following mixing procedure was followed (Toutanji et al 2005):

1. Weighing the ingredients (purified sulfur, silica sulfur, & JSC-1 soil).
2. Heating up the melting pot up to 145° C (295° F).
3. Placing half of purified sulfur powder or the silica-sulfur binder in the melting pot and allowing it to melt.
4. Placing half of the aggregate in the melting pot and stir for 30 second.
5. After 5 minutes, repeat steps 3 and 4.
6. In the means time, the molds were placed in the oven at temperature of 150° C (300° F).
7. After reaching at least 140° C, the molds are taken out of the oven and sprayed with oil to prevent the concrete from sticking to mold.
8. Pour the molten sulfur concrete in the mold, as shown in Figure 1.
9. After pouring, remove any extra material to get a well-finish at top surface and then allow the mold to cool at room temperature.



Figure 1: Pouring sulfur concrete in molds.

2.2 Results

Figure 2 shows hardened sulfur concrete specimens after cooling. Specimen (C) on the right was poured into an unheated mold while the other two specimens (A and B) were poured into a heated mold. The unheated mold caused the sulfur concrete on the outside to cool faster resulting in a hollow hole, while the other two samples lack holes because the mold was heated. It is also important to shake the mold so that no entrapped air pockets are formed.



Over 12 cubic specimens were made. The tested specimens are shown in Table 1. Group A specimens are made of coarse and fine aggregates, cement, and water with water-to-cement ratio of ~0.4, Group B specimens consisted of JSC-1 Lunar Regolith Simulant (65%) and sulfur (35%).

Table 1 : List of sulfur concrete mixes

	Percentage by Weight		Compressive Strength MPa (psi)
	Sulfur	JSC-1 Soil	
A (concrete)			17.2 (2500)
B (Waterless Con.)	35	65	22.0 (3191)

3. IMPACT TEST

A hypervelocity impact test was conducted its target a 5-cm cubic sample of sulfur concrete. This item consisted of JSC-1 Lunar Regolith Simulant (65%) and sulfur (35%). The sample was placed in the MSFC Impact Test Facility’s Micro Light Gas Gun’ target chamber, and was struck by a 1-mm diameter (~1.4e-03 g) aluminum projectile at 5.85 km/s. Figure 3 shows a photo of the sample after the impact. A conical crater was produced in the target face measuring 12.8 mm in average diameter (6.4 mm radius) and 3.1 mm in central depth. Surrounding the crater is a zone of fractured material, which appears as a crenate cracked area ~ 8 – 12 mm from the crater center, covering ~ 140 degrees, and exhibiting an attached flake and two scars from detached flakes, each ~ 3 – 4 mm long and 2 mm wide. Figure 4 shows the results of a simulation of this impact. The simulation crater is ~ 15 mm in diameter and 3.5 mm deep – in good agreement with the test crater dimensions – and shows a similar conical profile. Note the fractures extending about 1 cm into the sample below the crater.



Figure 3: Sulfur concrete sample after impact by 1-mm diameter aluminum projectile at 5.85 km/s. Horizontal diameter ~12 mm; vertical diameter ~14 mm; crater depth ~3 mm. Crater diameter was presumably increased by a conical shatter zone. A larger fractured zone is evident above the crater, and its inferred diameter would be ~20 mm. Internal damage to the specimen is currently unknown.

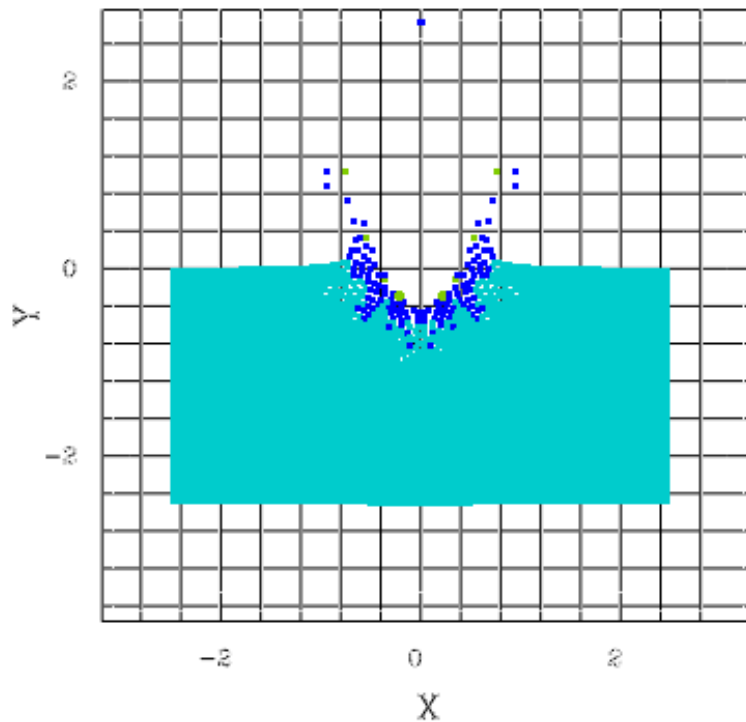


Figure 4: Cross section of an SPHC hydrocode model of the experimental shot. X and Y scales are in cm; the top half of the target block is shown. The grid lines occur every 0.4 cm. The crater is ~15 mm in diameter and 3.5 mm deep, which compares favorably with the test crater dimensions.

For the 30-foot-tall silo structure considered here, the probability of serious impact damage over a 20 year interval is found to be about 1%. If ten of these structures were built to form a lunar base, the probability of wall penetration of one of the structures would increase to about 10%, an unacceptable level for manned structures. These are preliminary results, and a more detailed analysis will be needed for each candidate design. This result does clearly show, however, the importance of a meteoroid threat analysis for any fixed surface base on the moon, and the need to design the structures with this threat in mind. In particular, the identification of important or vulnerable areas on the structure could strongly affect the final result.

Most meteor impacts will be from micro-meteorites. Although not a direct threat to the walls of a structure, vital communications equipment, external sensors, etc., might be more sensitive to small impacts. Over time, erosion of tougher structures will occur. Impact models can be used to evaluate these types of effects. Another consideration is the effect of a large meteor impact on or near the lunar base. Large impacts do occur every day on the moon, and even though such an event is not likely, it could happen. Some warning should be available if a large impactor is dangerously near, and a plan for evacuation to shelter, erection of a temporary shield, or relocation of the crew to a safer location must be considered. A detailed analysis of the damage caused by a catastrophic event could help design the size, shape, and placement of individual structures in the base to minimize detrimental effects.

Only a single experimental test has been done on simulated regolith material. Although the models of impacts on concrete agree reasonably well with this test, more data on a variety of lunar construction materials are needed. Once fully validated on several candidate materials, hydrodynamic models can predict damage at realistic velocities not attainable by experiment (20 km/s versus experiments at 7 km/s). The models can also be used in the design stage to evaluate the relative survivability of different structures.

Finally, a more detailed meteoroid environment model will be needed, including directionality and velocity dependence, to obtain improved estimates of impact probabilities. It is likely that, for most lunar locations, the directionality of windows, antennae, and other control structures can be designed to minimize impact damage.

4. RADIATION

Galactic cosmic ray, solar flares and solar winds are three types of ionizing radiation that pose a threat to humans in an extraterrestrial environment. Ionizing radiation is radiation where electron, protons or other individual particles carry enough energy to ionize an atom or molecule. On the Earth these types of radiations are deflected by our magnetic field or absorbed and altered by our atmosphere. On the moon there is a small fraction of an atmosphere, but it is not thick enough to absorb the radiation. In a lunar environment these types of radiation are present on the surface resulting in the preparation of radiation shielding for humans. Electronics are also susceptible to radiation but are designed and constructed to withstand the radiation present in their environment, humans are not and therefore need extra covering for safety. The data presented here is with respects to humans and not to electronics.

Solar winds come from the Sun's outer most atmosphere. Even though solar winds are present because of their low energy they are easily shielded against and do not pose as much of threat to astronauts as galactic comics rays and solar flares. Solar flares are a large eruption on the surface of the Sun that emits highly charged particle, with energy from 1-1000MeV/nucleon. Presently solar

flares are unpredictable but follow an 11-12 year cycle. During a solar maximum the Sun emits more solar flares and has a stronger interplanetary magnetic field. Galactic cosmic radiation has energies from a 1 GeV/nucleon to almost 10 GeV/nucleon, and come from somewhere out of our solar system. A galactic cosmic ray is an atomic nucleus, it can be any nuclei found in our periodic table, with all of its outer electrons stripped away. Exposure to galactic cosmic rays and other ionizing radiation increases the risk of cancer in astronauts along with other health risks.

The National Council of Radiation Protection and Measurement has set up the Scientific Committee 1-15 on Radiation Protection and Science Goal for Short-Term Lunar Mission. This committee will be determining an acceptable risk level for astronauts on the lunar surface and interplanetary space, the short term and career dose limits for lunar missions, the application of ALARA, “as low as reasonably achievable,” in shielding design for lunar habitats and other extravehicular activities in space, and developing ways to predict or mitigate effects of future galactic cosmic radiation and solar particular events for future Mars missions. Until this committee has come to a conclusion the radiation dose limit for humans on the lunar surface has not been determined.

The effect of ionizing radiation on humans is measured in units of Sievert (Sv) or radiation equivalent man (rem). 100 rem equals 1 Sv and a lethal dose of radiation is 4 to 5 Sv in a short amount of time. Radiation is also measured in two other units a Gray (Gy) and rads. 1 Gy equals 1 joule of energy per kg of living tissue and a rad is the amount of energy from any type of ionizing radiation deposited in any medium, also 1 Gy equals 100 rads. A rem is equal to the absorbed dose in rads times the quality factor of the type of radiation. Another point to make clear about measuring radiation is dose equivalent and equivalent dose. Dose equivalent is the absorbed dose at a certain point in the tissue, this absorbed dose is then weighted by a distribution of quality factors (Q). The quality factor is related to the linear energy transfer (LET) distribution of the radiation at the same point. Equivalent dose is the average absorbed dose in a tissue or organ, and instead of quality factor it is weighted by a radiation weighting factor (W_R).

Using a mathematical code created by Langley Research Center it is possible to compare the radiation effectiveness of certain composites. The mathematical code gives the ICRP 60 Dose Equivalent (cSv/yr) as the shield thickness (g/cm^2) increases. ICRP 60 is the International Commission of Radiation Protection’s 1990s revision of previous guidelines.

The environment that the mathematical code computes in is with respect to the radiation emitted by a galactic cosmic ray. During 1977 solar minimum there was a large radiation environment caused by the solar galactic rays. The following figures and tables have been calculated using the 1977 solar minimum environment.

4.1 Sulfur Concrete Mix

Figure 5 is the ICRP 60 dose equivalent curve from the mathematical code through different substances, such as sulfur concrete, aluminum, polyethylene and lunar regolith (JSC-1 simulant). JSC-1 is lunar soil simulant produced by Johnson Space Center.

A dose rate of 80 cSv/yr was recommended as a standard for comparison means. The shield thickness when the ICRP 60 curve hits 80 cSv/yr is then divided by the density to give the actual thickness a hypothetical wall would need to be to provide that adequate radiation shielding. See Equation 1.

$$Shield\ Thickness\ (cm) = \frac{ShieldThickness(g/cm^2)}{Density(g/cm^3)} \quad (1)$$

Table 2 below is a record of the composition of the substances, the density of the substances, the shield thickness, extrapolated from Figure 5, and the actual thickness the substance would need to be to provide the adequate radiation protect.

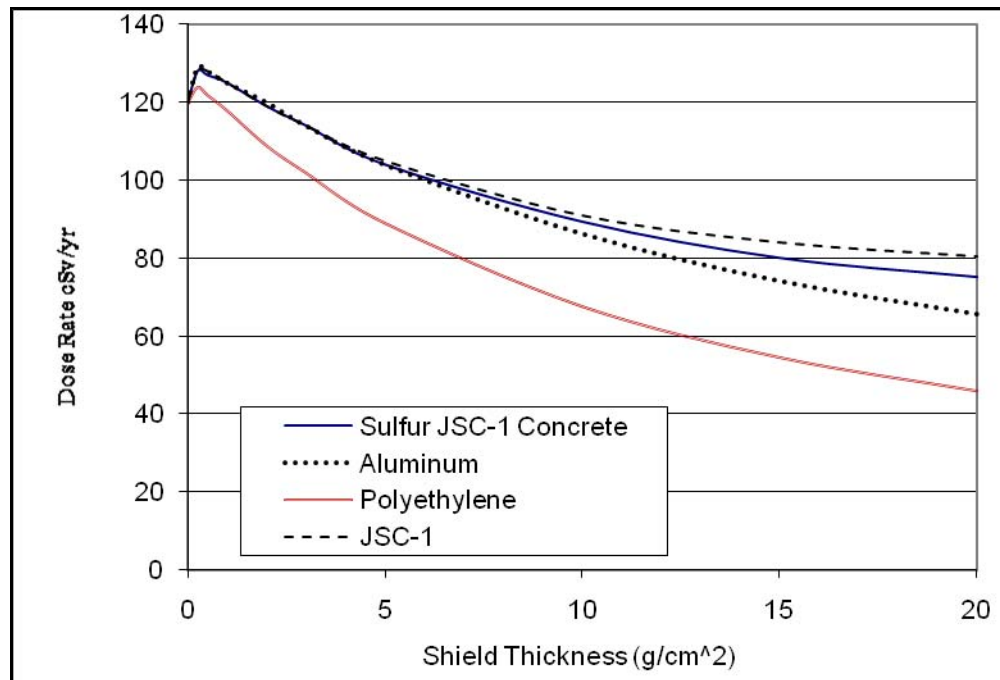


Figure 5: Lunar Radiation through Different Materials.

Table 2 : Thickness of Different Materials.

Composition	Density (g/cm ³)	Shielding Thickness (g/cm ²)	Thickness (cm)
Sulfur JSC-1 Concrete (Sulfur 35% Oxygen 28% Silicon 14% Iron 5.3% Carbon 0.0007%)	2.241339	15	6.6924281
100% Aluminum (Aluminum 100%)	2.7	12.5	4.6296296
100% Polyethylene (Carbon 85.6% Hydrogen 14.3 %)	0.95	7	7.3684211
JSC-1 Regolith (Oxygen 27.5% Silicon 14.1% Iron 5.1% Aluminum 5% Calcium 4.7%)	2.9	20	6.8965517

The sum of the percent composition does not add up to 100% because the program used has a limitation of calculating only 5 elements, resulting in the 5 most abundant elements or the most effective radiation deflection materials, such as carbon to be used. Hydrogen and carbon are both known as excellent shielding materials. Unfortunately hydrogen is not present on the moon and would have to be imported to the moon to be used a radiation shielding material. One of concerns in choosing a material for shielding purposes is the creation of secondary radiation, which is something hydrogen does not do. Secondary radiation is radiation that is cause by ionizing radiation passing through a substance and causing more radiation.

4.2 Polyethylene Lunar Soil Mix

A 1% polyethylene JSC-1 stimulant mix decreases the radiation dose quicker then at of plain JSC-1,

concluding that less material is needed to provide that much protection. Both samples have the similar densities, see Table 3, leading to the less amount of material needed to provided that much radiation shielding. Now taking the sample of 40% Polyethylene JSC-1 mix and examining those findings, it shows that by increase the amount of polyethylene does decrease the ICRP 60 curve, it also decrease the density, resulting in more material needed. In conclusion, just by adding a little bit of polyethylene goes a longer way in radiation shielding then adding a gross amount. This program worked well in examining such a situation.

Table 3: Polyethylene Composition.

Composition	Density (g/cm ³)	Shielding Thickness (g/cm ²)	Thickness (cm)
JSC-1 Regolith (Oxygen 27.5% Silicon 14.1% Iron 5.1% Aluminum 5% Calcium 4.7%)	2.9	20	6.8965517
1% Polyethylene 99% JSC1 (Oxygen 42.7%, Silicon 21.86%, Magnesium 5.33%, Calcium 7.3%, Carbon 1.71%)	2.8805	11	3.8187815
40% Polyethylene 60% JSC1 (Oxygen 26.1% Silicon 13.3% Magnesium 3.26% Calcium 4.5% Carbon 34.3%)	2.12	10.8	5.0943396
100% Polethylene (Carbon 85.6% Hydrogen 14.3 %)	0.95	7	7.3684211

4.2 Conclusion

Carbon and hydrogen are known as excellent radiation shielding materials, so the concrete that processes even the smallest fraction of the these two elements would provide some amount of radiation protection. A concrete wall made of sulfur and JSC-1 simulant would need to be thicker than a wall made of plain JSC-1 simulant to provide the same amount of protection. Even though the addition of sulfur increases the required thickness, a wall would need to be, it is not structurally stable to have JSC-1 alone in construction. Something is needed to binder the lunar soil together and the addition of sulfur seems the most logical choice, despite the problem dealing with radiation.

The mathematical code is not an effective way to determine the actual thickness of the concrete wall needed in a lunar environment. There are other parameters should be considered such as structural stability before an accurate construction standard is applied. Thus, this mathematical program can only be used for comparison means.

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