

## Performance of lunar sulfur concrete in lunar environments

Houssam A. Toutanji<sup>a,\*</sup>, Steve Evans<sup>b</sup>, Richard N. Grugel<sup>c</sup>

<sup>a</sup> Department of Civil and Environmental Eng., University of Alabama in Huntsville, AL, USA

<sup>b</sup> NASA Marshall Space Flight Center (MSFC EM50), Huntsville, AL, USA

<sup>c</sup> NASA Marshall Space Flight Center (MSFC EM30), Huntsville, AL, USA

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### ABSTRACT

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 such as impact and space radiation on the properties of sulfur concrete. A hypervelocity impact test was conducted, having as its target small sulfur concrete samples. The lunar concrete samples have been prepared using JSC-1 lunar simulant, produced by Johnson Space Center, as an aggregate addition. 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 ( $\sim 1.4\text{e}-03$  g) aluminum projectile at 5.85 km/s. 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. The effectiveness of sulfur concrete subjected to space radiation was analyzed using HZETRN mathematical code, provided by NASA. 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. Test results were presented, discussed and put into the context of the lunar environments.

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### 1. Introduction

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 a scarce resource on the moon. 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 lunar construction.

Sulfur "concrete" is an established construction material [1]. 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  $148^\circ\text{C}$ . Consequently the sulfur and aggregate are mixed and heated between  $130^\circ\text{C}$  and  $140^\circ\text{C}$ , 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 [2,3]. The amount of sulfur on the moon is less than 1% by mass and is 11th in weight abundance. 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 [4]. 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.

Sulfur concrete cubes, JSC-1 lunar regolith simulant (65%) and sulfur (35%), measuring 50.8 mm were made to characterize the compressive strength properties. For the hypervelocity impact test,

\* Corresponding author.

E-mail address: [toutanji@cee.uah.edu](mailto:toutanji@cee.uah.edu) (H.A. Toutanji).

similar sulfur concrete cubic specimens were used. For the radiation analysis a mathematical code created by Langley Research Center was used to compare the radiation effectiveness of different composites.

## 2. Experimental procedure

Sulfur powder and JSC-1 lunar regolith simulant were used to cast 50.8 mm cubes. The sulfur concrete mixes consisted of 35% sulfur and 65% JSC-1 aggregate by mass. The following mixing procedure was followed to cast the sulfur concrete [1]:

1. Weighing the ingredients (purified sulfur, silica sulfur and JSC-1 soil).
2. Heating up the melting pot up to 145 °C.
3. Placing half of sulfur in the melting pot and allowing it to melt.
4. Placing half of the aggregate (JSC-1) in the melting pot and stir for 30 s.
5. After 5 min, repeat steps 3 and 4.
6. In the meantime, the molds were placed in the oven at temperature of 150 °C.
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 Fig. 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.

## 3. Results

### 3.1. Compressive strength

Fig. 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 area, while the other two samples lack any 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  $\sim 0.43$ . Group B specimens consisted of JSC-1 Lunar Regolith Simulant (65%) and sulfur (35%). The hydraulic cement concrete specimens were water cured for 28 days before they were tested. The sulfur concrete specimens were left in room temperature for 24 h before they were tested. Results show that the compressive strength of sulfur concrete is higher than normal strength hydraulic cement concrete. This result is similar to an earlier study by Toutanji et al. [1].

### 3.2. Impact test

The hypervelocity impact test was carried out to collect preliminary data on the effect of micrometeoroid and orbital debris on the sulfur concrete. A hypervelocity impact test was conducted

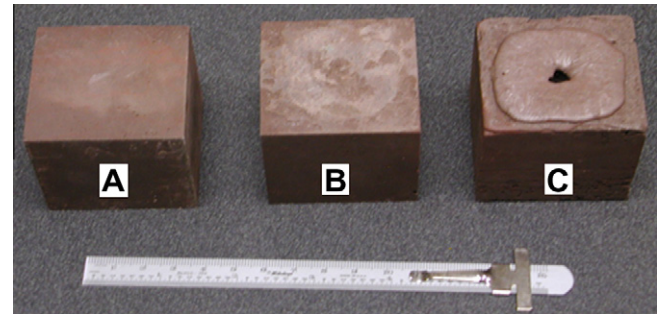


Fig. 2. Hardened sulfur concrete cubes ready to be tested.

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 Marshall Space Flight Center (MSFC) Impact Test Facility's Micro Light Gas Gun target chamber, and was struck by a 1-mm diameter ( $\sim 1.4\text{e-}03$  g) aluminum projectile at 5.85 km/s. Fig. 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  $\sim 8\text{--}12$  mm from the crater center, covering  $\sim 140^\circ$  and exhibiting an attached flake and two scars from detached flakes, each  $\sim 3\text{--}4$  mm long and 2 mm wide.

Fig. 4 shows the results of a simulation of this impact. The simulation crater is  $\sim 15$  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.

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 10 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.

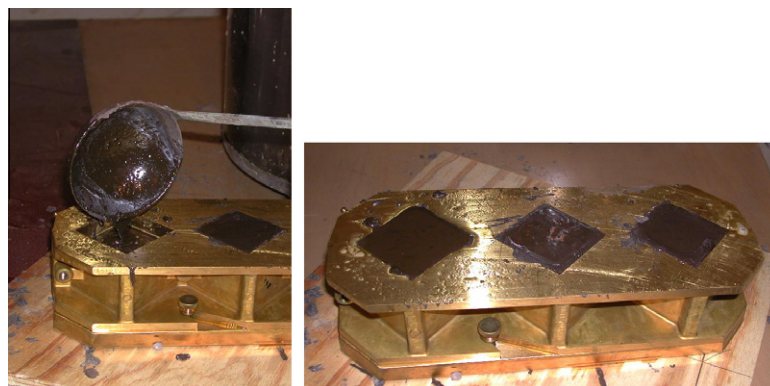
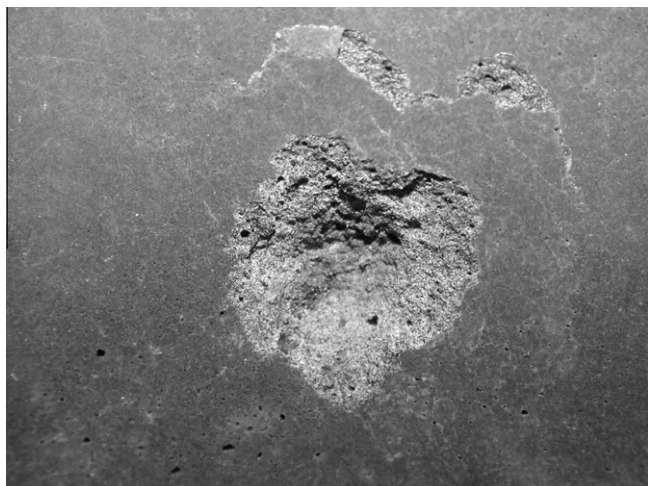


Fig. 1. Pouring sulfur concrete in molds.

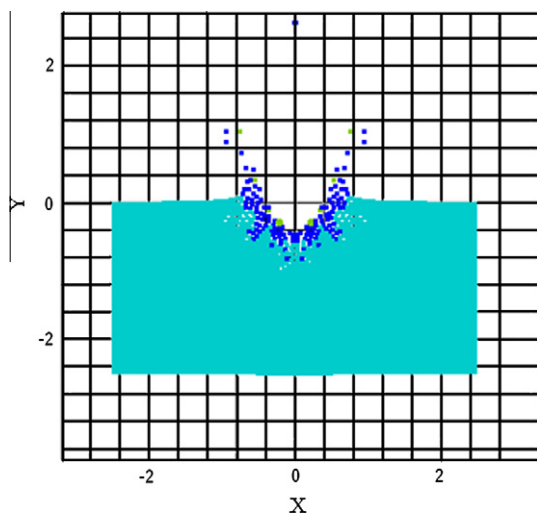
**Table 1**

Compressive strength of hydraulic concrete and sulfur concrete.

	Percentage by weight		Compressive strength (MPa) (psi)
	Sulfur	JSC-1 soil	
A (hydraulic concrete)			24.2
B (sulfur concrete)	35	65	31.0



**Fig. 3.** Sulfur concrete sample after impact by 1-mm diameter aluminum projectile at 5.85 km/s. Horizontal diameter  $\sim 12$  mm; vertical diameter  $\sim 14$  mm; crater depth  $\sim 3$  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  $\sim 20$  mm. Internal damage to the specimen is currently unknown.



**Fig. 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  $\sim 15$  mm in diameter and 3.5 mm deep, which compares favorably with the test crater dimensions.

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.

### 3.3. Radiation

Galactic cosmic rays, solar flares and solar winds are three types of ionizing radiation that pose a threat to humans in an extraterrestrial environment [5]. Ionizing radiation is radiation where electrons, protons or other individual particles carry enough energy to ionize an atom or molecule. On the Earth these types of radiation are deflected by our magnetic field or absorbed and altered by our atmosphere. On the moon there is some atmosphere but it is not thick enough to absorb the radiation. The radiation will impact the surface with virtually no attenuation from lunar volatiles. 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 herein is with respect 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 a threat to astronauts as galactic cosmic rays and solar flares. Solar flares are large eruptions on the surface of the Sun that emit highly-charged particles, with energy from 1 to 1000 MeV/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 comes 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 Goals for the Short-Term Lunar Missions [6]. This committee is charged in determining an acceptable risk level for astronauts on the lunar surface and in 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 (rem) [5]. 100 rem equals 1 Sv and a lethal dose of radiation is 4–5 Sv in a short amount of



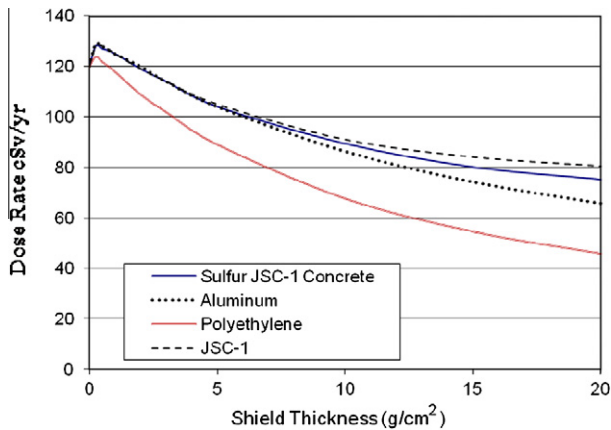


Fig. 5. Lunar radiation through different materials.

time. Radiation is also measured in two other units Gray (Gy) and rads. 1 Gy equals 1 J 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, 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 a quality factor (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 (NZETRN) created by Langley Research Center it is possible to compare the radiation effectiveness of certain composites [7]. The mathematical code gives the International Commission on Radiological Protection (ICRP) 60 dose equivalent (cSv/yr) as the shield thickness ( $\text{g}/\text{cm}^2$ ) increases. ICRP 60 is the International Commission of Radiological Protection's 1990s revision of previous guidelines [8]. The environment in which the mathematical code computes changes is with respect to the radiation emitted by galactic cosmic rays. During the 1977 solar minimum there was a large radiation environment caused by solar galactic rays.

### 3.3.1. Sulfur concrete composite mix

Fig. 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).

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, as can be calculated in Eq. (1).

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

Table 2 is a record of the composition of the substances, the density of the substances, the shield thickness (extrapolated from Fig. 5), and the actual thickness the substance would need to be to provide adequate radiation protection.

The sum of the percent composition does not add up to 100% because the program has a limitation of calculating only five elements. The results are based on the five most abundant elements or the most effective radiation deflection materials, such as carbon. Hydrogen and carbon are both known as excellent shielding materials. Unfortunately hydrogen may not be present on the moon and

Table 2  
Thickness of different materials.

Composition	Density ( $\text{g}/\text{cm}^3$ )	Shielding thickness ( $\text{g}/\text{cm}^2$ )	Thickness (cm)
Sulfur JSC-1 concrete (Sulfur 35%, oxygen 28%, silicon 14%, iron 5.3%, carbon 0.0007%)	2.241339	15	6.7
100% Aluminum (Aluminum 100%)	2.7	12.5	4.6
100% Polyethylene (Carbon 85.6%, hydrogen 14.3%)	0.95	7	7.4
JSC-1 regolith (Oxygen 27.5%, silicon 14.1%, iron 5.1%, aluminum 5%, calcium 4.7%)	2.9	20	6.9

Table 3  
The effect of polyethylene on radiation shielding.

Composition	Density ( $\text{g}/\text{cm}^3$ )	Shielding thickness ( $\text{g}/\text{cm}^2$ )	Thickness (cm)
JSC-1 regolith (Oxygen 27.5%, silicon 14.1%, iron 5.1%, aluminum 5%, calcium 4.7%)	2.91	20	6.89
1% Polyethylene 99% JSC1 (Oxygen 42.7%, silicon 21.86%, magnesium 5.33%, calcium 7.3%, carbon 1.71%)	2.88	11	3.81
40% Polyethylene 60% JSC1 (Oxygen 26.1%, silicon 13.3%, magnesium 3.26%, calcium 4.5%, carbon 34.3%)	2.12	10.8	5.1
100% Polyethylene (Carbon 85.6%, hydrogen 14.3%)	0.95	7	7.37

would have to be imported to the moon to be used as a radiation shielding material. One concern 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 caused by ionizing radiation passing through a substance and causing more radiation.

### 3.3.2. Polyethylene lunar soil mix

Replacing 1% of JSC-1 simulant with polyethylene (by mass) results in decreasing the radiation dose significantly; thus, less material is needed to provide the same amount of protection (see Table 3). Both samples have similar densities but a smaller amount of material is needed to provide that much radiation shielding. Now taking the sample of 40% polyethylene JSC-1 mix and examining those findings, it was shown that increasing the amount of polyethylene decreases the ICRP 60 curve; it also decreases the density, resulting in more material needed. In conclusion, adding a small amount of polyethylene goes a longer way in radiation shielding than adding a substantial amount. This mathematical code (NZETRN), created by NASA Langley Research Center, worked well in examining such a situation.

## 4. Conclusion

The following conclusions can be drawn from this study:

- Sulfur concrete exhibits better compressive strength than Portland hydraulic cement concrete of the specific water–cement ratio of 0.43. Sulfur concrete has a much rapid setup time.
- The hypervelocity impact test model developed by NASA predicted a similar size crater of equal dimensions to that produced by the experimental test. Although the model agrees reasonably well with the experimental test results, 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. This model could also be used in the design stage to evaluate the relative survivability of different structures.

- Carbon and hydrogen are known as excellent radiation shielding materials, so the concrete that processes even the smallest fraction of 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 entirely of JSC-1 simulant to provide the same amount of protection.

The addition of a small amount of JSC-1 simulant with polyethylene seems to provide the same protection as that of 100% JSC-1 simulant but with less material (thinner section). However, if a large amount of polyethylene is added that would result in decreasing the density of the composite and thus warranting more material. Polyethylene should be considered as an additive to lunar soil to improve radiation shielding protection. It should be noted that the mathematical code NZETRN is not an effective way to determine the actual thickness of the concrete wall needed in a lunar environment. There are other parameters such as structural stability that should be considered before an accurate construction standard is applied. Thus the mathematical code NZETRN program should only be used for comparison means.

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