Construction and Building Materials 29 (2012) 444–448

Contents lists available at SciVerse ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Performance of lunar sulfur concrete in lunar environments

Houssam A. Toutanji [a,*], Steve Evans [b], Richard N. Grugel [c]

[a] Department of Civil and Environmental Eng., University of Alabama in Huntsville, AL, USA
[b] NASA Marshall Space Flight Center (MSFC EM50), Huntsville, AL, USA
[c] NASA Marshall Space Flight Center (MSFC EM30), Huntsville, AL, USA

ARTICLE INFO

Article history:
Received 18 May 2011
Received in revised form 2 September 2011
Accepted 2 October 2011
Available online 29 November 2011

Keywords:
Sulfur
Concrete
Strength
Impact
Radiation
Lunar

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 (∼1.4e−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.

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 course 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 ∼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 ∼119 °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 [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 (H.A. Toutanji).

0950-0618/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.conbuildmat.2011.10.041

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 ~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 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 Marshal Space Flight Center (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. 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 ~8–12 mm from the crater center, covering ~140° and exhibiting an attached flake and two scars from detached flakes, each ~3–4 mm long and 2 mm wide.

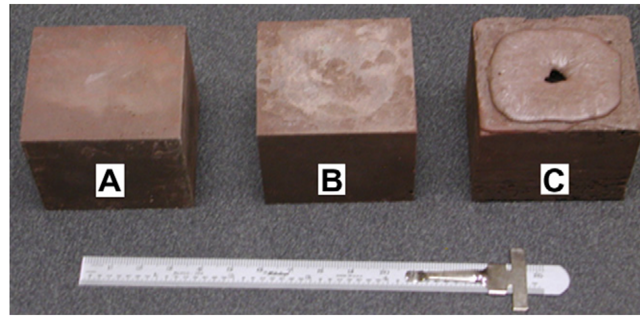

Fig. 2. Hardened sulfur concrete cubes ready to be tested.

Fig. 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.

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.

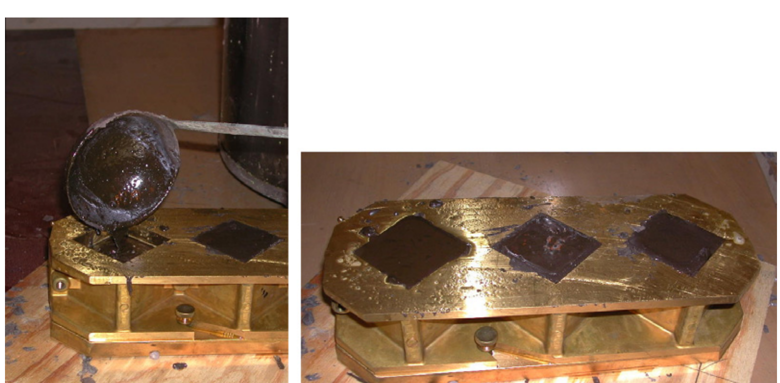

Fig. 1. Pouring sulfur concrete in molds.