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PRODUCTION OF LUNAR CONCRETE USING MOLTEN SULFUR

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by

Dr. Husam A. Omar

Department of Civil Engineering
University of South Alabama
Mobile, Alabama 36688

Abstract

The United States has made a commitment to go back to the moon to stay in the early part of the next century. In order to achieve this objective it became evident to NASA that a Lunar Outpost will be needed to house scientists and astronauts who will be living on the moon for extended periods of time. A study has been undertaken by the authors and supported by NASA to study the feasibility of using lunar regolith with different binders such as molten sulfur, epoxy or hydraulic cement as a construction material for different lunar structures. The basic premise of this study is that it will be more logical and cost effective to manufacture lunar construction materials utilizing indigenous resources rather than transporting needed materials from earth. Lunar concrete (made from Hydraulic Cement and lunar soil) has been studied and suggested as the construction material of choice for some of the lunar projects. Unfortunately, its hydration requires water which is going to be a precious commodity on the moon. Therefore this study explores the feasibility of using binders other than hydraulic cement such as sulfur or epoxy with lunar regolith as a construction material.

This report describes findings of this study which deals specifically with using molten sulfur as a binder for Lunar concrete. It describes laboratory experiments in which the sulfur to lunar soil simulant ratios by weight were varied to study the minimum amount of sulfur required to produce a particular strength. The compressive and tensile strengths of these mixes were evaluated. Metal and fiber glass fibers were added to some of the mixes to study their effects on the compressive and tensile strengths. This report also describes experiments where the sulfur is melted and mixed with the lunar regolith in a specially designed vacuum chamber. The properties of the produced concrete were compared to those of concrete produced under normal pressure.

Introduction

Throughout the history of space exploration endeavors, the moon has attracted most attention because of its closeness to earth. The Apollo manned space program has provided us

with a wealth of information about the moon, but since 1972 there was no attempt to go back to the moon for further exploration. Recently more attention has been paid to space exploration and a commitment was made to go back to the moon for extended periods of time.

Because of its minimal atmosphere, long nights and precise movements, the moon is an ideal place for deep space astronomy. NASA is currently studying several options of establishing an observatory on the moon's surface (Omar, 1992). In addition to astronomy, the moon will be an ideal place for doing low gravity research such as growing crystals and investigating the effects of reduced gravity on humans and plants. Furthermore the moon will serve as a stepping stone to other planets where spaceships will refuel and be launched from the surface of the moon.

NASA has recognized that in order to achieve its objectives of extended duration visits to the moon, a lunar outpost is needed to house the scientists and workers in addition to the equipment needed for research (Webb, 1991), (Franklin, 1991), (Bialla et al, 1992) and (Benaroya et al, 1992). Other structures will also be needed to support these missions such as landing and launch platforms, un-pressurized warehouses to house heavy machinery and stable foundations for the outpost and lunar observatories. Lunar concrete has been suggested as the material of choice because it utilizes the lunar soil and rock as construction materials, thus less materials have to be imported from earth (Lin, 1991), (Matsumoto et al. 1991), (Kaden, 1991), (Hwang et al, 1991). This will result in substantial savings in construction costs especially when it is estimated that it will cost \$100,000 to transport one Kg from earth to the moon (MSFC, 1992).

Although most researchers agree that concrete will be the ideal material to use for lunar structures because of its strength, durability and excellent shielding properties, there is little information on what is lunar concrete. Most of the research currently being performed is focused on hydraulic cement based concrete. But one of the main disadvantages of hydraulic cement concrete is that it requires water to gain strength. Although basic research has been done on producing water from lunar regolith (Kanamori et al, 1990), its use to hydrate concrete is doubtful especially in the first stage of the lunar outpost.

This project was carried out by the authors to study the feasibility of using lunar regolith and binders other than hydraulic cement to produce lunar concrete. The use of sulfur concrete as a lunar or Martian construction material was first suggested by Leonard and Johnson, 1988. The main advantages of using sulfur concrete in the lunar environment include that it does not need water to gain strength, it gains its full strength in a relatively short period of time and requires

low heat to manufacture. Sulfur Concrete (SC) has been thoroughly studied and is currently being produced and used for terrestrial applications in the United States and Europe (Shrive et al, 1981), (Anon, 1983), (McBee et al, 1985). It is normally used in acidic and saline environments which are corrosive to Portland Cement Concrete (Anon, 1988).

Preparation of Test Specimens

Test specimens cast were 50.8 mm (2 inch) cubes and dog-bone briquettes of varying ratios of sulfur powder and JSC-1 lunar soil simulant (McKay et al, 1993). The objective was to determine the relationship between compressive and tensile strengths and sulfur-to-lunar soil simulant ratio by weight. Specimens were prepared as follows. The sulfur and lunar soil simulant were weighed according to the particular mix ratio considered and mixed together thoroughly. Then the mix was placed in a conventional oven set at 150°C until the sulfur started to melt. This normally takes anywhere between 20 to 30 minutes depending on the sulfur content in the mix. Then the materials were mixed again and returned to the oven. This procedure was repeated until all the sulfur has completely melted and thoroughly mixed with the lunar soil simulant. The 50.8 mm (2 inch) metal cube molds were heated to 150°C prior to placing the concrete. This was found to prevent early solidification of the sulfur as it touches the mold. The concrete was then poured in three equal lifts. Each lift was hammer compacted with a 50.8 mm square wooden ram rod. The exposed surface of each compacted lift was raked prior to the placement of each succeeding lift in order to prevent cold-joints from forming. Specimens were finally allowed to cool at room temperature which normally took close to 30 minutes.

Workability

The workability of the produced sulfur concrete was found to depend mainly on the percent sulfur by weight present in the mix. For specimens with sulfur content below 30% workability was unacceptable. It was evident that there was not enough sulfur content to coat the lunar soil simulant particles in order to provide proper bonding. However, specimens with sulfur content between 30% and 40% were somewhat dry and needed compaction for proper placement. Their consistency is equivalent to that of a Portland cement mortar mix with water/cement ratio of 0.40. Concrete specimens with sulfur content exceeding 40% were much more fluid and would flow easily into the mold. They have an equivalent consistency of a Portland cement mortar mix with water/cement ratio of 0.55 or higher. No compaction was required when placing

these concretes. It was also observed that these mixes had a tendency to solidify more quickly than mixes with lower sulfur content. Thus reducing time allowed for placing the concrete in addition to complicating the mixing procedure. To remedy this situation, the mix procedure required constant attention and stirring.

Properties of Produced Concrete

The average density of the produced concrete was found to be 2200 kg/m³ which is similar to normal weight concrete. The appearance of the surface was smooth. There were no apparent voids on the inside or the outside of the specimens.

The sulfur content for specimens tested ranged from 25% to 70% by weight. Multiple specimens were tested for each mix design. As shown in table 1, the average compressive strengths of 6.07, 24.0, 33.8, 25.4, 24.7, 25.0 and 15.7 MPa were determined for sulfur contents of 25%, 30%, 35%, 40%, 50%, 60%, and 70%, respectively. The tensile strengths were observed to range anywhere between 10% and 15% of the compressive strengths for all specimens tested. The failure mode observed in compression was typical of brittle materials. Throughout loading history, the specimens would continually flake apart until completely crumbling upon reaching the failure load. The tensile failure mode was also typical of brittle materials were a flat failure surface was observed when the two pieces of the dog-bone briquettes were pulled apart.

Table 1: Non-Reinforced Sulfur Concrete Mixes

% Sulfur	25	30	35	40	50	60	70
Number of specimens	3	9	9	10	6	6	6
Avg. comer. Strength*	6.07	24.0	33.8	25.4	24.7	25.0	15.7
Avg. Tensile Strength*	0.33	2.9	3.7	2.0	2.7	2.6	1.4

* Average strength (MPa)

An investigation was conducted to study types of reinforcement to be used with this concrete in order to reduce its brittleness and increase its tensile strength. Metal (Aluminum) fibers and fiberglass fibers were studied. The metal fibers used were approximately 0.05 mm square in cross-section. Each fiber was approximately 1.25 mm in length with legs at either end

bent at 90°, each leg has a length of approximately 0.55 mm. Two percent (2%) by weight of metal fibers were added to concretes with 30%, 35%, 40%, and 50% sulfur by weight. As shown in table 2, Average compressive strength increase was dependant on the percent sulfur present in the concrete. The maximum increase in strength was gained at the 40% mix, nonetheless the 35% mix gave the highest strength of 43.0 MPa. No flaking was observed and the specimens were intact as the failure load was reached. Therefore, the mode of failure was considerably less brittle than non-reinforced specimens. Figure 1 compares the compressive strengths of reinforced and non-reinforced concretes. The metal fibers increased the ductility in tension but resulted in an average of 5% reduction in the tensile strength. The only possible explanation for such reduction is that these fibers are breaking the continuity of the sulfur bond thus creating weak regions at which failure is initiated.

The other fibers tested were 25.4 mm long Fiberglass fibers. Two ratios were tried, they were 0.25% and 0.50% by weight. It was observed that the fiberglass fibers reduced the compressive strength by an average of 27% and the tensile strength by an average of 20% while not adding any ductility to the produced concrete. Therefore, at this stage of the project, fiberglass fibers do not seem to be an effective type of reinforcement for lunar concrete.

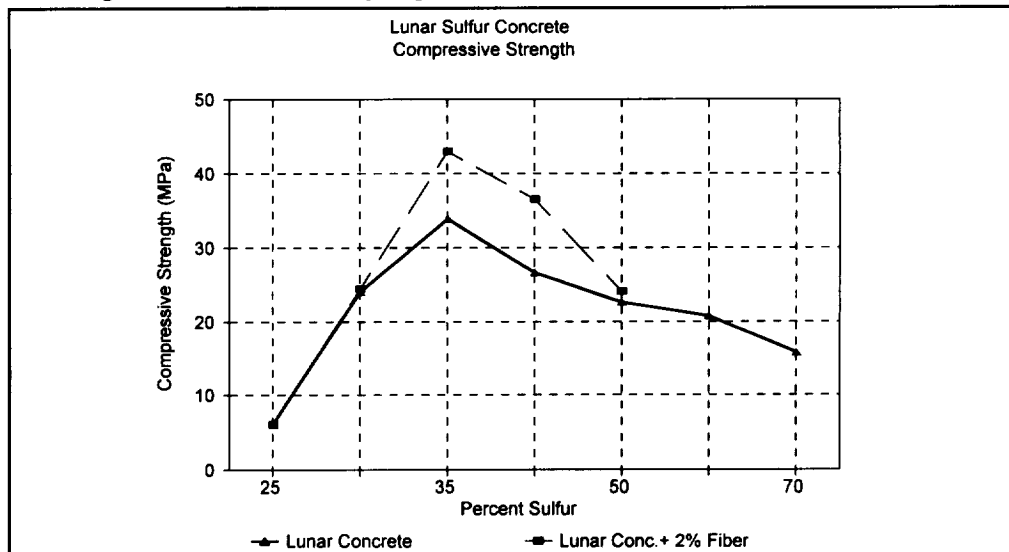
Table 2: Reinforced Sulfur Concrete Mixes with 2% Metal Fiber

% Sulfur	30	35	40	50
Number of Specimens Tested	9	9	9	9
Compressive Strength*	24.4	43.0	36.5	24.1
Percent Increase in Strength	1.7%	27%	37%	6.4%

* Average compressive strength (Mpa)

Summary and Conclusions

Sulfur concrete offers distinct advantages over hydraulic concrete in a lunar environment. Sulfur concrete does not require water. Although water can be manufactured on the moon, it is going to be a precious commodity therefore its use to hydrate concrete is very doubtful. In addition, sulfur concrete gains strength in a very short time when compared to hydraulic cement concrete thus substantially reducing construction time. This is extremely important because of the dangers inherent in being exposed in the lunar environment for extended periods of time.



Compressive and tensile strengths of sulfur concrete obtained in the exceed those for hydraulic cement concretes. The maximum compressive strength of non-reinforced sulfur

concrete was found to be 33.8 MPa for a 35% sulfur content by weight. While the maximum strength for the same sulfur concrete with the addition of 2% by weight Aluminum fibers was found to be 45.5 MPa.

Suggestions for Future Work

More testing needs to be carried out to evaluate other properties of sulfur concrete such as the stress-strain behavior, durability in the lunar environment and different types of reinforcement. In addition, tests should be performed to study the feasibility of epoxy concretes and evaluate the mechanical properties of these alternatives to hydraulic cement concretes before we can make an intelligent decision on what construction material to use in a lunar environment.

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