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A novel material for in situ construction on Mars: experiments and numerical simulations

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HIGHLIGHTS

- The developed Martian Concrete is highly feasible for construction on Mars.
- The optimal Martian Concrete mix consists of 50% sulfur and 50% regolith.
- The Martian Concrete is mechanically simulated by a discrete particle model.
- The Martian Concrete has compressive strength of above 50 MPa.

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ABSTRACT

A significant step in space exploration during the 21st century will be human settlement on Mars. Instead of transporting all the construction materials from Earth to the red planet with incredibly high cost, using Martian soil to construct a site on Mars is a superior choice. Knowing that Mars has long been considered a “sulfur-rich planet”, a new construction material composed of simulated Martian soil and molten sulfur is developed. In addition to the raw material availability for producing sulfur concrete and a strength reaching similar or higher levels of conventional cementitious concrete, fast curing, low temperature sustainability, acid and salt environment resistance, 100% recyclability are appealing superior characteristics of the developed Martian Concrete. In this study, different percentages of sulfur are investigated to obtain the optimal mixing proportions. Three point bending, unconfined compression and splitting tests were conducted to determine strength development, strength variability, and failure mechanisms. The test results show that the strength of Martian Concrete doubles that of sulfur concrete utilizing regular sand. It is also shown that the particle size distribution plays an important role in the mixture’s final strength. Furthermore, since Martian soil is metal rich, sulfates and, potentially, polysulfates are also formed during high temperature mixing, which might contribute to the high strength. The optimal mix developed as Martian Concrete has an unconfined compressive strength of above 50 MPa. The formulated Martian Concrete is simulated by the Lattice Discrete Particle Model (LDPM), which exhibits excellent ability in modeling the material response under various loading conditions.

1. Introduction

Sulfur has been used as a molten bonding agent for quite a long time in human history. The use of sulfur was mentioned in the literature of ancient India, Greece, China and Egypt [7]. For example, sulfur was one of the raw materials to manufacture gunpowder by ancient Chinese [29]; sulfur was also used to anchor metal in stone during the 17th century [6]. Starting in the 1920s, sulfur concrete has been reported to be utilized as a construction material [24]. Various researchers and engineers studied and succeeded in obtaining high-strength and acid-resistant sulfur concretes [1–3]. In the late 1960s, Dale and Ludwig pointed out the significance of well-graded aggregate in obtaining optimum strength [4,5].

When elemental sulfur and aggregate are hot-mixed, cast, and cooled to prepare sulfur concrete products, the sulfur binder, on cooling from the liquid state, first crystallizes as monoclinic sulfur (S_β) at 238 °F (114 °C). On further cooling to below 204 °F (96 °C), S_β starts to transform to orthorhombic sulfur (S_α), which is the

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stable form of sulfur at ambient room temperatures [8]. This transformation is rapid, generally occurring in less than 24 h and resulting in a solid construction material. However, since S_α is much denser than S_β, high stress and cavities can be induced by sulfur shrinkage. Hence, durability of unmodified sulfur concrete is a problem when exposed to humid environment or after immersion in water. In the 1970s, researchers developed techniques to modify the sulfur by reacting it with olefinic hydrocarbon polymers [9,16], dicyclopentadiene (DCPD) [10,12,11,15,17], or other additives and stabilizers [13,14,18] to improve durability of the product. Since then, commercial production and installation of corrosion-resistant sulfur concrete has been increasing, either precast or installed directly in industrial plants where portland cement concrete materials fail from acid and salt corrosion [24].

For earth applications, well developed sulfur concrete features (1) improved mechanical performance: high compressive & flexural strength, high durability, acid & salt water resistant, excellent surface finish and pigmentation, superior freeze/thaw performance; (2) cost benefits: faster setting-solid within hours instead of weeks, increased tolerance to aggregate choice; and (3) environmentally friendly profile: reduced CO_2 footprint, no water requirements, easily obtainable sulfur as a byproduct of gasoline production, recyclability via re-casting, compatibility with ecosystem, e.g. for marine applications. Current pre-cast sulfur concrete products include, but are not limited to, flagstones, umbrella stands, counterweights for high voltage lines, and drainage channels [38].

For example, in January 2009, around 80 m sewage pipeline in the United Arab Emirates (UAE) was removed and replaced by sulfur concrete. In the same time period, a total of 215 fish reef blocks made of sulfur concrete (2.2 tons/block) were stacked at a depth of 15 m, 6 km off the coast of UAE [35]. With regular concrete fish reefs, the growth of algae and shells takes time because concrete is alkaline. However, since sulfur concrete is practically neutral in alkalinity, algae and shell growth was observed soon after installation.

While sulfur concrete found its way into practice as an infrastructure material, it is also a superior choice for space construction considering the very low water availability on the nearby planets and satellites [23]. After mankind stepped on the lunar surface in 1969, space agencies have been planning to go back and build a research center on the moon. Since local material is preferred to reduce expenses, starting in the early 1990s, NASA and collaborative researchers studied and developed lunar concrete using molten sulfur. Around the year 1993, Omar [20] made lunar concrete by mixing lunar soil simulant with different sulfur ratio ranging from 25% up to 70% and found the optimum mix with 35% sulfur to reach a compressive strength of 34 MPa. Later he added 2% of steel fibers to the mixes and increased the optimum strength to 43 MPa. However, lunar concrete has serious sublimation issues because of the near-vacuum environment on the moon. In 2008, Grugel and Toutanji [31,33,41] reported experimental results of two lunar concrete mixes: (1) 35% sulfur with 65% lunar soil simulant JSC-1, and (2) 25% sulfur and 20% silica binder mixture with 55% JSC-1. The two mixtures, similar in strength ($\sim$ 35 MPa), revealed a continuous weight loss due to the sublimation of sulfur when placed in a vacuum environment, 5×10^{-7} torr, at 20 °C for 60 days. Based on the measurements, it was predicted that sublimation of a 1 cm deep layer from the two sulfur concrete mixes would take 4.4 and 6.5 years respectively. The sublimation rate varied from rapid at the high lunar temperatures (<120 °C) to essentially nonexistent at the low lunar temperatures (−180 °C–−220 °C). However, the low temperature on the moon is too harsh to maintain intact mechanical properties of sulfur concrete. After cycled 80 times between −191 °C (−312 °F) and 20 °C (68 °F), the samples failed at about 7 MPa under compression, which is about 1/5 of the average strength, 35 MPa, of the non-cycled samples.

While the moon is the closest and only satellite of earth, its near-vacuum environment, broad temperature range and long day-night rhythm, about 30 earth days, are not the most adequate for human settlement. Venus is the closest planet to Earth, however it is also the hottest planet in the solar system with an average surface temperature over 400 °C [45], making it uninhabitable for humans. Mars, on the other hand, is not too hot nor too cold, and has an atmosphere to protect humans from radiation. Its day/night rhythm is very similar to that on Earth: a Mars day is about 24 h and 37 min [25]. Thus, Mars is the most habitable planet in the solar system after Earth. In recent years, many countries, including the U.S., China, and Russia, announced to launch manned Mars missions in the next decades. Due to the dry environment on Mars, sulfur concrete is a superior choice for building a human village on the red planet. Studies of Martian meteorites suggest elevated sulfur concentrations in the interior, and Martian surface deposits contain high levels of sulfur (SO_3 up to 37 wt%, average 6 wt%), likely in the forms of sulfide minerals and sulfate salts [37]. Except of the easiest option of finding a sulfur mine on Mars, like the one in Sicily on Earth, elemental sulfur can be extracted from sulfides or sulfates through various chemical and physical processes, for example, by heating up the sulfur compounds [19]. NASA has advanced programs on In Situ Resources Utilization (ISRU) [30] for this specific purpose. Moreover, the atmospheric pressure (0.636 kPa) [34] as well as temperature range ($\leqslant$35 °C) are highly suitable for the application of sulfur concrete. As shown in Fig. 1 [31], the most possible construction site on Mars has environmental conditions in the Rhombic (stable) state of sulfur and is three orders of magnitude in pressure above the solid–vapor interface. Thus, sublimation is not an issue and a relatively warm area can be selected as the construction site. Furthermore, with the temperature on Mars lower than 35 °C, the drawback of sulfur concrete melting at high temperature will not be an issue for initial constructions such as shelters and roads while certainly might be of concern for long term settlements in which fire resistance would be important.

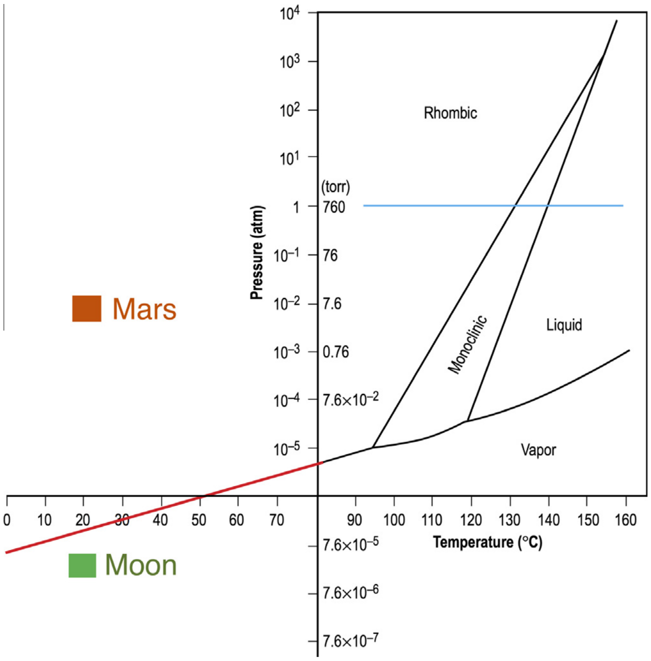

Fig. 1. Sulfur phase diagram with labeled environmental conditions on Mars and Moon [31].