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# Optimizing Strength and Impermeability of Martian Sulfur Concrete for Building Structures

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# Introduction:

Building structures on Earth is like second nature to humans. All the materials are already on the planet, and can be transported worldwide to be able to begin construction. Scientists are looking beyond Earth to see the possibilities of inhabiting and building on Mars. Mars was chosen since it is the closest neighboring planet to Earth (Good, 2019). However, construction on Mars comes with its fair share of problems. The resources that are used to construct a building would have to come from Mars, since the cost of launching one kilogram of material into low Earth orbit is approximately $2,920, and build a structure on Mars would be approximately between 100-200 kilograms of materials, let alone food and other devices required for construction (Jones, 2018). In order to solve this problem, scientists have been looking into ways to use materials that are abundant on Mars for construction. The method that this study will address is creating sulfur concrete with Martian Regolith, which is possibly one of the most viable options to use for building on the planet.  Other methods of construction exist as well, where other scientists are looking into building a structure out of 3D printed ice. However, Sulfur concrete will be a more viable option, since the regolith is more readily available than liquid water ice.

Sulfur is readily available on Mars, however it is not in its elemental form (King & McLennan, 2010). It is possible to extract elemental sulfur from sulfur compounds on Mars, and the planet has a natural sulfur cycle. It is possible to create elemental sulfur in a reduction equation, where the $MgSO4$ or $FeSO4$ compounds are hydrated to produce $H2S$, which can be used to make elemental sulfur. This process can be difficult since it runs the risk of producing sulfur dioxide, which is toxic to breath in on Earth, but on Mars, this risk can be lowered due to the lack of atmosphere. Sulfur is located in Martian Meteorites and throughout the planet in the soil, mostly in the form of sulfur salts. This study is looking at the effect that elemental sulfur has on the permeability and strength of sulfur concrete at different percentages of regolith.

Other scientists have studied aspects of building with sulfur concrete on Mars. One study conducted by a student at Northwestern University tested the compression strength of sulfur concrete made with a specific Martian regolith simulant called JSC-1a (Wan, 2016). The study found that the compression strength of sulfur concrete made with the JSC-1a simulant was most durable at 50% (± 2.5%) by weight. However, this study is limited since it does not test for percent voids or water absorption, in order to find the permeability or lack thereof in the concrete. This is important since the concrete must be impermeable for air so that a potential mars inhabitant would be able to survive the conditions indoors without a spacesuit. Because of this, permeability of sulfur concrete made with Martian regolith simulant should be tested to make sure that the environment is survivable.

Another study looked into the usage of sulfur concrete for contour crafting in buildings on Mars. This study was conducted by students at the University of Texas, and used JSC-1 and JSC-1a Martian Regolith simulants with sulfur to create the sulfur concrete . However, this study focused more on other utilizations for the concrete, with the contour usages of it. This tests different aspects of the sulfur concrete, like resistance to cracks, and rigidness vs smoothness, instead of looking at factors like strength. In the study, the results were that there was reduced deformation in the concrete when used in contour. This is different compared to the study conducted in this paper, where strength, absorption and percent voids (to test impermeability) are tested. The gap in knowledge is the impermeability of the concrete and what ratio of sulfur to aggregate creates the most viable concrete.

The difference between the JSC-1a and the Mojave Martian Simulant is the composition and availability. The Mojave Martian Simulant is basalt based and more commercially available, whereas the JSC-1a simulant isn't produced anymore and is only available at NASA ("Mojave Mars," 2008). The simulant being used in the study is mostly basalt, which is important because it shouldn't change the results in any way

The importance of this experiment is that it will look into the possibilities of colonizing on Mars, especially since there are many problems occurring on Earth. Also looking into construction methods on Mars could help with construction on Earth, while looking at different ratios for the strongest type of sulfur concrete. In the future, another study will have to be done with sulfur salts to test if the ratios of sulfur to regolith, to see if the results change with sulfur salts.

# Methodology:

Sulfur (S) was chosen due to its high abundance on Mars which is suggested by elevated percentages of sulfur compounds in the interior of Martian meteorites (King & McLennan, 2010). When sulfur is molten, it acts as a bonding agent that will seep between the particles of a mixture and solidifying it into a stronger material. Because sulfur is a good bonding agent, sulfur concrete can be made without using water. This makes it practical as a building material on Mars, which has a limited water supply.

To simulate the resources available on Mars, Mojave Martian Simulant (MMS) was chosen to create the sulfur concrete ("The Martian Garden," 2019). The simulant is 99.4% similar to the regolith on Mars, so it is an accurate material to test with on Earth ("Mojave Mars," 2008). In Fig. 1, the Martian Regolith simulant is shown to be almost identical in concentration to the Pathfinder SFR, the MER Spirit soil and the Mer Opportunity soil. This is important since it demonstrates how MMS is an accurate representation of the soil available on Mars.

Four different ratios of aggregate to sulfur were tested: 50% Mojave Martian Simulant by weight and 50% sulfur by weight, 60% and 40%, 70%, and 30%. and 80% and 20%. A control group would be sulfur concrete made with sand and gravel as an aggregate with sulfur, to test the strength of sulfur concrete made with Earth materials against the different ratios of the concrete made with the simulated Martian materials. These percentages were chosen since sulfur concrete made on earth is generally made between 50% and 80% aggregate, so in this case its viable to use similar percentages to test the materials on Mars (Khodair, 2019). Then the sulfur is melted at 140° C in a chemical oven and poured into a 2” x 4” cylindrical mold. The regolith was heated separately to the same temperature; then the sulfur and regolith were mixed together in a mixing bowl using a spatula. All of the tools that were used were preheated as well. Once the concrete was well mixed, it was put it back into the oven quickly for 3 minutes so that it was at the proper temperature when it was poured into the molds.

The small plastic molds measured 2"x4" and were previously tested to make sure that they were able to withstand the 140° C temperature. After being placed in the oven at this temperature for two hours, the plastic did soften and lose some rigidity, however it did seem like it could work as a viable mold for the sulfur concrete without losing shape.

The concrete was taken out of the oven and sat for a period of 24 hours. After that, each sample had their mass taken, and then submerged in water for 2 weeks. Then the mass was taken again, and the buoyant masses were taken by placing them in a cage suspended in water. Then the two different densities were calculated by the following formulas:

(Dry Mass / Saturated Mass - Buoyant Mass) = Bulk Density

(Dry Mass / Dry Mass - Buoyant Mass) = Apparent Density

Then Percent Voids were calculated with the following formula:

Apparent Density - Bulk Density / Apparent Density

# Results:

The dry masses were taken for each sample of Martian Sulfur Concrete and are demonstrated in fig. 1. Masses were not taken for the 80% Martian Regolith and 20% sulfur sample, since the samples were falling apart when they were taken out of the molds. The dry masses increase as the amount of regolith is increased, which was expected.

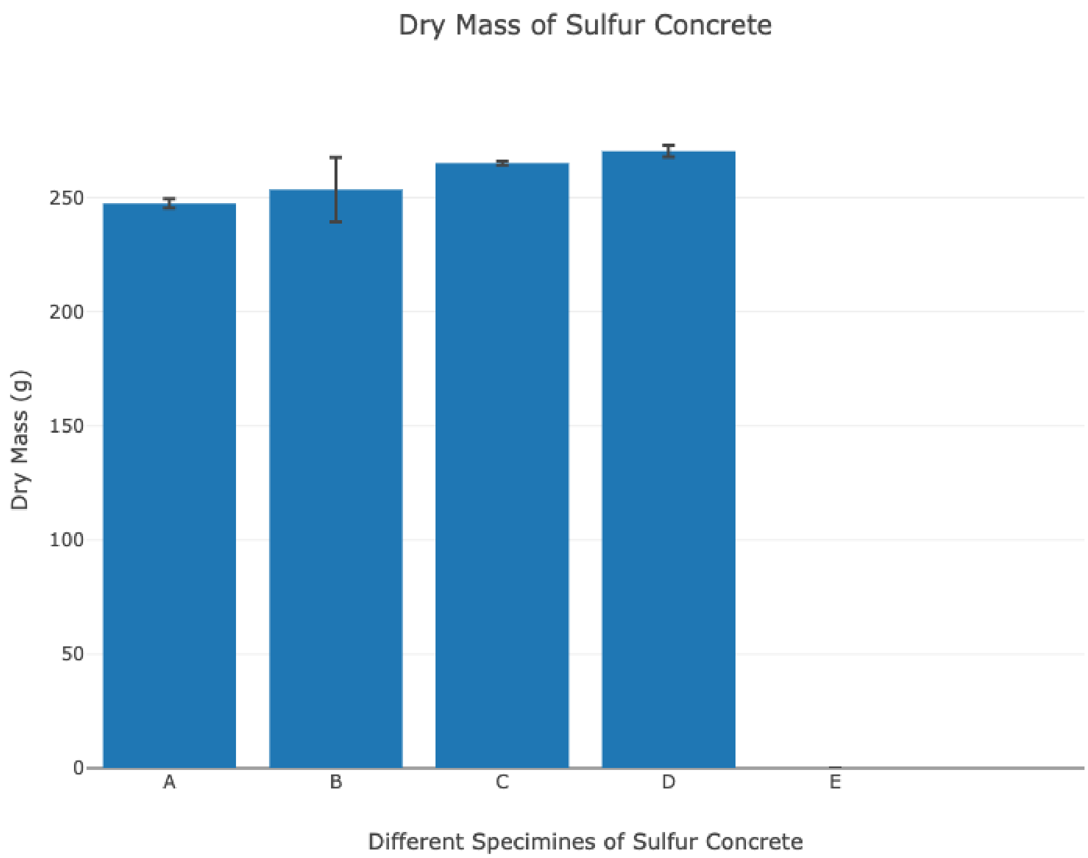


Figure1: The average dry mass of each sample of sulfur concrete, where sample E was unable to be measured, since the samples were falling apart when they were taken out of the molds

After two weeks of sitting in water, the saturated mass (fig 2) and the buoyant mass (fig 3) were both taken. A general trend with the saturated mass was an increase in the mass, as the ratios got heavier. However, the buoyant mass of the sulfur concrete increased and then decreased, which may be due to measuring one less sample of sulfur concrete, most likely due to a couple of the sample C ratios falling apart.

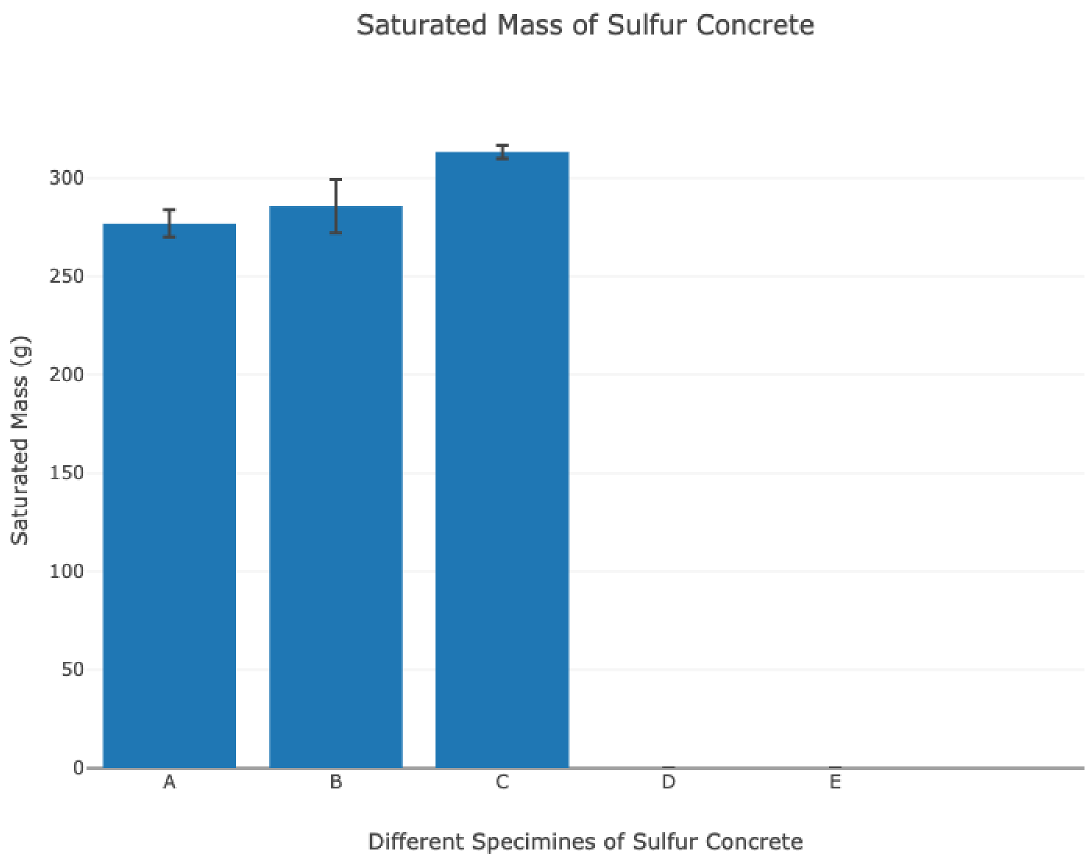


Figure 2: The saturated mass of each sample of sulfur concrete. Both samples D and E were unable to be used, since they fell apart in water, so their mass  comes out to be zero in this case.

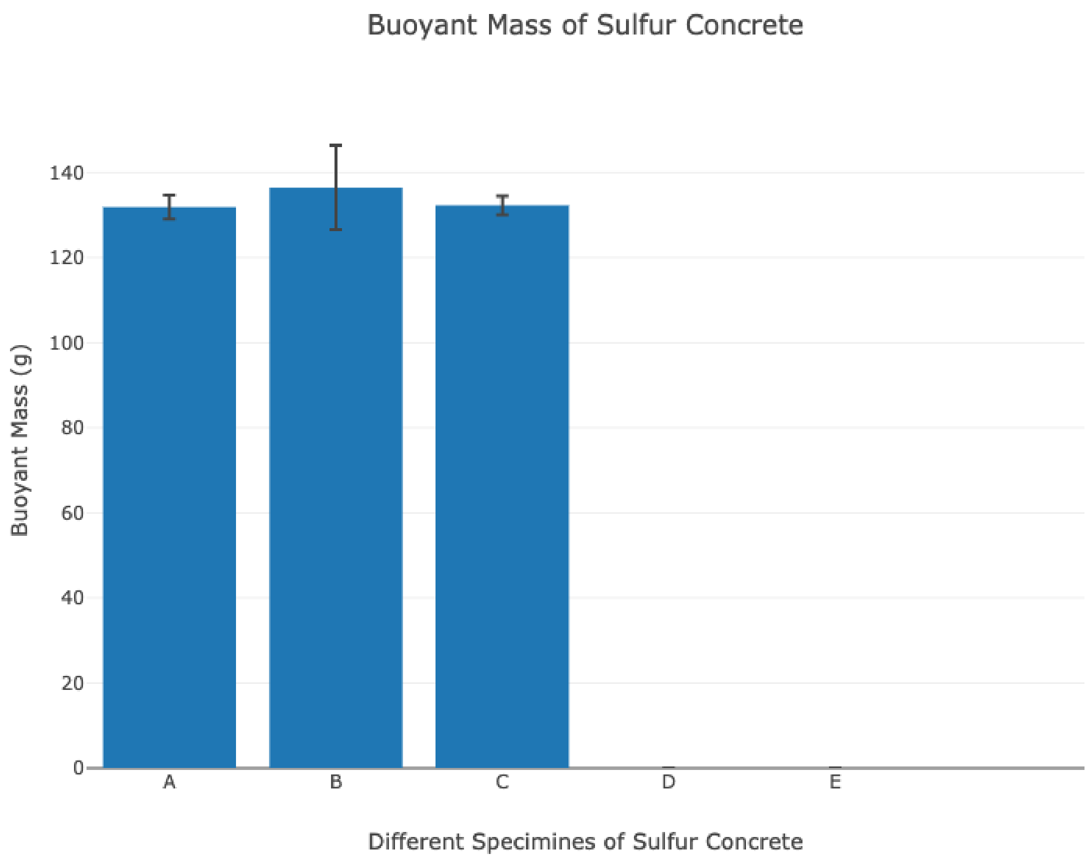


Figure 3: The buoyant mass of the different specimens of sulfur concrete, which was taken by placing the sulfur concrete into a cage that was suspended in water.

The apparent density of the specimens was calculated with a formula provided above, and the density follows a similar trend to buoyant mass. The density increased from sample A to sample B and then decreased to sample C.

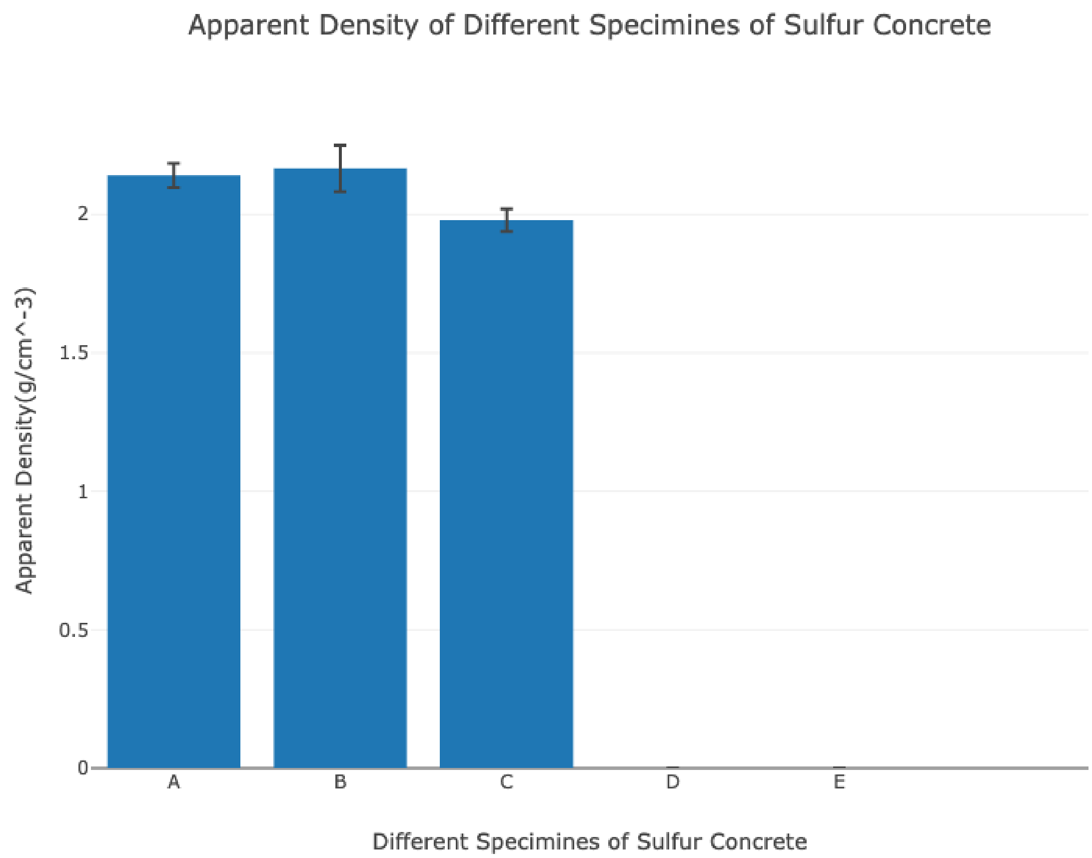


Figure 4: The apparent density of different specimens of sulfur concrete, which were calculated by dividing the dry mass from the dry mass minus the buoyant mass.

Bulk density (fig 5) was calculated by dividing the dry mass from the saturated mass minus the buoyant mass. Since the dry mass of sample C was larger, the bulk density was expected to decrease.

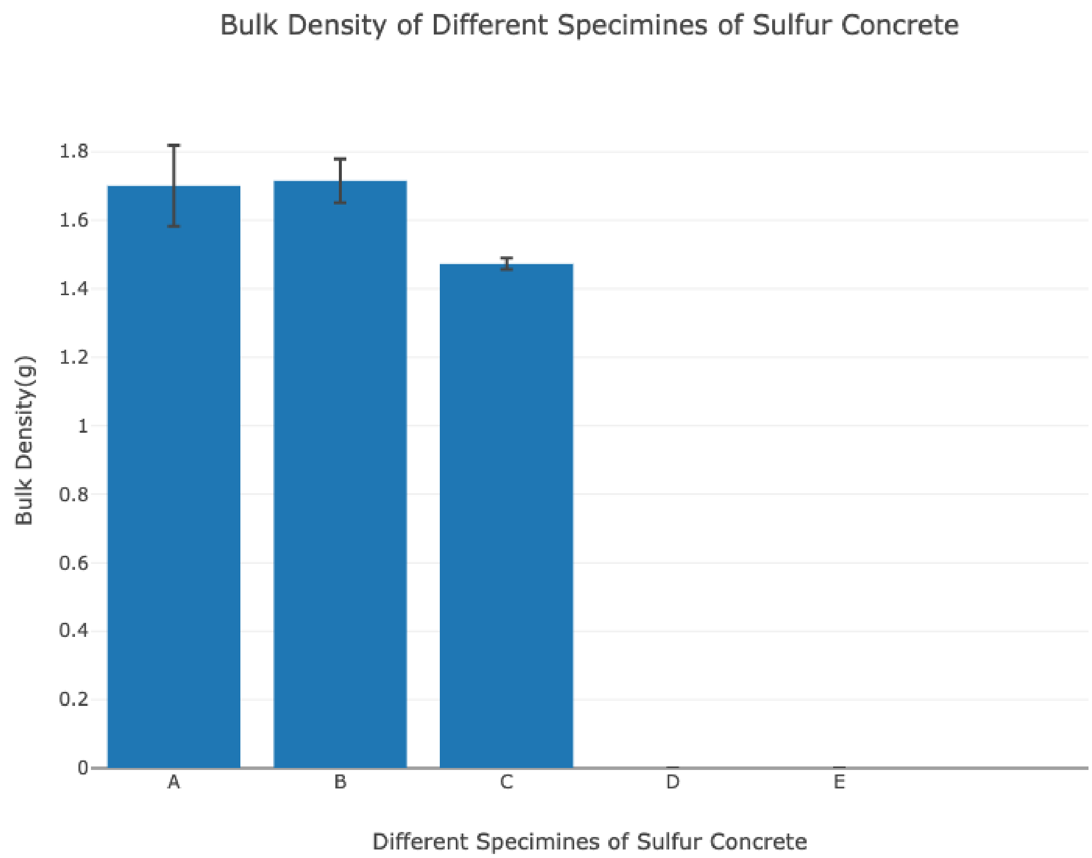


Figure 5: the bulk density of the different concrete specimens, which was taken as an average of each of the samples in each specimen category, which increased, then decreased, due to the amount of samples in the average and the dry mass increasing over each of the specimens

The percent voids were calculated with the formula apparent density minus bulk density, which then was divided by apparent density and multiplied by 100 to get a percentage. This is pictured in figure 3. As the ratio of regolith in the concrete increases, the percent voids increases, which means the impermeability decreases, or the specimens become more permeable.

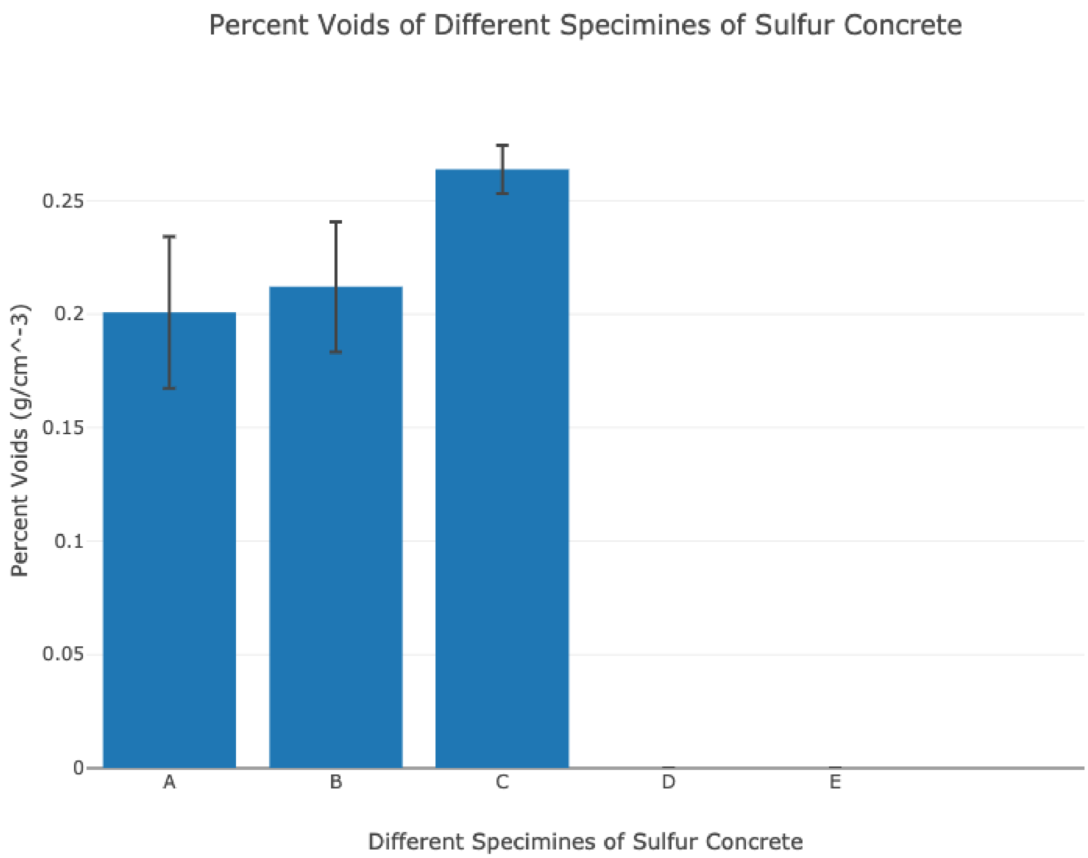


Figure 6: The percent voids of each of the different specimens of sulfur concrete. The samples increase in percent voids, so the permeability increases, therefore the samples are not impermeable.

# Discussion:

Was my hypothesis supported? Why or why not → use evidence

Explain my results

Any new understandings as a result

Does this agree with what other people have said

Evaluation → limitations of the study (only discrete bricks and not a full scale building)

## Implications/conclusion

The results do provide answers to my testable hypothesis, which was that the sulfur concrete with the least regolith will have the least percent voids, and then the samples will begin to increase in percent voids. This is true because the fifty percent sulfur and fifty percent regolith samples had the lowest percent voids, so they were the least permeable.

The study conducted by a student at Northwestern University demonstrated similar results for percent voids, however that study only made one group of Martian regolith sulfur concrete, and used a different regolith, so the results were expected to vary from the study.

Some limitations of my study were that the samples of regolith began to fall apart as the study was conducted, and to combat that different ratios should have been tested. Also, there were not any extra materials to make more samples, so if there were any mistakes the samples were rendered useless. This is a limitation because if there were more materials, more samples would have been tested, but it was too expensive to keep buying the regolith to make more samples.

In conclusion, the samples of sulfur concrete with the least regolith and the most sulfur were the least permeable, since they had the lowest percent voids. This is useful because it demonstrates that when or if humans go to Mars, they can build structures using primarily Martian sulfur and Martian regolith.

The next steps for my research will be to test samples that are primarily sulfur, so 60% sulfur and 40% regolith, and see if those samples have even less percent voids. I'm expecting a parabolic relationship, so that the best mixture will end up being the 50% regolith and 50% sulfur.

# Bibliography

References


Comparison of sulfur concrete, cement concrete and cement-sulfur concrete and their properties and application. (n.d.). *Current World Environment*. Retrieved from http://www.cwejournal.org/vol10noSpecial/comparison-of-sulfur-concrete-cement-concrete-and-cement-sulfur-concrete-and-their-properties-and-application/

Good, A. (2019, July 15). Nasa. Retrieved September 21, 2019, from https://www.nasa.gov/feature/jpl/want-to-colonize-mars-aerogel-could-help

Jones, H. W. (2018). The recent large reduction in space launch cost. *48th International Conference on Environmental Systems*, *ICES*(81). Retrieved from https://www.ices.space/wp-content/uploads/2018/03/ICES-2018-cfp_FINAL.pdf

King, P. L., & McLennan, S. M. (2010, April). Sulfur on mars. *Elements*, *6*. https://doi.org/10.2113/gselements.6.2.107

The martian garden. (2019). Retrieved September 11, 2019, from The Martian Garden website: https://www.themartiangarden.com/

Martian scientist make martian concrete. (n.d.). Retrieved October 17, 2018, from MIT technology review website: https://www.technologyreview.com/s/545216/materials-scientists-make-martian-concrete/

Peters, G.H. (2008). Mojave mars simulant—characterization of a new geologic mars analog. *Icarus*, *197*(2), 470-479. https://doi.org/10.1016/j.icarus.2008.05.004

OSH answers fact sheets. (n.d.). Retrieved October 17, 2018, from https://www.ccohs.ca/oshanswers/chemicals/chem_profiles/sulfurdi.html

Oxygen and sulfur compounds from rocknest samples. (n.d.). Retrieved May 29, 2019, from Nasa website: https://www.nasa.gov/mission_pages/msl/multimedia/pia16575.html

Davila, A.F. (n.d.) Perchlorate on mars:A chemical hazard and a resource for humans. *International Journal of Astrobiology*. Retrieved from https://www.researchgate.net/publication/242525435_Perchlorate_on_Mars_a_chemical_hazard_and_a_resource_for_humans

*Performance of sulfur concrete in planetary applications of contour crafting*. (n.d.). Retrieved October 17, 2018, from http://sffsymposium.engr.utexas.edu/sites/default/files/2016/183-Yuan.pdf

*Properties of sulfur concrete*. (n.d.). Retrieved October 17, 2018, from http://www.dtic.mil/dtic/tr/fulltext/u2/a101464.pdf

Sample records for gas permeability concrete. (n.d.). Retrieved August 20, 2019, from https://worldwidescience.org/topicpages/g/gas+permeability+concrete.html

Sulfur and the sulfur cycle on mars. (2009). *Lunar and Planetary Science Conference*, *40th*. Retrieved from https://www.lpi.usra.edu/meetings/lpsc2009/pdf/2152.pdf

Sulfurcrete:Sulfur concrete technology. (n.d.). *Sulphurinstitute*. Retrieved from https://www.sulphurinstitute.org/pub/a03beacb-aea4-7241-ac2c-cf23139cc5d7

Wan, L. (2016, May). *A novel material for in-situ construction on mars: Experiments and numerical simulations*. Retrieved September 19, 2019, from https://arxiv.org/pdf/1512.05461.pdf