3-D Printing/Geopolymer Concrete

Introduction to the articles

On Earth, concrete is used for roads and some buildings. Concrete is strong due to a network of strong bonds between ions. These bonds are made stronger by reactions with water that occur when it is first poured. In outer space, concrete would also be an attractive building material due to its strength and ability to provide protection from the Sun and dust in the atmosphere. Concrete is a mixture of cement, water, and aggregate (rock), with the aggregate serving as barriers to cracks as they move through the concrete.

Problem

On Earth, cement is a major contributor to climate change. In 2021, cement production released over 1.84 billion tons of carbon dioxide into the atmosphere. Eliminating carbon dioxide emissions from cement production would have a similar effect to removing 20% of vehicles from the road. Cement production also requires significant amounts of reasonably clean water, which is in short supply off of Earth, as well as in some places on Earth.

Article 1 is a popular article that describes one alternate method of making concrete-like structures, 3-D printing, while Article 2 is a journal article that explains how to make another alternative material called *geopolymers*.

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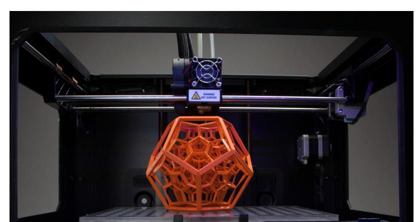
Article 1: 3-D printing homes on the Moon and Mars

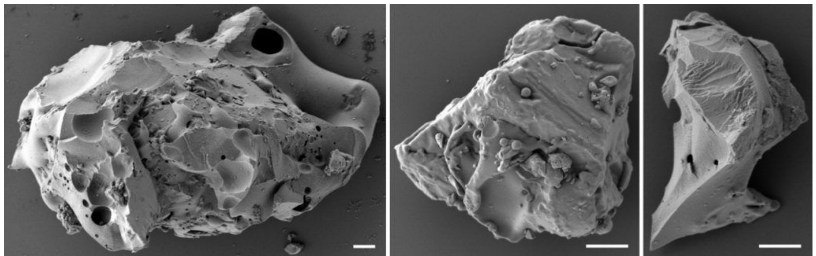


Adapted from: Creative Tools (2012), CC BY-2.0 Deed

Houses, even neighborhoods, on the Moon may seem like science fiction, but we have the technology today, even if it is not quite ready for space. We call this technology 3-D printing. You may have seen 3-D printers before. Many 3-D printers work by heating plastic and layering it into the desired shape based on instructions in a computer. 3-D printing works on a wide range of materials; any material can be 3-D printed if it can be softened, then quickly hardened into the desired shape once it has been layered in place. On the Moon or Mars, the dust and rock particles, mixed with a liquid, would be the material for 3-D printing.

NASA has already hosted a 3-D printed habitat challenge on Earth (NASA.org), and 3-D printed homes can be purchased in some places and can be as large as 10'6" x 38' x 100', if the whole home is printed in one piece. The 3-D printer cannot do everything--a foundation needs to be built and other materials are necessary for internal portions of the structure--but the walls can go up in just a few days using the 3-D printing process.

If we were to use a 3-D printer to build structures on the Moon or Mars, there is one challenge that materials scientists are thinking about in particular. Rocks and dust particles on these bodies are very different from on Earth because they have not been eroded by water. In general, dust particles and rocks are much *sharper* on other space objects than on Earth (as seen in the image, with each scale bar being 0.001 mm). If humans breathe this dust, it could damage their lungs with the rough surfaces. Thus it is very important to build shelters so that humans are protected. This also means scientists and engineers must ensure the 3-D printers can operate reliably in this harsh environment without being damaged by the sharp edges of this dust.



NIST, Chiaramonti Debay

Even though it is dangerous to people, this sharp, jagged regolith could be a good building material. It would have to be dissolved in a solvent in order to make a slurry (liquid-like mix). The tested solvent, which would have to be flown to or manufactured on site, contained poly(lactic-*co*-glycolic acid) (PLGA) as well as several other chemicals, some of which are toxic. Using this solvent, along with regolith from either Mars or the Moon, would mean that no carbon dioxide would be released during construction, and the bulk of the solvent can be reused. However, high temperatures are required for this process--up to 1100 $^{\circ}$C (2012 $^{\circ}$F)--to evaporate the solvent and help develop bonds between the regolith and PLGA. Furthermore, PLGA would have to be brought to the Moon or Mars, and any regolith used would be mined, damaging the surface of the planet or moon.

As scientists and engineers work to improve the process for use in space, a test structure called Mars Dune Alpha is being built at the Johnson Space Center in Houston so that astronauts can get a feel for what it would be like to eat, sleep, grow food, and do experiments in one of these 3-D printed structures. In the image, the walls are 3-D printed with a substance much like the regolith-based mixtures that would be used on Mars. This substance is not nearly as strong as something like concrete because the bonds between layers are not as strong as the bonds between ions in concrete's repeating structure.

NASA, Bill Stafford

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Article 2: Geopolymers as concrete alternatives for terrestrial and lunar construction: A literature review

Background

The Moon and Mars have been identified as potential sites for human space exploration. However, either environment is different from Earth's. Long-term habitation on either object would require unique solutions for a wide variety of human needs, including shelter. Although concrete would be easy to manufacture on site, cement production is a significant source of carbon dioxide emissions. Any process that can avoid these emissions would be desirable on Earth, as well as off of Earth, if astronauts seek to limit changes to the atmosphere.

Several hybrid concretes, which use materials available on the Moon or Mars along with some brought from Earth, have been proposed as a way to build shelters. Another possibility is geopolymer concrete. On Earth, a simple starting material like fly ash (a type of industrial waste left over from burning coal, shown in the image) is typically used. Fly ash contains elements like aluminum and silicon, both of which can be found on the Moon or Mars. These elements are reacted with substances like sodium silicate and sodium hydroxide to make an equivalent of cement, but with mainly covalent bonds. Adding aggregate (large rocks) and water makes *geopolymer concrete*, so-called because it acts like a polymer, with long chains of covalent bonds. These long chains are a different way of giving the material strength that conventional concrete gets from the repeating networks of bonds in its structure.

All the necessary elements are found off of Earth and the water could be fairly easily recovered, as it evaporates out (instead of becoming part of the structure like in conventional concrete).

Methods

Various studies were examined to identify geopolymer concrete production methods and mechanical properties. In addition, one study was found which provided information on the carbon dioxide emissions of geopolymers.

Findings

A 2016 chemical engineering study (Wang et al.) mixed tektite rock (leftover pieces from meteorite impact) with sodium hydroxide and sodium silicate in water. 20 x 20 x 20 mm cubes were formed in molds under pressure, the samples were vibrated to remove air bubbles, and then placed in a vacuum chamber at 60 ^{o}C for 12 hours. The compressive (push) strength of the geopolymer was found to be 35.79 megapascals (MPa). Residential concrete must have a strength above 17 MPa (Neville, 2015). Using the same process and team, a similar study the next year found compressive strength as high as 45.3 MPa.

Alexiadis et al. (2017) mixed lunar dust simulant with sodium hydroxide and Mars dust simulant with potassium silicate. The mixture was dried at 80 ^{o}C for three hours and then cured (allowed to sit) at room temperature for 28 days. These small samples were found to have a compressive strength of 18.4 for lunar dust and 2.5 MPa for martian dust.

Finally, Kiruthika et al. (2023) compared conventional concrete and geopolymer concrete mixes. The geopolymer concrete mix had a strength of 55 MPa and the conventional mix a strength of 52 MPa. They found that the carbon dioxide emissions associated with the geopolymer concrete production were about 44% of those from conventional concrete production. These findings are synthesized in Table 1.

Table 1

Comparison of Material Composition and Strength

Study	Materials	Strength
Neville, 2015	Residential concrete (legal minimum)	17 MPa
Wang et al., 2016	Tektite, NaOH, sodium silicate	35.79 MPa
Wang et al., 2017	Tektite, NaOH, sodium silicate	45.3 MPa
Alexiadis et al., 2017	Lunar dust simulant, NaOH	18.4 MPa
Alexiadis et al., 2017	Mars dust simulant, potassium silicate	2.5 MPa
Kiruthika et al, 2023	Geopolymer concrete	55 MPa
Kiruthika et al, 2023	Conventional concrete	52 MPa

Conclusion

Geopolymers meet the minimum requirements to be a concrete alternative both on and off of Earth with lower carbon dioxide emissions. However, some of the materials used, such as water, must be conserved in any environment, meaning that more work is needed to make processes more efficient and ensure that structures are made where they are most needed.

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