# Towards 3D-printable cementitious materials on Earth and beyond

***An introduction to development efforts for cementitious materials that are compatible with 3D printing, including cement-based and geopolymer-based binders, as well as functionally graded materials.***

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The construction industry is currently among the least digitised and automated sectors. 3D-printing technology has been successfully applied to a diverse range of materials, including metals, polymers, and ceramics (see Ngo *et al*[1]), but its adoption within construction presents challenges not encountered in other fields. Concrete construction of infrastructure elements using traditional processes are labour intensive and time consuming. In some scenarios, fully automated and without the use of formwork, 3D-printing technology has the potential to shorten construction time, reduce labour and material costs, and minimise construction waste, all the while improving architectural freedom, functional integrity and construction accuracy. Ongoing research efforts look into incorporating reinforcement into the 3D printing process either by distributing fibre reinforcement or via an additional robotic arm placing the reinforcing bar. It is also possible to print slabs on the ground, which the research team has proven under NASA 3D Printed Habitat competition – Phase 3 – Level 1 – Foundation Test Competition.

Despite the vast potential of this novel technology, multiple challenges hinder its wider adoption, including a requirement to print at a much larger scale than other

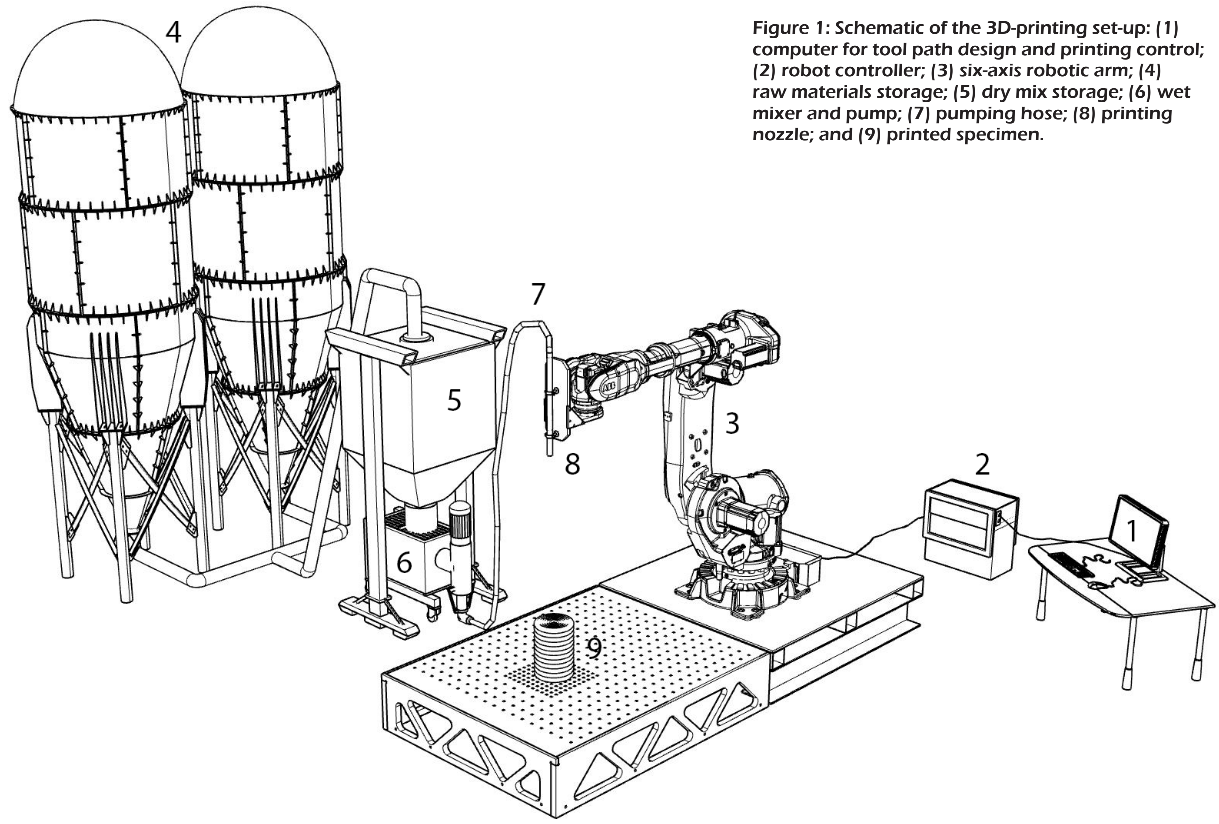


**Figure 1: Schematic of the 3D-printing set-up: (1) computer for tool path design and printing control; (2) robot controller; (3) six-axis robotic arm; (4) raw materials storage; (5) dry mix storage; (6) wet mixer and pump; (7) pumping hose; (8) printing nozzle; and (9) printed specimen.**

industries, the resistance of selected trades involved in the construction process to change their current practices and the shortage of a skilled labour force. Additionally, techniques developed for 3D printing with other materials do not, in general, apply directly to concrete binders and there are research gaps that need to be addressed prior to commercial applications in the construction industry.

**3D printing with cement-based mortar**

There are distinct differences between conventional concrete and printable cementitious mixtures. Concrete, traditionally a mixture of cement, water, fine and coarse aggregates, and admixtures, has to be extruded via a nozzle during the 3D-printing process and the presence of aggregates can easily cause clogging. If the printing material cannot be extruded in a timely manner, it may harden within the pumping hose or cause the hose to burst – resulting in printing disruption, the need for hardware replacement and cold joints in the printed structure itself. The printing material also must be sufficiently flowable for smooth transportation from the mixer to the printing nozzle (Figure 1), which is consistent with the consistence requirement of conventional concrete. Due to the layer-by-layer printing with no formwork, the material is further required to be buildable immediately after the extrusion in order to maintain the filament's shape, sustain the weight from upper layers and minimise deformation under load. This leads to a higher-level requirement: printing materials are expected to be fresh and flowable during transportation through the printing system but stiff and buildable after extrusion from the printing nozzle (see Le[2] and Li[3]).

To be compatible with features of 3D printing, researchers at Pennsylvania State University developed a printing system (Figure 1) and successfully used a cement-based mixture to 3D print the first-ever fully enclosed habitat at an architectural scale without any support structure (Figure 2).

**3D printing with a geopolymer – MarsCrete**

Cement – the most widely used human-made material – and cement-based mixtures can be optimised for 3D printing, which will enable rapid uptake of 3D printing by the construction industry. But what next? With NASA's Artemis programme, humans have set out to explore the moon and Mars is considered to be the next frontier for human space exploration. However, since transportation of cement from Earth to Mars is not feasible, and the sources of calcium-bearing minerals (eg, limestone, as the principal raw material for cement production) are limited on Mars, innovative materials using in-situ resources will need to be developed to build Martian habitats.

Our strategy in designing a binder compatible with the Martian environment was to maximise the use of indigenous materials and resources available on the Red Planet. We studied the Martian regolith, specifically volcanic basalt rock that is one of the main components of the dusty Mars surface and which would serve as an excellent source for aggregates. Kaolinite, a layered silicate clay mineral available in specific locations on Mars, could be calcined to form metakaolin and constitute a binder. The Martian regolith also holds sodium and silicon compounds, which can be used as agents to activate metakaolin with water obtained from ice. Considering the composition of indigenous Martian minerals, a printable geopolymer-based mixture called MarsCrete was developed (see Hojati[4]). This material was 3D printed to create a dome-shaped structure (Figure 3) that met requirements defined by NASA.

**3D printing with functionally graded materials**

The cement- and geopolymer-based materials discussed above are shown to be printable in various applications, but they can be engineered even further. Normal concrete has a weight of approximately 2400kg/m$^3$. Such high-density concrete has a negative influence on its performance under load, especially in the case of a layer-by-layer printing process. Compared with 3D printing of a single, homogenous cementitious material, functionally graded 3D printing of materials with varying component ratios offer multiple benefits, eg, lighter weights with variable densities, programmable mechanical properties integrated specific functionality (eg, air-tightness, water-tightness, thermal and acoustic insulation, etc).

To investigate such concepts, we selected granulated cork and expanded clay as lightweight aggregates and produced 3D-printed functionally graded cementitious

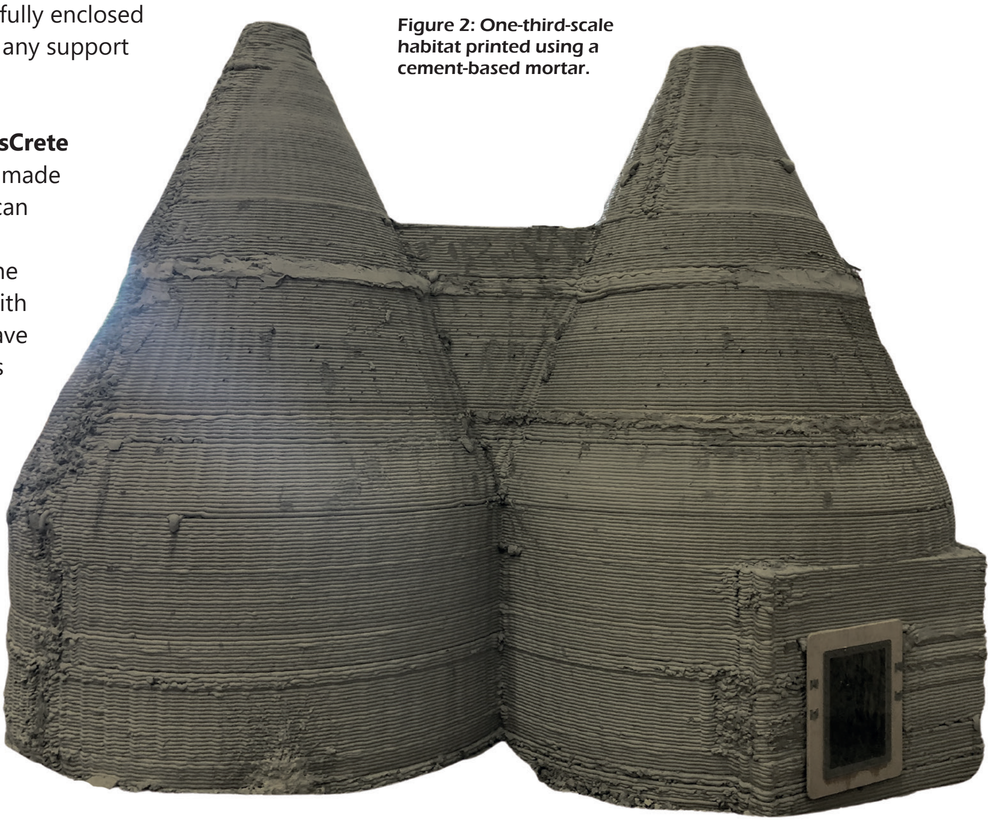

Figure 2: One-third-scale habitat printed using a cement-based mortar.

Figure 3: 3D-printed dome structure using MarsCrete.

materials, enhancing the thermal and acoustic insulation properties while reducing the weight (see Craveiro[5]). We also developed a functionally graded material using compositional gradients from 100% structural geopolymer to 100% glass (Figure 4a) (see Hojati[6]). Such a material with a varying content of glass (ie, varying optical transparency) can be used in a 3D-printed habitat to bring more sunlight into the interior of the structure. (Figure 4b).

**Future avenues**

The future of 3D printing in the construction industry is very promising, as it offers geometric freedom for off-site and small-scale manufacturing (eg, precast fabrication of slabs or columns), speeds up the construction process for emergency housing and low-income housing, and enables the long-term human exploration of space, to name just a few opportunities.

There are challenges, however, that require further research and experimentation. For example, without formwork, the printed materials are immediately exposed to the ambient environment, which accelerates the water evaporation and, thus, the plastic and drying shrinkage. The printing process introduces interlayer bonding issues (ie, cold joints) and anisotropic properties to the printed elements.

The formation of voids between subsequent layers and the layer-by-layer appearance defects have a potential impact on the long-term durability of the 3D-printed materials. Concerns have also been raised regarding the use of reinforcement in the printed structures to ensure structural integrity under different load configurations. Additionally, standardisation of assessment methods for the printing performance of materials is needed.

In terms of applications of 3D-printed technology for Martian habitats, exposure to microgravity conditions, cosmic rays and intense solar radiation due to the thin atmosphere, extreme temperature ranges, low pressure, and necessary processes to synthesise the MarsCrete's constituents, will also need to be researched.

Ongoing research and development of materials and methods will help to accelerate applications of 3D printing in construction on Earth and beyond. ■

Figure 4: (a) Functionally graded materials seamlessly transitioning from 100% geopolymer to 100% glass; (b) conceptual rendering of a 3D-printed shelter using functionally graded materials.

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