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3D Printing in Concrete Materials and its Applications

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Abstract: **In recent decades, there has been growing strides in construction industry for using 3D printing in concrete. 3D printing in construction can be referred to various printing technologies used to fabricate architectural or construction components. While the use of 3D printing in concrete is still at an early stage, efforts to adapt the latest 3D printing technologies are being made worldwide, albeit slowly and cautiously, through numerous projects led by industry, government agencies, as well as academia. A number of different techniques and approaches have been attempted including on-site and off-site fabrication of construction components utilizing industrial robots, gantry systems and tethered autonomous vehicles. This paper presents recent trends and some of research and development efforts in 3D concrete printing including its applications in extraterrestrial environment.**

Keywords: **3D concrete printing, additive manufacturing, contour crafting, extraterrestrial applications.**

I. INTRODUCTION

With the technological advancement in today's world and noticeable progress in additive manufacturing techniques, also known as 3D printing, the automation of work in construction industry seems more realistic in the near future. Some believe that 3D printing in concrete is not only a novelty of advanced technology but has the potential to revolutionize the construction industry because the use of this technology could pave the way for reduced construction costs and times and allow construction in more remote locations, and more flexible designs. In addition, it offers some new sustainable benefits that are not available in typical construction. According to a recent study [1], construction materials and manpower requirements may be substantially reduced if automated 3D printing technology is further developed to a point where higher efficiency can be achieved than current construction methods.

Additive manufacturing is a process of creating three-dimensional objects by forming successive layers of materials guided by computer control [2,3]. It was first attempted starting 1980's with the first 3D printer developed in 1984. To date, demonstration projects involving 3D printing in construction include fabrication of structural components, housing, small bridges, artificial reefs, sculptures, etc. For example, a research team in the United Kingdom has worked on developing computer controlled 3D concrete printers that would allow architectural features, and curved and geometrically complex concrete designs [4]. They were designed to be capable of directly applying concrete to the building site without additional formworks. In the experiments conducted by Loughborough University, researchers utilized robotic arms to print concrete structures in various curved shapes [5]. In China, research teams are experimenting with constructing entire structure using 3D printed concrete structural elements [6]. On a more successful note, 3D printing technologies have advanced to a point where concrete can be 3D printed around rebar installed prior to printing [7], allowing the 3D Printed Concrete to be strengthened with reinforcement just as typical reinforced concrete construction methods would allow.

Over the last two decades, NASA has funded several projects for developing innovative 3D printing techniques that have potential applications of constructing a structure using extraterrestrial materials [8]. It is expected that this kind of effort may lead to developing useful technologies for constructing off-Earth shelters for astronauts and equipment such as habitats on the Moon or Mars.

There are various 3D printing techniques that can be used at construction scale such as extrusion, powder bonding, and additive welding. In particular, Contour Crafting has gained popularity in science and engineering communities because it allows for rapid prototyping, fabrication of complex geometries, creation of multi-material composites and product customization. Contour Crafting is an extrusion based additive manufacturing process, which can be achieved by many different ways from slurry extrusion to sintering to melting techniques with varying levels of complexity, costs and technological readiness. Contour Crafting also allows for a smooth surface finish over accumulated successive thick layers by depositing wet concrete through a nozzle and against a side sharping trowel [9-13]. One example where Contour Crafting was utilized is a 400 square-foot, single story house that was completed in 24 hours at a total cost of $10,134 (US dollars). In this project (Fig. 1), the foundation and walls were 3D printed using the Contour Crafting process [14] followed by the installation of windows and doors as well as painting, which took place after the main structural members were printed.

Numerous engineers expect a great future for 3D printing in construction and some industry experts believe that such technologies may trigger a new industrial revolution. Overall, potential advantages of 3D concrete printing include faster construction, lower labor costs, increased complexity and accuracy, greater integration of function, and use of recycled materials thereby producing less waste. This paper presents recent trends and some of research and development efforts in 3D concrete printing including its applications in extraterrestrial environment.

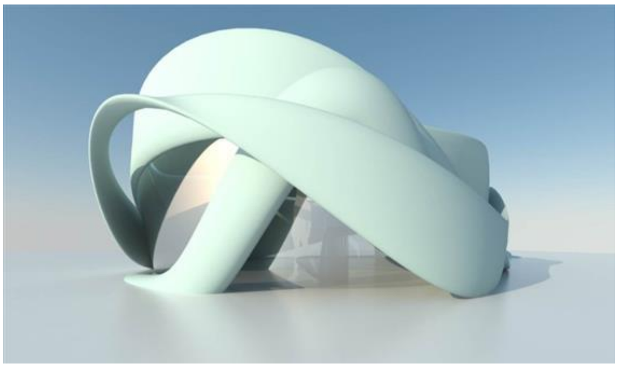
Fig 1: Contour Crafting process of Apis Cor house [14]

II. CONSTRUCTION WITH 3D PRINTING

Along with the advancement of science and technology, there has been a need for developing more sustainable and cost effective construction practices [15]. 3D printing of concrete can be considered as a state-of-the-art development in the construction industry. Examples of 3D printing demonstration projects include the fabrication of construction components (e.g., cladding and structural panels and columns), bridges, artificial reefs, follies, and sculptures. The use of parametric modeling tools and analytic software, which are typically used for quantitative and qualitative analyses, would aid further development in 3D printing. Recent efforts toward advancing 3D printing technologies mainly tend to focus on integrating the advantages of digital fabrication within factory-based construction manufacturing, and developing methodologies for the production of long-lasting performance-based components. In the recent past, several different approaches have been demonstrated including on-site and off-site fabrication of buildings and construction components that utilize industrial robots, gantry systems, and tethered autonomous vehicles. Using Automated Additive Construction, low-fidelity and large-scale compressive structures can be produced with a wide variety of materials. Compression intensive structures need not utilize materials that require tight specifications for internal force management, meaning that the production of the building materials do not require complex analysis. As a certain degree of surface roughness can be tolerated in 3D printing construction, a lower-fidelity of deposited materials may provide low-cost alternatives for automating building processes. Although the long term data associated with the materials used in this 3D printing process are yet to be available, it is believed that recent efforts coupled with continued advancement in 3D printing technologies would allow for sustainable working products in the near future.

3D printing technology has the potential to create innovative structures in a more efficient and more sustainable way. According to statistics released by the U.S. Environmental Protection Agency [16], the output of construction and demolition in the U.S. has increased work by 25% in the last decade. In addition, the total of construction and demolition debris has reached close to 350 million tons according to the Construction Materials Recycling Association [16]. Cost effectiveness is an important aspect that has motivated engineers to look into recycled materials to produce a new type of concrete. Since only the necessary raw materials need to be produced for each project in 3D printing and that the use of recycled materials is widely encouraged, it is expected that the amount of waste materials resulted from 3D printing construction would decrease significantly. A couple of examples, a 3D printed 90-m^2 (969 ft^2) conceptual hotel and a 3D printed cabin (8 m^2 or 86 ft^2 in area and 25 m^3 or 883 ft^3 in volume), that highlight the use of recycled waste materials in 3D printed construction can be found in Fig. 2.

Another key driver for advancing 3D printing technologies within the construction industry is a growing need for high-speed construction and/or rapidly produced housing. An example of high-speed 3D printed construction is a canal house (Fig. 3) recently erected at a canal-side plot in Amsterdam, Netherlands [17,18]. This 3D printed canal house project was intended to link science, design, construction and community, and, at the same time, demonstrates how 3D printing could revolutionize construction by increasing construction efficiency, reducing pollution, and waste. In this project, the latest 3D printing technologies played a significant role by allowing rapid construction and low-cost housing in impoverished areas and those affected by disasters. This project utilized a technique called 'Kamermaker' (also called RoomBuilder) that prints building blocks on site from molten bio-plastic. The material used consisted of plant oil and microfibers. For the reinforcement purpose, each building block was designed such that an internal honeycombed center could be back-filled with Eco-concrete. It also provided space for utilities (e.g., pipes, wiring, cables, etc.) to be installed internally. The building blocks were used to form component parts that could be slotted to create a 4-story, 13-room structure modeled on a traditional Dutch canal house. One of the most distinct design features of the canal house is its geometrically faceted plastic façade, which adds a contemporary 3D printing twist to the traditional canal house silhouette. Some believe a project like this has demonstrated that some of the most critical challenges to any new construction system such as cost, speed and availability of materials may have been somewhat overcome, especially for the region where demand is high with limited funds. However, it is a general consensus among the engineering communities that more work is still needed. Future improvements to housing construction with 3D printing should aim for more flexibility while complying structural or design codes (i.e., international building codes, constructional standards, etc.).



(a) 3D printed conference center

(b) 3D printed urban cabin

Fig 2: 3D printed structures constructed with recycled waste material [19]

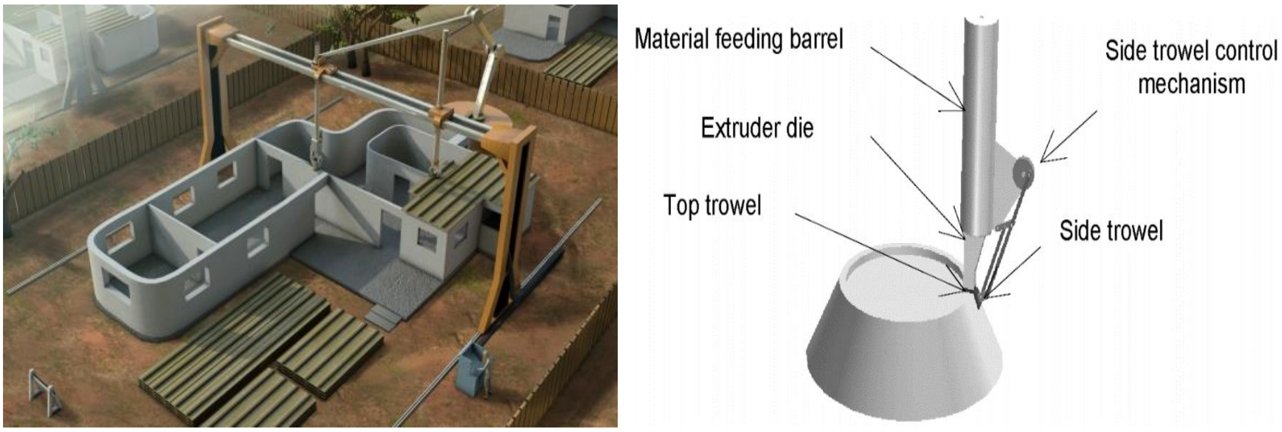
Fig 3: 3D printed canal house [17]

III. 3D CONCRETE PRINTING

Contour Crafting, shown in Fig 4, was first developed in the late 1980's [20]. With the adaptation of modern technologies and advancement in 3D printing techniques (e.g., use of a crane system guided by computers), structures or structural components can be constructed even faster and more efficiently. In addition, its unique layered manufacturing method allows for building construction components with a relatively smooth surface finish. The smoothness of the extruded parts can be attained by coercing the extruded flow in both horizontal and vertical directions and with the use of side sharping trowels whose position can be adjusted for each layer and for varying slope of the surfaces. The outlet consists of multiple vents, one for each side, and other for the inner of a wall structure. By bending the nozzle, non-orthogonal surfaces can be created. Contour Crafting is also capable of using aggregates mixed with additives like fiber reinforcements.

D-shaped printing [21,22], typically used to print building models, utilizes powder deposition, selectively hardened by applying a binder and layers of fine aggregate set down to the desired thickness and then compacted. A fully assembled D-shaped printer, shown in Fig. 5, consists of around 300 faucets that are attached on a scaffold aluminum casing. During the construction process, the printer moves over the printing area and deposits binding materials. Once completed, select parts are excavated out of the loose precipitate bed. Coarse materials need to be preliminary mixed with powdered metal oxide, which will react with the applied liquid binder.

Similar to the D-shape printing, a recent study in architectural field demonstrated a 3D printing technique that used fiber reinforced cement mix with small size aggregates to improve workability of the mix [23,24]. Two different types of binders were used in this study. One was alcohol-based, water-soluble polymer and high adhesive, which was primarily used to make the mix denser and improves the curing process and flexural strength. The second was hybrid concrete polymer used to provide additional strength.



(a) Contour Crafting 3D printer **(b) Schematic of Contour Crafting extrusion**

Fig 4: 3D Contour Crafting [20]

(a) Fully assembled D-Shape 3D printer

(b) D-shape 3D printed structure

Fig 5: D-shape 3D printer and 3D printed structure [22]

IV. 3D PRINTING IN EXTRA-TERRESTRIAL ENVIRONMENT

Human population on Earth has been drastically increasing, currently standing at 7.5 billion as of 2018 with a forecast of touching 10 billion by 2056 [25]. With the fast increasing human population and apparent depletion of natural resources, scientists and researchers are exploring the possibility of colonizing neighboring planets (simulated in Fig. 6). In recent decades, NASA has funded numerous research projects for developing innovative 3D printing techniques with potential applications of constructing 'off-Earth' habitats such as habitats on Mars. When constructing a shelter or a structure on Mars, three key factors among others should be considered: materials, strength and constructability [8]. First, the best way to build a structure on Mars would be to use indigenous materials locally available because bringing construction materials from earth will vastly increase the payload the rocket would need to carry. Sulfur concrete may be a superior choice for building a structure or structural components on Mars since it is known as a "sulfur-rich" planet and because of its dry environment and lack of water. Sulfur concrete requires no water but consists of aggregate (e.g., sand, crushed stone, etc.) and elemental sulfur heated to its melting point (to be used as a binder) [26]. Second, durability of a structure to be built is also of critical importance since human will, once arriving on the red planet, require high quality structures in which to live and work. Along with physical testing, computer simulation through finite element modeling can be utilized to investigate structures' mechanical responses with various parameters including environmental loadings, which will be inherently different from Earth. Finally, 3D printing practices may have the potential to improve the construction process on Mars where life-supporting resources will be very limited.

While the use of sulfur to make concrete is hardly a new concept since elemental sulfur was used as a bonding agent in ancient times [29], the thought of using sulfur concrete as construction material for extraterrestrial missions was first introduced by Leonard and Johnson [30]. One of the main advantages of using sulfur concrete in extraterrestrial applications would be its capability to gain its full strength in a relatively short period of time without the need of water. A study by Omar [31] investigated the feasibility of using molten sulfur and lunar regolith as construction materials for lunar structures. The basic premise of this study was that it would be more logical and cost effective to utilize indigenous resources in extraterrestrial construction rather than transporting them from Earth. A series of compressive and tensile strength testing were conducted on sulfur concrete mixes with different sulfur to soil ratios to study the minimum amount of sulfur required for an optimized strength. In some of the mixes, metal and glass fibers were added to investigate their effects on the sulfur concrete. The results of this work revealed that the maximum compressive strength of sulfur concrete was 33.8 MPa (4.9 ksi) for a 35% sulfur content by weight while the strength of the same sulfur concrete with the addition of 2% metallic fibers by weight was 45.5 MPa (6.6 ksi).

(a) Construction on Mars using 3D printer [27]

(b) Lunar base construction [28]

Fig 6: 3D printing in extra-terrestrial environment [27,28]

Sulfur concrete made of Martian soils may have high potential for NASA's missions on Mars as it seems to meet NASA's In-Situ Resource Utilization (ISRU) requirements for structural construction on Mars. Lately, research effort was carried out by Wan [32] to obtain the optimal mixing proportions for 'Martian concrete' consisting of element sulfur and Martian soil simulant JSC Mars-1A [33], which is rich in metal element oxides. In this study, researchers investigated various percentages of sulfur mixed with JSC Mars-1A that were heated above 120°C (248°F). Based on the results of compression, tensile and flexural testing conducted to determine strength development, it appeared that the strength of the Martian Concrete was twice of sulfur concrete mixed with conventional soil. It was also learned through analyses that the influence of particle size distribution on the mixture's final strength was significant. The test results revealed that the best mix proportioning for Martian Concrete was 50% sulfur and 50% Martian soil simulant with the maximum aggregate size of 1 mm (0.039 in.) and that the maximum unconfined compressive strength was over 50 MPa (7.3 ksi).

Taking advantages of indigenous resources available on Mars (e.g., sulfur, basalt, Martian regolith, etc.), production of Martian concrete through 3D Contour Crafting appears to have the great potential for space applications such as building shelter for astronauts and protective hangers for equipment [34-39]. Yuan [40] implemented sulfur concrete extrusion process on a mini-scale auger extruder and a novel full-scale extruder. For the small-scale experiment, a mini-scale 3D Contour Crafting auger extrusion was utilized to produce Martian concrete consisting of 65% Martian regolith simulant (JSC Mar 1A) and 35% elemental sulfur powder. In the mini-scale system, the mixture was pushed downward through a funnel to the extrusion tube by a rotating auger while the extrusion tube was heated and kept at 140-150°C (284-302°F) by electric heating elements. In order to automatically counteract the bridging effect and to prevent extreme friction during the extrusion process, researchers installed a piezo transducer to the auger and a horizontal vibration piezo to the nozzle outlet [35,36,39]. For the full-scale Contour Crafting, a new mixer/extruder combination mechanism was introduced with the intent of heating the entire mixing and extrusion chambers to a certain temperature [36]. The extruder used in this experiment had a larger reservoir for processing larger amounts of sulfur concrete. Unlike the mini-scale auger extruder, the material was moved downward through a stage-wise mixing mechanisms on the upper sections while a special extruder at the end of the nozzle provided the main extrusion force. Moreover, when compared to the mini-scale experiment, the friction with the walls of the nozzle was far less than the mixture at the ambient temperature or pre-heated mixture because the mixture was completely melted before entering the nozzle. For rapidly lowering the temperature of the exiting material, an aluminum extender end was added to the outlet of the nozzle.

V. DISCUSSION

Additive manufacturing of construction components is a relatively new concept but may offer an innovative way of constructing architectural and structural components. 3D printing technology has high potential to solve some of the issues (e.g., time consuming, inefficient construction approaches, etc.) in construction industry. Although 3D printing technology is still at an early stage, many researchers believe that it would open new doors in developing new trends, which would lead to allowing more economical, sustainable, eco-friendly and faster means of construction. Researches are being conducted worldwide to optimize the capacity, bond strength and the use of reinforcement in 3D printed concrete. In addition, efforts are being made to develop standards/specifications of 3D printed concrete so that code-based design of 3D printed concrete structure or structural components can be initiated and move forward with this technology.

While the use of additive manufacturing and Contour Crafting in terrestrial applications seems promising, there still exists more to be explored and other critical challenges for extraterrestrial applications such as construction in a low atmosphere as well as under reduced gravity. Although these challenges are yet to be overcome, it is envisioned that continued research efforts may provide the solution for extraterrestrial shelter (e.g., electromagnetic space radiation, thermal, micro-meteorites, dust storms, rocket blast eject at launch/landing, etc.) for human crews and robotic equipment on planetary surfaces. In addition, it is expected that new possibilities for space exploration and space mission architectures will continue to arise.

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