3D Concrete Printing Technology Current Progress and Future Perspective: A State-of-the-Art Review

C. Venkata Siva Rama Prasad

Abstract 3D printing is a transformative window of opportunity to have a tremendous economic and societal influence over the next years. The technique, originally contained in the production of tiny objects, developed shape in the 1980s and moves into large-scale building application using concrete and additional cement and binding materials. This article offers state-of-the-art 3D concrete printing achievements in the field of equipment, materials and computer modeling. There will be several demonstration projects and potential and difficulties related to 3D concrete printing will be explored. Formulation of ink using local and local products is and will continue to be a serious difficulty. Further developments in large-scale 3D printers will continue. The review should be fascinating both to experienced engineers and beginners in 3D printing, even those focusing mostly on transition through current study to implementation of 3D printing in construction. This content covers evolution of 3D printing concrete with regard to its functionality, mechanical features and the construction plan, in attempt to implement 3D printed concrete reachable thoroughly. Furthermore, the applications of 3D printed concrete and its development have also been highlighted.

Keywords 3D concrete · Digital concrete · 3D concrete printing technology · Construction techniques · 3D concrete buildings · Additive manufacturing

1 Introduction

The first 3D printer, created in 1984, has become one of the fastest developing technologies in the recent decades. It was highly complex in the beginning and, furthermore, costly machinery. Since decades, 3D printing began to be widespread in all sorts of areas of business and printers were often utilized. Much has been accomplished in the medical, automobile and aerospace industries. Open source solutions make the development of new products, as well as creative 3D printing applications,

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available to everybody in many areas. The aim for many firms in various industries all over the world was to improve the printing material and 3D technology. Real change in the building business began in 2014, when the first home was printed and a new building technology chapter began. There has been significant talk, in particular in recent years, about the lack of innovation in the construction business [1]. The productivity of the construction industry has remained constant, or even decreased, as compared to other sectors (for example manufacturing and agriculture) which have witnessed a notable rise in productivity in the last two decades. A recent thorough McKinsey research identified many major initiatives to solve this productivity gap, including the integration of digital technologies, novel materials and enhanced automation. Many new developments that have transformed others have slowly been adopted by the construction industry. Newer trends have suggested that digitalization, new materials and technology and sophisticated automation are progressing in the sector [2]. For example, the relatively quick use of BIMs, particularly in East Asian locations like Singapore, has proven the prospective to transform the whole building sector in the form of digital technology. This highlighted the potential of RILEM which was held in Zürich, Switzerland in September 2018 and which has led to new innovations in digital manufacturing techniques like 3D printing with concrete and additional additive manufacturing procedures.

With 40% of the industry participants, the construction industry has taken note, and it would seem that most observers, as well as many other academic and industrial conferences on this issue, concur on the inevitability of the digitization progress. In this document we reiterate the reasoning behind digital concrete manufacture, and subsequently highlight the latest developments in the field of digital concrete manufacture, which are rapidly developing, as regards (1) material and processing, (2) structure and performance and (3) applications that lead to research. In future, automation of labor in the construction sector looks more probable; given the technical development 3D printing is indeed a noteworthy advancement in today's society and additive production process [3]. Some people feel that the adoption of this skill may lead the way for lower construction costs and timeframes, and permit building at further distant sites and further flexible designs and not just in advance, but also to the revolutionization of the building industry. It also offers some unique sustainable advantages that are not typically present in building. Because of the continuous development of automated 3D printing technologies in order to achieve more efficiency than existing techniques of building, the latest study suggests that construction materials and workforce needs may be significantly cut. Additional production is a technique of producing 3D things by generating additional layers of computer control-guided materials. The first 3D printer produced in 1984 was tried in the early 1980s [4]. To now, 3D construction demonstration projects include the manufacture of structural apparatus, houses etc. As an illustration, a research group from UK has developed 3D modeling that consent to mathematically complicated structures in a computer controlled manner. They were meant to immediately pour concrete without further formworks on the building site. Researchers used robotic weapons to print concrete constructions in various curved forms during testing performed by Loughborough University. In China, research teams use 3D-printed concrete structural parts to experiment with the building of a whole structure. On a further thriving note, 3D printing technology has evolved to the point where rebar inserted 3D concrete may be printed before the printing process, enabling the reinforcement of 3D printed Beton just as normal reinforcing techniques would enable. Over the last two decades, NASA has supported a number of studies aimed at creating new 3D printing processes that can be used to create structures utilizing alien materials. The development of helpful technology for building off-earth shelters for humans, equipment and the like on the Moon or Mars habitat is predicted to result in this type of work [5]. There are many 3D printing processes, including extrusion, pulver bonding and additive soldering that may be utilized at the building scale. Contour Crafting has been particularly popular among scientific and technical groups, as it permits quick prototyping, manufacture of complicated geometries, multi-material combinations and customization of products. Contour Crafting is a manufacturing method based on extrusion additives, which may be done by several means from gathering materials to stages of heating, prices & technical preparedness, it additionally permits accumulated thick strata of a smooth surface to be finished by putting down wet concrete into a pin and a side sharp bobble [6]. A single storey home constructed in one day with 10,134$ is an example where Contour Crafting was used (US dollars). The foundation and the walls of this project were printed using the Contour Crafting method, which was continued after the prints of the major buildings, after completion, doors would be fixed. Many engineers foresee a promising future in building for 3D printing, and other industry specialists feel that these technologies can ignite a new manufacturing revolt [7]. Overall, the possible benefits of 3D concrete printing include quicker building, reduced working expenses, higher complexity and precision, increased function integration and less waste-producing utilization of recycled resources. This study highlights contemporary advances in 3D concrete printing research and development, including applications in alien environments [8].

2 3D Concrete Printing Latest Technology and Its Materials

The introduction of additives to synthetic resins, which reasoned the polymerization practice to instigate after the resins were bleached, was the initial step in budding the technique. Stereo lithography is a technology that can craft items with remarkably high exactness and multifaceted geometry, which is why it is utilized in a multiplicity of disciplines such as medicine, the car and aviation industries, and even art and design [9]. Selective laser sintering (SLS) has become a piece of digital in which a light ray is used to merge powder particles collectively to create an object. The materials utilized in SLS technique are typically strong and flexible. Nylon or polystyrene are the most common. Modeling of fused deposition FDM is a technology developed by S. Scott Crump in 1988. Ductile materials are extruded through a double headed nozzle as they solidify throughout the cooling process. The cross-section layers

Fig. 1 Apis Cor house contour crafting [12]

produced from the digital replica supporting the printer are used to deposit both modeling and supporting materials. Resistive heaters in the nozzle keep the filament at the proper melting point, allowing it to flow freely through the nozzle and build the layers [10]. After generating one layer, a platform is lowered and the next layer is constructed, much like in other technologies. This procedure is repeated until the entire object has been finished. Materials commonly utilized in FDM expertise are known as filaments and employed as rolls of thermoplastic products in printers, such as ABS, or PLA, a thermoplastic of a completely different kind. It is biodegradable and better for the planet than ABS. Fused deposition modeling has been in the last two decades the world's most trendy and commonly used 3D printing process. Due to its different qualities and applications, wide-ranging materials were created during the last decades that enable the appearance of wood in the prints [11] (Fig. 1).

In the late 1980s Contour Crafting was initially established, depicted. Adapting the latest technology and advancing 3D printing method (e.g. application of computer-guided grid structure) allows for even quicker, more efficient construction of structures or structural components. Its unique layered production approach also enables constructing components with a rather smooth surface finish. The extruder may be obtained with the application of side sharpening troubles that can be set for the different layer and slope of the surfaces by coerced extruded flow in either horizontal or vertical direction. The outlet comprises of multiple winding systems, one on both sides and one inside a wall. Non-orthogonal surfaces can be produced by bending the dust. Contour Crafting is also able to use aggregates along with fiber enhancements such as additives [13].

D-shaped prints, often used in printing building models, utilize powder deposition, selectively hardened to compact with the desired thickness by applying a binder and fine aggregate layers. A fully built D-formed printing device comprises of about 300 rough shells, which are mounted on an aluminum box. The printer moves across the printed area and deposits binding ingredients during the construction process. Select sections from a loose precipitate deposit are excavated once finished. Ground materials require to be combined with powdered metal oxide beforehand to act in response with the fluid binder applied [14] (Figs. 2 and 3).

Fig. 2 Contour crafting 3D printer [12]

Fig. 3 D-shape 3D printed structure [12]

3 3D PRINTING Construction on MARS

There has been a dramatic increase in human populations on Earth, currently reaching 7.5 billion by 2018, with an estimate of 10 billion by 2056. As human populations increase rapidly and natural resources become apparently depleted, scientists and researchers explore the potential to settle adjacent planets. NASA has financed several research programs over recent decades to create revolutionary 3D printing technology that might potentially be used to construct "off-earth" homes such as mars habitats. Three major aspects, among others, are addressed while building a shelter or construction on Mars: materials, strength and build ability [15]. First of all, the ideal approach to create a construction on Mars would be to employ local materials because building materials from the Earth would significantly amplify the payload of the rocket. Sulfur concrete can be the best choice for house structures or structural components on Mars. Sulfur concrete is called a "rich-sweetened" planet. Sulfur concrete requires no water but comprises of aggregates and elemental sulfur, it is also crucial that a structure should be created for its longevity since humans will require high-quality structures for living and working after it reaches the red planet. Computer simulation using finite element modeling can be used, in conjunction with physical testing, for investigating mechanical reactions of structures with varied factors, including ecological loads, that'll be essentially diverse according to planet. Ultimately 3D printing technologies can improve the construction process on Mars, with very limited support for life. While the use of sulfur in concrete is scarcely a novel design as the use of elementary sulfur as a bonding agent has occurred in ancient times, Leonard and Johnson first suggested sulfur concrete as building material for extraterrestrial missions. The ability in extraterrestrial applications of employing sulfur concrete would be one of the key advantages: it could achieve full strength without water over a very short time period. The viability of employing molten sulfur as construction material in lunar structures has been examined in a study carried out by Omar [16]. The fundamental concept of this work was to use indigenous materials more logically than economically in extraterrestrial construction. Sulfur concrete blends with varying sulfur-to-soil ratios conducted series compressive and tensile strength testing to examine minimum sulfur needed for an optimal force. Some of the mixtures have been added to examine the impact of metal and glass fibers on sulfur concrete. An end outcome of this, investigation shows a max 33.8 MPa (4.9 ksi), for sulfur contents of 35% by height, was the compressive strength of sulfur cement while 45.5 MPa, for a further 2% by weight, was added to the same sulfur concrete (6.6 ksi) [16] (Fig. 4).

Producing Martian concrete through 3D Contour Crafting seems immense budding to building applications in space of a protective protection for astronauts and device covering sheets, taking advantage of indigenously available resources at the Martian market (e.g. sulfur, basalt, etc.). Experimentation on a simple level, the 3D Contour Crafting Auger extruder is used for make Martian cement, include 60% of the Martian regolith stimulant (& 30% elementary sulfur powder). Yuan [40] used the mini-scale augur extruder and novel, complete extrusion extruder to create Martian cement. In the mini-scale method, a revolving auger was added to the

Fig. 4 Construction on Mars using 3D printer [12]

mixture by a funnel to the extrusion tube while heating and maintaining electrical heating elements in the extrusion tube at 140–150 °C (284–302 °F). The researchers mounted a piezo transducer on egg and lateral vibrating piezo on the nozzle outlet to robotically eliminate the bridging consequence and to avoid severe friction in the extrusion process [17]. In order to fully heat the whole mixing and extruder chamber to a specified temperature, a novel blender/extruder combo mechanism has been introduced for complete Contour Crafting. The extruder utilized in the experiment featured a larger container for the treatment of huge quantities of sulfur concrete. The material was pushed down through a mixing mechanism in the top parts as opposed to the mini-scales auger extruder, and the principal extrusion force was delivered by a unique extruder at the end of the tubular [18]. Moreover, the friction of the nozzles walls was much higher than those of the pre-heated or air mix when compared to the mini-scale experiment, because it was totally molten before the nozzle came into contact. To rapidly lower the demand of the releasing ingredient, an aluminum extension end was attached to the pin's exit [19].

4 3D Printing in Concrete Applications in Construction Industry

As NASA's standards on in-situ application of resource application (ISRU) of Mars structural buildings appear to satisfy, the potential for NAS' Mars missions may be large for sulfur concrete built from Martian soil. Recently Wan has undertaken research to create the optimum "martian concrete" mixing ratio, including sulfur element and the JSC Mars-1A Martian simulator rich in metal oxides. Resources of JSC Mars-1A Mixed Sulfur produced by heating of even more than 120 °C (248 °F) were evaluated by researchers in this study. On the basis of compression and tensile tests carried out to assess the strength development, the strength of Martian concrete looked to be double the force of sulfur concrete mixed with regular soil. Analytical analysis also showed the effect of the distribution of the particle size on the ultimate strength of the combination. The finding shows that the optimal mix ratio for Martian concrete and the highest strength was above 50 MPa with a maximum overall size of 1 mm and a 50 percent Martian soil simulator (7.3 ksi). Producing Martian hormigon using 3D-contour production would be quite capable of using local resources on the Martian market, for example, producing a refuge for astronauts and protective hangers for equipment (e.g. sulfur, basalt, etc.). The mini-scale Contour Crafting Auger extruder was used for the small-scale experiment for the construction of Martian cement, consists 60% of Martian regolith (JSC Mar 1, A) & 30% of mostly sulfur powder. Even in case of process of making Martian cement, Yuan used a mini-scale augur extruder and unique, full extruder. A rotating auger was inserted into the combination with a drum on a mini-scale approach, while the extrusion chamber was heater and maintained electrical heating elements at 140–150 °C (284–302 °F) in the extrication chamber. In order to reduce the bridging

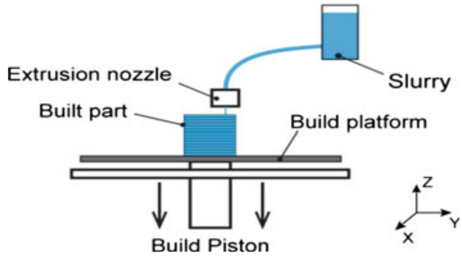

Fig. 5 Schematic of extrusion-based technique [21]

effect automatically by a horizontal vibration piezo and to avoid intense friction in the extrusion progression, the researchers attached a piezo transducer on the egg. A new blender/extruder combination mechanism was introduced to complete Contour Crafting in order to fully heat the entire blending and extruder chamber to a set temperature. The extruder used to process enormous amounts of sulfur concrete that was equipped with a large container [20].

5 Latest 3D Concrete Printing Technologies in the World

In recent times, various 3DCP methods to apply AM in concrete building have been created. Such solutions are primarily focused on different approaches, specifically, extruder & powder-based technologies. These methodologies are discussed in the following sub-sections. The resemblance and variation between the various 3DCP technologies and merits and cons have been emphasized.

5.1 Extrusion-Based Method

The extruded method is similar to the fussed deposit modeling (FDM) method within this cemented material is extruded from a nozzle attached to the portal grid, or 6-axis robot arm in order to build a building step by step. This approach has been intended for construction purposes in the field, construction works includes intricate geometry and huge budding to contribute significantly to the construction sector. Figure 1 illustrates a drawing of powder-based approach (Fig. 5).

5.2 Contour Crafting Method

University of Southern California, USA, has created Contour Crafting (CC) technology. This equipment uses the extrusion technique to extrude a vertical concrete

Fig. 6 A CC machine-fabricated concrete wall block with custom-made reinforcing ties manually placed within layers [12]

shaping by two layers of cement mix. Manually custom constructed ties of reinforcement are placed (horizontally and vertically every 30 and 13 cm), while the device extrudes the layers constantly. Smoothly extruded surfaces are connected to the print head. After finishing the extruded shape, the concrete is next sprayed manually to 13 cm high and after a hour, the very first batch is sprayed, with such a second batch and the lateral pressure of the concrete can be controlled by allowing a one-hour batch to partially heal and solidify. The CC machine creates a concrete wall form (Fig. 6).

5.3 Concrete Printing Method

A team of Loughborough University in the UK has been developed for concrete printing technology. The technology likewise utilizes a technology based on extrusion and is related to CC technology to a certain extent. The 3D printing method nevertheless been created keeps 3D mobility and has reduced deposition resolution, allowing for more flexibility of inside and outer geometry. Furthermore, the material used for concrete printing is fiber-reinforced, high performance finely aggregated concrete with greater material qualities than those achieved using CC technique [22]. A full scale bench produced with concrete printing is shown in below figure. The bench had a length of 2 m and a max width 0.9 mts and ht 0.8 m. The bank consists of 12 vectors which minimizes weight and could be used for additional construction services as an acoustic structure, thermal isolation and/or path. The bank also shows a strengthening technique in which properly selected void shape leads for post-reinforcement positioning (Fig. 7).

Fig. 7 Concrete printing created a full-scale bench with usable voids and post-tensioned reinforcing [21]

5.4 Concrete On-Site 3D Printing

The use of novel and sophisticated machines, the small mineral aggregates (fine aggregate mortar instead of concrete), and the small sizes of printed items Contour Crafting and Concrete Printing equipments show numerous technological benefits and are subject to certain inherent limitations (i.e. specifically, the 3D printer's length must be greater than the size of the element to be generated). To get over these restrictions, the TU Dresden, German, is now developing the new approach to 3DCP on-site construction technology called CONPrint3D, which aims to direct 3DCP to building sites. High geometric freedom, utilization of commonly used building tools and low dependence on professional labor constitute the key benefits of CONPrint3D technology. CONPrint3D focuses not only on developing improved construction processes that are time, work and efficient on resources but also on making the new process cost-effective while increasing the acceptability of existing industry professionals. This is achieved through as far as feasible the use of existing construction and fabrication processes and the adaptation of the new process to building restrictions. One key feature is the adaptation of concrete pump autonomously and accurately provides material to particular positions utilizing a specialized printer head attached to the boom.

5.5 3DCP Using Ultra-High Performance Concrete in Large Scale Construction Industry

In France, a research team was able to offer a novel method with UHPC on awareness due to constraints observed in listed CC and concrete printing methods. The method

Fig. 8 Multifunctional wall element [21]

employed to deposition UHPC layer via an extrusion printed head installed on a 6-axis robotic arm uses the extrusion-based technique. Major advantages of the proposed technology is (1) that 3D printed georamas not relying on temporary aids can be produced, (2) that 3D printing can be fully utilized by using the tangential continuity method of slicing, leading to mechanically sound structural designs.

The technology being proposed produced the "multifunctional wall element" (Fig. 5) consisting an absorbent shape that may be either filled with UHPC components and insulated material such as thermal insulation material. Few portions have been deliberately left empty to accommodate pipes or electrical cables. The wall element manufacture with a weight of 1360 mm = 1500 mm/170 mm, took around 12 h (for 139 layers), with a weight of 450 kg (Fig. 8).

6 Conclusions

- Additional building component manufacturing is moderately novel but may provide an innovative technique to build architectural and structural components. 3D printing technology offers a great budding for solving several problems in the construction sector, e.g., time consumption, wasteful building approaches etc.
- While 3D printing technology is at an early level, lots of academics suppose it will open new doors to generating new trends that will make building more cost-effective, sustainable, eco-friendly and speedier.
- Worldwide research is undertaken to improve efficiency, bonding & application of 3D printed concrete structures. Furthermore, attempts are being made to produce 3D printed concrete standards/specifications in order to commence and proceed toward codal provisions of the 3D printing concrete construction.
- Use of minerals & contour manufacturing in more ways shows promise, other essential problems, such as building in a low atmosphere and low severity, have yet to be studied.

- Although these challenges still need to be overcome, ongoing research can provide a solution to extraterrestrial shelters on planetary surfaces for human professionals and robotics technology (e.g., radiation from an electromagnetic space etc.). Furthermore, new options for space exploration and the design of space missions are projected to remain.

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