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Development, Challenges and Future Outlook of 3D Concrete Printing Technology

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ABSTRACT: In recent decades, 3D concrete printing technology has taken a growing stride, which enables design optimization in the construction field. 3D Concrete printing has many benefits over conventional construction methods like a reduction of the overall construction cost and time, reduce environmental pollution and provides safety to the workers by reducing accidents on construction sites. At present, improvement in construction productivity with achieving high-quality work is a challenge to meet the global demand of the construction sector. In this paper, we will deal with the various methods utilized for 3D Printing, the development in 3D concrete printing technology and the performance requirements of inking materials. The Paper throws light on the several prospects provided by 3D Concrete printing technology. Risk and challenges are also discussed in this paper even having many benefits of this technology as the technology is in the initial stage and has many limitations. Environmental concerns are also discussed in the paper. After reviewing previous work done in the development of 3D concrete printing technology, a significant gap like change in materials composition, nozzle design, Printing speed, etc. were identified to meet the requirements of on-field applications. Finally, future scope and the possibilities of using the 3D concrete printer in the field are also evaluated.

Keywords: 3D concrete printing, Additive manufacturing, Automation, Computer-aided design, Construction technology, Contour crafting, Digital construction.

Abbreviations: 3DCP, Three Dimensional Concrete Printing; greenhouse gases; SLS, stereolithography apparatus; IMJ, Inkjet Material Jetting; LOM, Laminated object manufacturing; IBJ, Inkjet Binder Jetting; SLS, Selective Laser Sintering; EBM, Electron Beam Melting; LENS, Laser Engineered Net Shaping; ED, extrusion deposition; BAAM, Big Area Additive Manufacturing; CAD, computer aided drawing.

I. INTRODUCTION

Construction using Conventional methods are most familiar and proven throughout the world. However, it has many drawbacks like high overall cost, longer time of construction, harder to perform quality control, wastage of materials, poor construction productivity, the safety of the workers on construction site, environmental pollution. With technological advancement in today's world, the construction industry has undergone an intensive evolution in the area of developing advanced materials and innovative construction techniques. It seems that 3D printing technology has been developing very fast and looks more realistic in the future. Digital materiality is the aim of 3D printing technology, which will establish a new method of construction and will replace the conventional method of construction for the upcoming time [1]. In this process, physical objects are created by depositing suitable material on successive layers on the digital model by using require software and hardware [2]. After the invention of a three-dimensional (3D) printer by Charles W. in the year 1984, this technology becomes very popular due to its wide scope of applications and developing very rapidly throughout the world. A first house was built using this technology in the year 2014 which has started a new era in the field of the building industry [3]. Convectional construction methods take a longer time to complete the construction while by using 3D concrete printing method it can be completed in a very short time. Different types of skilled and unskilled labour are required at different stages in conational method, while very less manpower needed in 3D concrete printing methods. High quantity of material wastage is observed in the conventional method, while very less or no wastage is found in the 3D concrete printing method. However, even having many benefits over the conventional construction methods, still, the 3D concrete printing technology is in his earlier days and required technical investigation on many points. In the early stage, this technology was very complex and also more expensive but with the development in technology, 3D printing technology becomes simple and less expensive so very commonly used in all types of industrial applications. Nowadays, to produce appropriate advanced printing material for a 3D printer for various applications has become an ultimate targeted area for many companies worldwide. 3D printing technology is known as 'additive manufacturing technology'. The use of concrete as an inking material in the 3D printer is currently under investigation by the researchers for industry applications [4]. Technological advancement made possible to print actual full-scale structures with a 3D printer on-site today [5]. Hence, 3D printing has become an advanced method of construction, by utilizing appropriate binding material.

Presently many demo projects involving 3D printing in construction including fabrication of structural components, housing, small bridges, artificial reefs, sculptures were carried out by leading construction companies as researchers and studied for their realistic application. This technology gives flexibility in design, reduces construction cost and time, allows the construction in a remote area which has the potential to transform the construction industry [6]. Furthermore, it offers practical advantages that are not available in conventional construction. The requirement of construction material and manpower requirement may be considerably decreased with the progress in automated 3D printing technology. Also, higher efficiency expected to be achieved compared to current construction methods. In the 3D concrete printer, concrete is directly layered on the construction site without using additional formwork [7]. The possibility of utilizing industrial waste material in a three dimensional (3D) concrete printer should be investigated [8]. NASA has funded several projects for developing advanced 3D printing methods that have probable applications of building a structure using interplanetary materials since last two decades [9]. It is anticipated that this technology will be used for building extraterritorial shelters for astronauts and equipment in the future. The paper throw light on comprehensive literature, technology review of 3D printing with future scopes and possible use areas in the building sector.

II. REVIEW OF 3D PRINTING METHODOLOGY

The working principle of most of the 3D printing methods is to transform computerized models into physical objects using different inking materials. The inking (binding) materials are printed on successive printed layers directly [10]. Many drawbacks of conventional methods can be reduced or removed by 3D printing. This method has also resolved the difficulties related to the accuracy, efficiency, handling of complexity, cost, and environment [11]. The use of this technology is very common in the aerospace industry, automobile sector, medical field and also in the food industry [12, 13]. The application of 3D printing technology for making full-scale objects for the architecture purpose is under investigation. The first 3D printing patent was registered by Charles Hull for his stereolithography apparatus (SLA) in 1986. Many 3D printing technologies and processes emerged soon afterward. Various materials used in a 3D printer include a polymer, fiber-reinforced polymer, metals, ceramics, and granular materials like cement and sand.

III. CLASSIFICATION OF 3D PRINTING PROCESS

Instant formation of solid objects from raw material as per the requirement either by applying heat or adding binding material is the basic principle of the 3D printing technology. The Classification of the 3D printing process with their working principles and various applications are discussed below.

A. Photo polymerization process

The photo polymerization on process is further classified into two processes: stereolithography (STL) and Inkjet Material Jetting (IMJ). In the stereolithography process, photopolymer resins are used as an inking material in this process while polymers are used as basic raw material in the inkjet material jetting process [14].

B. Sheet Lamination process

The sheet lamination process is further classified into two processes: Laminated object manufacturing (LOM) and Inkjet Binder Jetting (IBJ). In the Laminated object manufacturing process paper composites and metals are used as an inking material and layers of inking materials are bounded by adhesive coating and laser cutting. While powder of metals and sand are drop on the binder in the inkjet binder jetting process [14].

C. Powder-bed fusion process

The powder-bed fusion process is further classified into three processes: Selective Laser Sintering (SLS), Electron Beam Melting (EBM) and Laser Engineered Net Shaping (LENS). In the selective laser sintering process, plastic, metal, and ceramic materials are used as an inking material by laser scanning and heat-induced sintering [15]. The electron beam melting process works on the same principle but the inking material used is only metal. While the combination of different metals is used by applying heat and injecting in Laser Engineered Net Shaping process.

D. Extrusion process

The Extrusion process works on the extrusion deposition (ED) principle used polymers, composites, cement and aggregate as an inking material. Fusion or mixing of raw material, extrusion from the nozzle and deposition are the septs of the process and mainly used for Big Area Additive Manufacturing [BAAM], 3D curve printing, Scaffold additive manufacturing, and Contour crafting [16].

E. Electrospinning process

In this process, ultrathin fibers are used through electrohydrodynamic jetting. Electrostatic repulsion propels the feedstock, which is composed of long-chain polymers dissolved in a polar solvent, from the electrospinning emitter to a collector. It is extensively used to fabricate tissue engineering scaffolds. Since electrospinning has a lack of controlled fiber deposition, researchers are investigating various approaches to make the deposition controllable by regulating the operation parameters like the applied electric field, temperature and flow rate, and the properties of the feedstock such as the conductivity, viscosity, polymer dissolved, concentration, and surface tension. Almost all processes follow a similar procedure [17]. The electrospinning process works on the principle of Electrospinning in which long-chain polymers are used as a raw material.

IV. 3DCP MATERIALS &METHODOLOGY

The 3D concrete printing technology having limited inking material as the technology is in the developing phase. Research to determine the most suitable inking material and their optimum proportion for 3D concrete printing having all required characteristics is carried out throughout the world in different universities and industries. Experiments using resin mortar and clay with concrete as an inking material shows significant results [18]. Investigation using byproducts such as steel slag, fly ash, and some chemicals were also successfully conducted to make 3D printed geopolymers by the researchers. Construction waste was utilized as a raw material with cement and fiberglass for 3D concrete printing to recycling the waste in China.

Currently, cementitious materials like Portland cement, dry mortar, clay, special gypsum materials and other dry materials such as sand and fly ash are used as an inking material for three-dimensional printing represented by epoxy resins [19]. Aggregates up to 4 mm size should be used because the dimensions of the nozzle are comparatively small. To compensate for the low w/c ratio and improve the workability of the concrete mix, a superplasticizer must be added. An accelerator will be used for achieving higher strength at a quicker rate at the time of pouring. While retarder is added to avoid the early setting of concrete. Balance among all ingredients has to be maintained for achieving required functioning from the concrete.

Because of unique conveying, placing and hardening methods used in the 3D concrete printer, special care must be taken while designing concrete mix [20]. For the designing optimal concrete mix, certain goals were fixed. The concrete mix must have maximum compressive strength as per the design grade and maximum flow ability in the system with a high speed of concrete setting. The concrete mix also has high workability and maximum build ability upon pouring and must maintain a suitable setting rate for ensuring bonding with the successive layer.

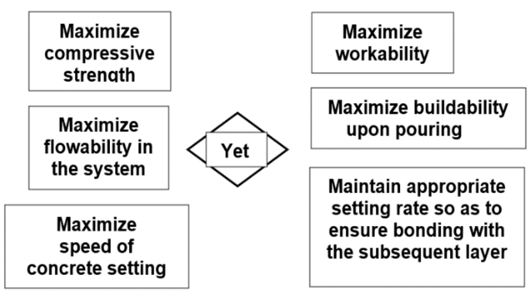


Fig. 1. Goals for designing optimal concrete mix for 3D concrete printer.

It is observed that some of the goals look conflicting. The challenge is to maintain balance among all goals. For achieving maximum compressive strength in concrete, the water-cement ratio must be minimum but, to maintain workability in the concrete, the appropriate water-cement ratio must be maintained. Furthermore, the design concrete mix should be flowable but at the time of pouring. It should also be buildable and it must hold itself with succeeding layers. Lastly, after pouring, the mix should set the earliest to ensure the required bond strength with the succeeding layer. To satisfy these goals, specific measures of the mix must be set. The five most significant characteristics of the 3D printing concrete mix that must be investigated are flowability, extrudability, buildability, open time and compressive strength [21].

V. FORMULATION OF COMPUTER MODEL FOR 3DP

The issues concerned with the mechanical performance of the 3D concrete printer and the performance required from the concrete mix for achieving printable objects are discussed in the previous sections. Apart from these issues, formulating computer models is one of the key elements for the implementation of 3D concrete printing technology. Development in 3D computer graphics makes it feasible to fabricate such digital models easily using commercially available as well as open-source software packages.

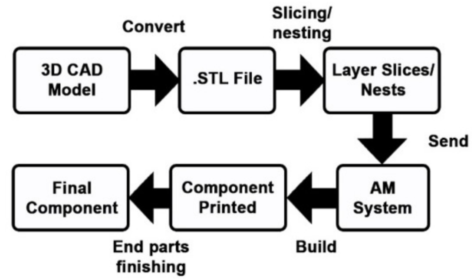
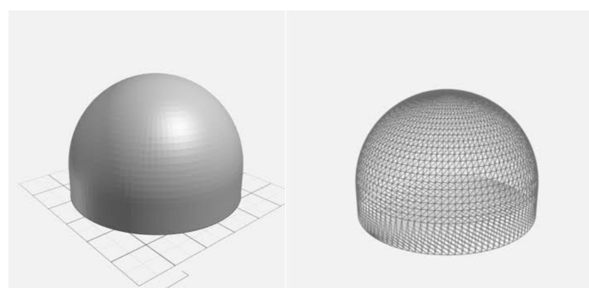


Fig. 2. 3D Printing Process stages.

In the 3D printing process, computer-aided drawing is prepared and converted into Standard Tessellation Language (STL) file format. STL format converts the 3D CAD model into a 3D wireframe model considering external closed boundary based on the cross-sections distance given for each layer [11]. This process is also known as a layer slicing or nests. The 3D CAD model, which is converted into a wireframe model is read by the 3D printer using nesting software and based on the slices the AM machine performs the ink deposition task to print the physical objects. The Additive manufacturing system is responsible for the performance of the mechanical functions of the 3D concrete printer and controlling the extrusion of concrete mix from the nozzle [22]. Printed objects are sent for the post-printing processes such as cleaning, finishing, curing, etc.



(a) 3D CAD Model (b) STL Model in Solid View Wireframe View

Fig. 3. 3D CAD Model to STL format.

Advantages of 3D concrete printing

– Feasible for onsite or factory applications.

– Only require quantities of materials for printing are used which minimize the use of resources and also reduce the waste generation.

– Design constraints present in conventional methods can be eliminated and interesting architectural shapes can be created.

– Reduce transportation costs if products are printed on-site.

– Lower the labour costs.

– Reduced cost of customized design.

– Minimize health and provides safety on site.

Challenges of 3D concrete printing

– Because of the very low speed of printing, it is become extremely difficult to print a large quantity of work by using this technology.

– Availability of limited printing material and ingredients used in 3D printing.
– The Effects of different environmental factors of 3D concrete printed structures are not known.
– Skilled persons are required to operate the 3D printer.
– It becomes very difficult to transport the large size 3D printer at the construction site.
– It has a high initial cost of creating a digital model and requires skilled persons.
– Printing cantilever parts is the major limitation of the technology.

VI. APPLICATIONS OF 3D CONCRETE PRINTING

3D Concrete printing technology is in the developing phase and many points are required to investigate as mentioned in earlier discussion but still, this technology contains the answer to many unsolved questions of conventional methods of construction which may lead construction sector in the next era. The following are the application of 3D Concrete printing construction [23, 24].
– Construction using 3DCP consumes lesser time and cost so it can be a solution to the housing crisis throughout the globe.
– Use for achieving high productivity and uniform quality of workmanship in construction.
– To construct the building with single mechanical equipment is possible with 3DCP and to avoid multiple types of machinery at the site.
– It can also use to construct the 3D printed bridge.
– Any architectural geometry can be printed using the 3D concrete printer.
– 3D concert printer also used to print structural precast elements in factories.
– For building off-Earth structures, 3D printing has been suggested as a useful technology.
– To build off-earth structures in the future.
– It can also use for aerospace as well as defense applications.

VII. ENVIRONMENTAL CONCERNS AT THE TIME OF USING 3D PRINTING

The selection of the appropriate raw materials and the proportion of the raw materials used are the main factors that directly affect the Cumulative Energy Demand (CED) of the 3D concrete printing. After studying the limited application of 3D printing technology, it is observed that this technology required less quantity of material and also required less energy compared to any other methods of production. Convectional materials such as metals and plastics contain high energy demand. Only required materials were used by the 3D printer so very little or zero waste is generated during construction. It is very easy to transport the printed physical objects from one place to another as they are light in weight and consuming very less fuel for transportation. RepRap makes self-replicating printers. The main aim of their printer is to use recycled waste materials and which will make it economically cheaper.

VIII. 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 a high potential to solve some of the issues (e.g., time-consuming, inefficient construction approaches, etc.) prevailing in the construction sector [25, 26]. Although 3D printing technology is still at the initial 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 globally to optimize the capacity, the bond strength between the subsequent layer and the use of reinforcement in 3D printed concrete [27, 28]. 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. Further, the use of reinforcements in the 3D Printable concrete will open a completely new direction in this area [29].
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, rocket blast eject at launch and landing, dust storms, thermal, micrometeorites, etc.) for robotic equipment and human crews on planetary surfaces [8]. In addition, it is expected that new possibilities for space exploration and space mission architectures will continue to arise.

IX. CONCLUSION AND FUTURE SCOPE

Effective utilization of 3D concrete printing technology in construction will solve many drawbacks of conventional construction methods and also improve construction productivity which directly affects the economy factor. Still many points should be investigated for achieving the desired output from the 3DCP as mentioned below.
Printing Techniques Analysis. The investigation required in the printing technique includes selection new nozzle with optimum size and shape, a novel method of extrusion and also a new method of delivery that enhance the overall quality of the printing.
Material Analysis. A detailed analysis of material can be done for the physical and workable property of the materials. Data analysis can be done for obtaining the highest stability for layer-wise concrete 3D printing.
Control System. Systematic research on control systems can be done which controls the 3D printer, direct and manage devices to carry out the allotted job. The Control system can be based on the concept of kinematics equation for governing of the cable-suspended subsystem.
Data Analysis. Analyzing and utilizing the data in the proper format so as to most effective printing is obtained by the printer. Data need to be processed in the most effective way to achieve the best result in the physical object. Data analysis for a different type of material can be done and studied to archive the optimized value for the best design for a stable building.
Architectural Design. Complex geometric architectural design or elements of a structure, either are difficult or impossible to achieve by conventional constructional methods which can be archived if properly commanded

by a 3D printing technique. Any complexity of components can be resolved by 3D printing.

Cost-Benefit Analysis. The Cost-benefit analysis will include different costs involved in construction as well as in quality maintains of the building. Cost comparison will include material, labor and construction cost. It also includes include direct and indirect cost, opportunity cost and cost of potential risks. The benefits include an increase in productivity, quality, lower investment and reduction in time required for construction and reduction in waste.

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