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**Review Article**

# Bibliographic analysis on 3D printing in the building and construction industry: Printing systems, material properties, challenges, and future trends

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## ABSTRACT

In recent years, significant advancements in developing large-scale 3D printers and construction materials have been made to meet industrial-scale 3D printing construction demand. Constructing the buildings and structural components using 3D concrete printing is significant. The main benefits of additive manufacturing (AM) are freedom of design, construction waste reduction, mass customization, and the ability to manufacture complex structures. The major issues include optimizing the printing material with suitable properties for 3D concrete printing. However, this technology for green building construction seems to improve conventional methods by reducing human resource requirements, high investment costs, and formworks. The research community's interest in 3D printing for architecture and construction has grown significantly over the last few years. As a result, there is a need to combine existing and ongoing research in this area to understand better current problems and their potential solutions based on future research work. This paper reviews the latest trend of research and state-of-the-art technologies in 3D printing in building and construction by analyzing the publications from 2002 to 2022. Based on the above-mentioned analysis of publications, printing methods, concrete printing systems, and the influence of constituent materials and chemical admixtures on concrete material properties are briefly discussed. The challenges and recommendations of 3DCP, including reinforcement, development of new materials, multi-nozzle combinations, life cycle assessment of 3DCP, and development of hybrid systems, are then examined. This paper concluded with a discussion of the limitations of existing systems and potential future initiatives to enhance their capability and print quality.

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## 1. INTRODUCTION

Additive manufacturing (AM), also referred to as 3D printing, is a process that creates a three-dimensional object from a computer-aided design (CAD) model by layering on the material to achieve the object's final shape [1, 2]. In 1998, at the University of Southern California, Behrokh Khoshnevis invented a large-scale 3D printing process

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called "Contour Crafting," which later became the standard method for real-world constructions [3]. In 2007, Italian engineer Enrico Dini invented the D-Shape, a large-scale powder-based 3D printer [4]. In 2014, a Chinese company named Win Sun built ten houses in shanghai using a gigantic 3D printer with dimensions of (150 m×10 m×6.6 m) within 24 hours [5]. High-grade cement and glass fiber was used to build these ten houses by Win Sun. They also built the world's first 3D printed Villa and a five Story apartment. In 2015, Andy used a large-scale 3D Printer to build a Castle using sand and cement. The castle was built in parts and then assembled [6]. In 2015, a huge 3D printer named Big Delta was introduced by Worlds advanced saving project (WASP), which measures 12 m tall, 6m wide, and surprisingly uses less than 100 watts of power. It was constructed outdoors using eco-friendly materials such as clay, straw, water, and dirt. An elevator was connected to deliver the solid material [7]. The construction engineering industry has much potential for large-scale 3D printing.

As 3D printing becomes more prevalent in construction, the design and preparation of concrete materials compatible with 3D printers have been identified as a significant issue. Some cementitious materials were explored for 3D printing construction applications. Gibbons investigated the feasibility of using rapid hardening Portland cement (RHPC) in a powder-binding 3D printing system to create structures [8]. Maier explained that calcium aluminates types of cement (CAC) have a high potential to be used for 3D printing structures because of suitable fresh and hardening properties [9]. A slag-based geopolymer ecofriendly material introduced by Xia and Sanjayan, composed of slag, fine sand, and a silicate-based activator [10]. The proposed geopolymer demonstrated sufficient deposit ability to replace the currently available material in powder-based 3D printers and excellent and distinct accuracy during structure construction. The method was later scaled up and used in large-scale 3D construction. A cementitious composite material composed of plaster and clay-like materials can be smoothly extruded using the Khoshnevis contour crafting system [11]. Physical properties and performance of 3D printing concrete materials, such as fluidity, extrudability, and buildability, are entirely dependent on the composition and characteristics of their constituents in both hardened and fresh states [12].

A material prepared by Nerella using limestone, brick, light concrete, and aerated concrete to replace already used material for concrete 3D printing. Printed objects have a strength 9.85% higher than before [13]. A high-performance cementitious material developed by Lim for concrete 3D printing. It consists of sand, water, and reactive cementitious compounds. The water-to-binder ratio used was 0.28 [14]. Feng worked on the mechanical properties of 3D printing structures by using cementitious powder but was unsuccessful in maintaining an excellent mechanical strength of structures [15]. Gosselin made another effort to prepare the concrete printing material using Portland cement, crystalline silica, silica fume, and limestone filler, but the material's performance was far away from replacing 3D printing material. There is currently no widely accepted standard for material selection and design procedures for 3D printing [16].

Generally, 3D printing is primarily concerned with designing and preparing concrete compatibility with the printer. The printable concrete should have suitable properties like flowability, buildability, extrudability, good setting time, enough strength, low shrinkage, etc. To meet these requirements, partially replace cement with mineral powders to enhance the physical and mechanical properties of the concrete printing material [17, 18]. Fresh and hardened concrete properties are improved by adding mineral admixtures such as limestone, fly ash, silica fume, and Nano-silica [19, 20]. 3D printing of concrete materials' mechanical and physical properties depend on the dosage and type of chemical additives and mineral admixtures in fresh and hardened states [21]. Another way to improve the 3D concrete material is by adding superplasticizer, retarder, and accelerator additives. This is a hot topic and ongoing research these days. Concrete fluidity increases without affecting mechanical strength as the addition of superplasticizer increases [22, 23]. To stabilize the rheological properties and consistency of concrete and enhance the dimensional stability of concrete, viscosity modifying agents are very effective [24].

In addition, raw material and chemical additives make the material suitable for the requirement of 3D printing construction to work optimally as designed. The most critical factor in 3D printing concrete is the setting time. The Vicat needle test is frequently used to determine the setting time of materials, but it cannot continuously record the setting time of materials [25]. In recent years, many efforts have been made to measure concrete's setting time and hardening properties effectively with the help of ultrasonic methods such as ultrasonic wave transmission and ultrasonic wave reflection methods [26, 27]. Later, Voigt, Sharma, and Liu modified the setting time measuring methods mentioned above to use them more accurately and effectively [28–31].

With global demand for $CO_2$ emission reductions, it is critical to introduce innovative construction technologies to pave the way for a sustainable construction future. It will help to reduce the construction cost, material waste, and time waste while providing a competitive edge. It can save up to 40% of the cost of the total budget of a concrete work building project. This is possible with the 3D printing construction technology [32].

This paper introduces the diverse range of concrete printing processes currently being developed worldwide and discusses the latest research trends by conducting a comprehensive review of the published literature over the

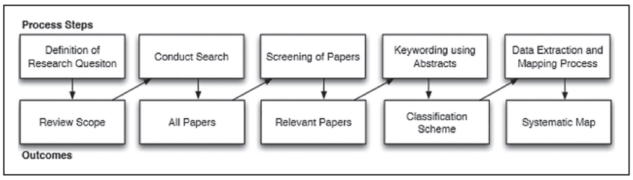

**Figure 1**. Petersen's Well-ordered mapping system [33].

last two decades. It is organized as follows. Publications screening methodology and state-of-the-art technologies for 3D printing by showing the significance of BIM incorporation discussed in section 2. Subsequently, the paper will highlight the ongoing research on 3D concrete printing systems and printing material properties along with additive selection given in section 3—moreover, the Challenges, limitations, and future work recommendations discussed in section 4, and finally, the concluding remarks in section 5.

## 2. BIBLIOGRAPHIC ANALYSIS

The interest in 3D printing building and construction has increased in recent years. While the increase in interest enhances the quality of literature in this discipline, it causes to make challenges for the researchers to express an overview of the research development. Mapping the number of publications can be an effective way to comprehend the research trend. Peterson suggested a well-ordered mapping study shown in Figure 1. It provides quality and type of research results with an overview of the research area [33]. To understand the research development in a specific discipline, it is essential to capture the literature review systematically. It will be helpful to understand the trend of research development in the field of 3D printing for building and construction.

### 2.1. Data Source Analysis and Methodology

Two multi-disciplinary scientific research databases were examined for this review analysis, including Science Direct, Web of Science, and Scopus. Almost 12000 journals and 160,000 conference proceedings are covered by these databases mentioned above. Only the journal papers and conference papers were selected, directly related to 3D printing for B&C industry applications. The Boolean operator, quotations, and parentheses were used to refine the research content, while other publications such as book reviews and other irrelevant content were excluded.

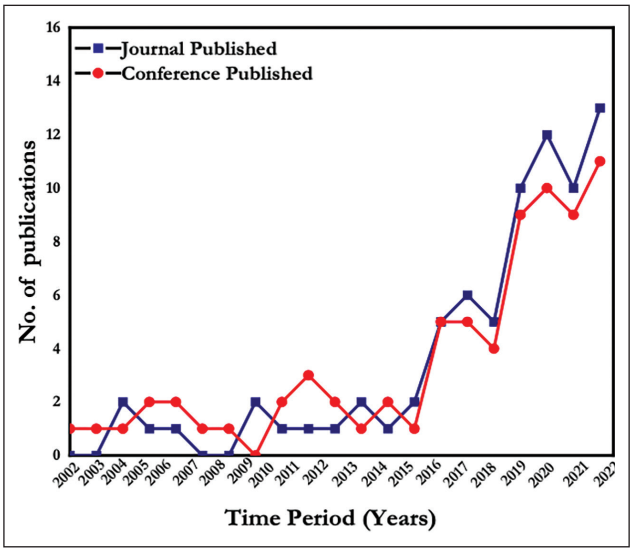

**Figure 2**. Represents the journal and conference publications trend from 2002 to 2022.

During the Web of Science search, 1767 publications were discovered that matched the initial search's keywords, and 374 were screened out. For Scopus, 2124 publications were found, and 308 were considerable of the total. In the case of Science Direct, 326 publications were screened out from a total of 1445 because of the limit criteria of Science Direct. Thus, these publications were screened for duplicates and categorized according to their title and abstract for relevance. The screening system for publications used during the search of various databases and keywords used in titles are shown in Tables 1 and 2, respectively.

**Table 1.** Frequently used keywords in the title of publications

| Keywords | 2002 to 2003 | 2004 to 2005 | 2006 to 2007 | 2008 to 2009 | 2010 to 2011 | 2012 to 2013 | 2014 to 2015 | 2016 to 2017 | 2018 to 2019 | 2020 to 2021 | 2022 | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Printing | 0 | 0 | 0 | 0 | 1 | 3 | 4 | 3 | 2 | 5 | 3 | 21 |
| Additive manufacturing | 0 | 0 | 1 | 2 | 2 | 1 | 0 | 2 | 1 | 5 | 2 | 16 |
| Rapid prototyping | 1 | 0 | 0 | 2 | 1 | 2 | 1 | 2 | 2 | 1 | 2 | 14 |
| Concrete construction | 0 | 0 | 0 | 0 | 0 | 2 | 1 | 1 | 3 | 3 | 0 | 10 |
| Contour crafting | 1 | 1 | 3 | 1 | 0 | 0 | 1 | 1 | 0 | 2 | 1 | 11 |
| Large scale | 0 | 1 | 0 | 2 | 1 | 1 | 3 | 1 | 1 | 4 | 7 | 23 |
| Construction material | 0 | 0 | 0 | 0 | 1 | 3 | 1 | 5 | 3 | 1 | 0 | 14 |
| Mega scale | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 0 | 1 | 1 | 5 |
| Digital construction | 0 | 0 | 1 | 0 | 0 | 0 | 2 | 2 | 0 | 1 | 2 | 8 |
| Green suildings | 0 | 0 | 0 | 0 | 3 | 1 | 2 | 1 | 1 | 1 | 3 | 12 |

**Table 2.** Data-based keyword search performed on 07 January 2022

| No | Same words searched | At least with one of these words searched | Web of Science |  | Scopus Search |  | Science-Direct |  |
|---|---|---|---|---|---|---|---|---|
|  |  |  | Doc. founds | Doc. screened | Doc. founds | Doc. screened | Doc. founds | Doc. screened |
| 1. | 3D printing | Construction | 200 | 45 | 389 | 25 | 300 | 67 |
| 2. | Rapid prototyping | Engineering | 75 | 23 | 120 | 34 | 290 | 45 |
| 3. | Additive manufacturing |  | 320 | 54 | 201 | 12 | 123 | 23 |
| 4. | Digital fabrication | Green buildings | 480 | 90 | 257 | 56 | 66 | 67 |
| 5. | Contour crafting |  | 54 | 20 | 34 | 10 | 75 | 31 |
| 6. | Additive construction | Automation construction | 76 | 12 | 90 | 25 | 87 | 20 |
| 7. | Digital construction |  | 120 | 35 | 290 | 12 | 128 | 15 |
| 8. | Concrete printing | Carbon dioxide reduction | 80 | 20 | 259 | 78 | 234 | 39 |
| 9. | 3D concrete construction |  | 93 | 31 | 104 | 20 | 90 | 12 |
| 10. | Construction 3D printing | Large scale construction | 269 | 44 | 380 | 36 | 52 | 7 |
|  | Total documents |  | 1767 | 374 | 2124 | 308 | 1445 | 326 |

Doc.: Documents.

### 2.2. Screened Data Results and Discussions

From the screening process, 132 publications were selected and classified based on the work represented. At the same time, innovative research studies found during the screening process, such as dynamic casting by smart way technique [34], automation method of brick laying techniques [35], and one about jammed structures, were considered mentioned in the latest [36]. Although these studies had a significant impact on recent research, they did not fit the purpose of this paper and were therefore excluded.

### 2.3. Publications Output Characteristics From 2002 to 2022

Figure 2 illustrates the information about the published papers in journals and conferences related to 3D printing for B&C from 2002 to 2022.

In the first 15 years of 3D printing for B&C studies, there were 43 publications from 2002 to 2016. From 2017 to 2022, there were a total of 89 publications found related to 3D printing in B&C. Those were slightly over double the of published in the first 15 years. That research shows the significant rise in interest in 3D printing for B&C applications, especially in the past six years.

From the statistics and search, it is noticeable that from 2002 to 2012, the conference proceedings are higher in numbers than the journal publications. Furthermore, from 2013 onwards, it can be seen that the number of journal publications started at a good pace and a higher rate as compared to conference proceedings. As a result, journal publications overtook the conference proceedings till the present. This significant change depicts the start of comprehensive and exciting research in that innovative discipline.

### 2.4. 3D printing for B&C Publications Origin

Only first-author publications were considered to represent the contribution of different countries in the research of 3D printing for B&C applications. Figure 3 shows the origin countries of publications found related after the examination. Selected papers show that the USA and the UK contribute the most in the discipline research of 3D printing for B&C. About 51% of the total publications were identified from these two countries on the list, followed by Singapore and China with about 15% of the total publications jointly. Moreover, the remaining contributions of different countries are shown in Figure 3.

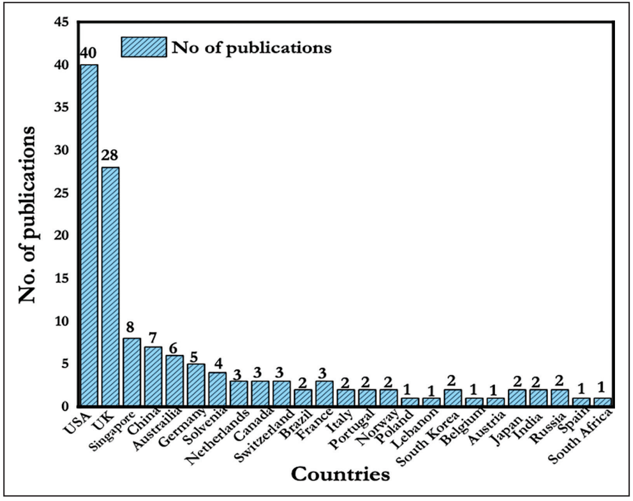

**Figure 3**. Research publications origin countries trend.

Most publications from the United States and the United Kingdom come from the University of Southern California, the Massachusetts Institute of Technology, and a few other renowned universities in this field, accounting for more than 33% of the publications selected for this study. According to Figure 3, the United States of America ranks first in the publication of 3D printing for B&C research.

Moreover, Figure 4 illustrates that the USA's contribution toward publications remains constant over time while the publications from all over the world have dif-

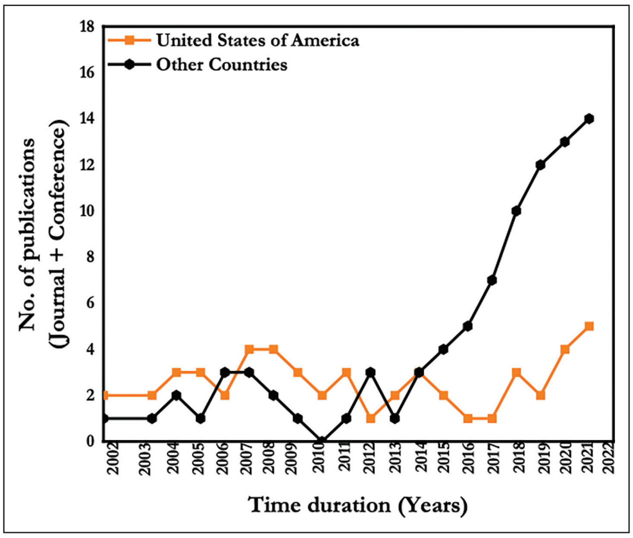

**Figure 4**. Comparison of the growing trend of the publications between the USA and other countries.

ferent fluctuating trends from 2002 to 2022, especially in the last six years. The global trend of 3D printing in B&C research is moving toward globalization of scientific research, with the remaining countries gradually closing the gap with the USA.

### 2.5. Major Research Findings

To check the development trend of 3D printing for B&C, selected publications were classified to get information deeply. The results depict that most of the authors focused on almost six categories of research in the identified publications as each paper contained more than one research interest, so publications were grouped on the bases of interests separately. It is entirely unpredictable which research interests will define the scope of each paper. As the same group of researchers took the research, other research interests were eliminated due to irrelevant context according to this paper's review aims. The purpose of conducting this study is just comparison, and it looks appropriate to mention these six focused categories of research. Detailed descriptions are mentioned ahead.

(1) Printing technique analysis included new methods to deliver the material for printing purposes, such as the innovative idea of using a nozzle for the material extrusion and a suitable material delivery method for a smooth flow. This kind of research is mainly observed in the selected publications and differs from conventional printing techniques [37]. These printers included printing and the extrusion method category, as Yoshida described [38]. His work is mainly based on material analysis, architectural design, and construction.
(2) Some material analysis publications generally analyzed the material and improved its properties. After this data analysis was done to check how many layers can be constructed using the 3D printing technique, this research contributes to data analysis and material analysis [39].
(3) Another category worth mentioning is the control system observed. There is a concept about controlling a device or machine by the given command to perform a required task that could be useful for the 3D printing operating system for B&C, so it is selected from the publication and mentioned [40].
(4) Data analysis depends on the computer system and the software being used. It also depends on the way how they exchange the data with each other. It helps to create a physical object by processing the given information or command.
(5) Architectural design is discussed in many of the selected publications. The thing appropriate to mention here is that sometimes the architectural design is impossible to construct using a 3D printing layer mechanism or procedure. It is best if use curvature demonstration of an object otherwise impossible with simple techniques to build it [37].
(6) The other observing thing was the literature review which included the work done by the previous persons and review articles in plenty and many examples demonstrated by the authors [41].

Due to the limited amount of selected papers and focused research areas, results have been divided into Table 3 and grouped in every two years of research. Printing technique analysis deals with the gantry or robotic system to control the printing process and other technical features as some excellent research has been found related to this [42, 43]. The material analysis focuses on product surface finish

**Table 3.** Research Interests Found from selected publications from 2002 to 2022

| Research interest | 2002 to 2003 | 2004 to 2005 | 2006 to 2007 | 2008 to 2009 | 2010 to 2011 | 2012 to 2013 | 2014 to 2015 | 2016 to 2017 | 2018 to 2019 | 2020 to 2021 | 2022 | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Printing technology | 2 | 1 | 4 | 3 | 2 | 1 | 2 | 3 | 2 | 2 | 2 | 24 |
| Material inspection | 1 | 0 | 0 | 3 | 1 | 1 | 2 | 2 | 3 | 4 | 4 | 21 |
| Construction design | 0 | 0 | 3 | 1 | 1 | 1 | 4 | 3 | 1 | 2 | 2 | 18 |
| Literature review | 2 | 0 | 2 | 2 | 2 | 1 | 1 | 2 | 2 | 7 | 3 | 24 |
| Controlling mechanism | 1 | 3 | 1 | 1 | 2 | 3 | 2 | 4 | 2 | 0 | 6 | 25 |
| Data inspection | 0 | 2 | 1 | 1 | 3 | 2 | 2 | 2 | 1 | 1 | 5 | 20 |

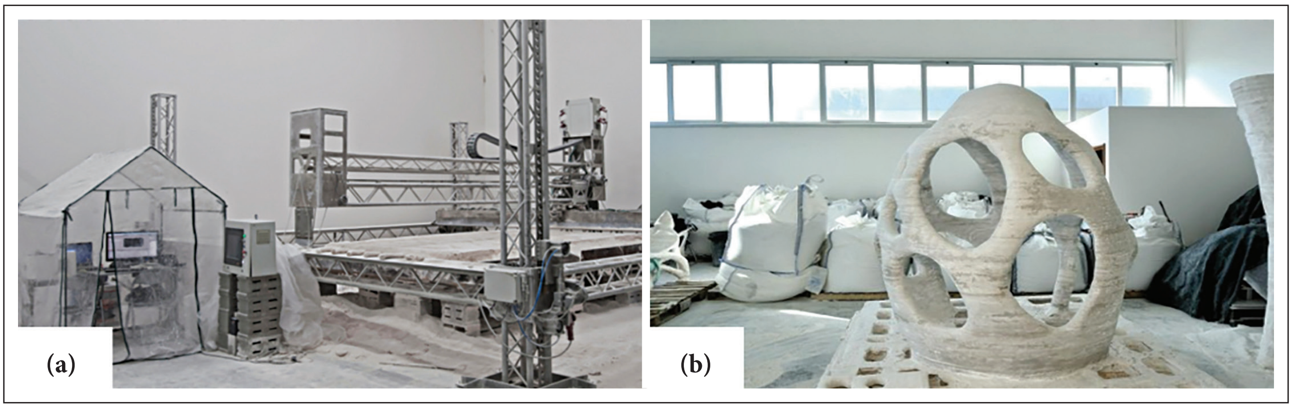

**Figure 5**. **(a)** D-shape second generation 3D-Printer **(b)** final printed structure after removal of extra sand-based materials [41, 51, 52].

and other functionally graded components production [44, 45]. Printing construction material properties and characteristics adjustment attempts were also carried out, which is the primary reason for developing an interest in material analysis [46, 47]. Large-scale printing rose in the last couple of years, as shown in Table 3, and as the printing technique and material properties will improve, the construction of complex structures will also improve, as some previous research proved [48, 49].

### 2.6. Selected Publication Titles Review

Analysis of publication title results illustrates that authors frequently use some words in the publication titles selected during the screening process. Repeated words such as 3D printing, concrete, additive manufacturing, and large-scale manufacturing are mentioned in Table 3 briefly, with the growing trend of each famous term used in the titles. The word " concrete " is not much noticed in the far past publications. It just started a couple of years before as the material options for 3D printing increased.

Alternatively, some words used went down over the last decade, such as large scale and free form construction, and there is a possible reason for that may be the authors do not like to use this word or may sometimes be these words did not fulfill the actual proper meaning. For example, and as observed in one of the studies, free-form structures utilizing material extrusion are impossible due to the inability of large cantilevers and angles to be printed [16].

## 3. 3D PRINTING STATE OF THE ART TECHNOLOGIES IN B&C

Selected publications represent the rapid development of large-scale 3D printing, and most authors categorized it into two primary techniques named as (1) binder jetting technique and (2) material deposition and extrusion techniques. The basic principle of these techniques is to build a physical object by depositing material layers one by one over each other. It started with the help of a CAD model, which shows the 2D shape, and after processing the model and operating the command, it created a 3D prototype shape. Only 10 percent of the total number of selected publications focused on the binder jetting technique, which will discuss in this section.

### 3.1. Binder Jetting

Binder jetting is a 3D printing process in which objects are created by layering a binder over a powder bed. Binder is ejected in tiny droplets spread across the powder material's thin layer on the build tray. This method connects the two parts of 2D cross-section components over each layer of the powder [41]. The process continues until the final object is completed. Using a vacuum cleaner, unbound material can be removed and suitable to use further again for another 3D printing task after recycling the material [50]. This method can work on complex geometries with voids and overhanging features. Because of the narrow distance between the layers, this method's resulting surface finish is excellent. Layer thickness matters a lot. It depends and measures on the penetration of the binder between the two components or cross sections; if the layer is too thick, it is difficult for the binder to penetrate completely between the layers [51]. Figure 5 illustrates the D-shape printer and the final printed component after removing additional sand-based materials.

### 3.2. Method of Material Deposition

Material deposition method (MDM) is a 3D printing process in which material follows and comes out as the CAD model, similar to fused deposition modeling (FDM) [52]. The extruded material must be able to bear its weight and the coming layers over layers without any collapse or deformation [53]. Many automated systems use MDM for fabrication, which will be discussed in this section.

### 3.3. Stick Dispenser

A stick dispenser is a device developed by Yoshida, and it is a kind of hand-help printing device that allows a con-

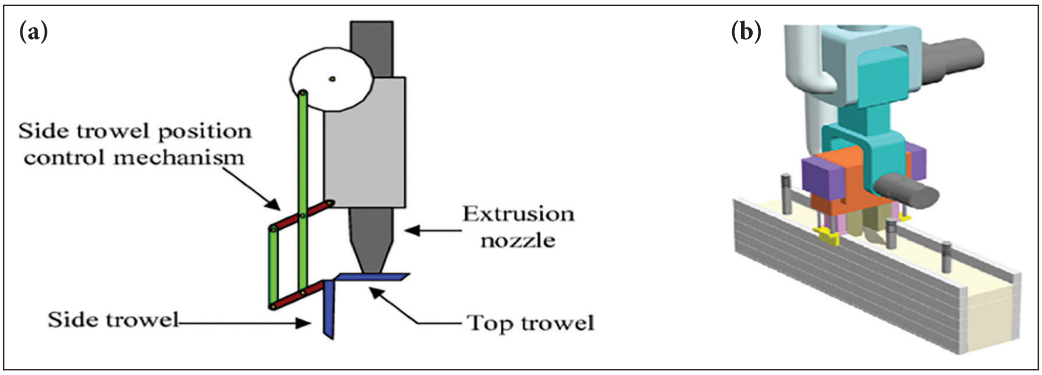

**Figure 6**. **(a)** Single nozzle **(b)** multiple nozzle assemblies [55, 56].

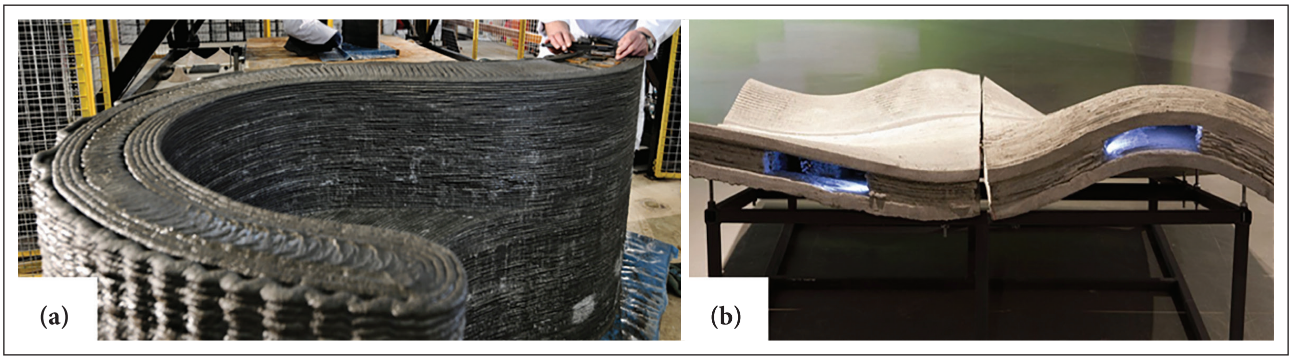

**Figure 7**. 3D concrete printing progress at Loughborough University [57].

stant feed of chopstick material composites [38]. Chopsticks coated in wood glue are randomly dropped during this process, forming a porous structure that is later evaluated using volume-based analyses. The device is guided by basically two main tools one is a depth camera, and the second one is the real-time projector. Using a simple color code and these two tools help inform the place where the chopsticks are deposited. There is a condition of low light while using the projector. There was some mechanical properties test carried out by applying the different load conditions, and the results show that the load bearing capabilities are not good enough, but this method is innovative for the use of aesthetic purpose by making the complex architectural design [38, 53].

### 3.4. Contour Crafting (CC)

Contour crafting is a process that utilizes a gantry-based system to extrude material layer by layer in a systematic manner. The uniqueness of this technique is the use of trowels with the nozzle, as shown in Figure 6. The benefit of the trowels is that they guide the printer about the smoothness and surface accuracy. The trowels can be adjusted at different angles according to the object's shape, which gives an extra benefit of surface finish even during the higher thickness of the layers of the material [54]. Some authors describe explicit material and compositions in the selected publications [55, 56]. It is also noted that CC technique conduits for electricity, plumbing, and structural reinforcement can be used [54].

### 3.5. Flow-Based Fabrication

MIT researchers designed a single pneumatic system connecting with the end effector of six robotic arms, which enables the extrusion of water-based polysaccharide gels and natural composites. The design and fabrication of the printed parts are two-dimensional (2D). High stiffness, light weight, and high wear and resistance will be the characteristics of the advanced manufacturing materials structures [57]. This work has many applications, such as temporary lightweight shading structures to highly complex automated structures for architectural purposes, as shown in Figure 7.

### 3.6. Digital Construction

A system developed by the researchers working at MIT can be used for the analyses and fabrication with a feature of on-site sensing [58]. The system is intended to achieve high speeds, accuracy, and ease of access through a small robotic arm, as illustrated in Figure 8. The whole system is designed around a large boom used for gross positioning. An accelerometer and ground reference sensor accurately positioned the end effector for the closed-loop system. There was a need to use a material with rapid cure time and high insulating value, so polyurethane foam was selected as

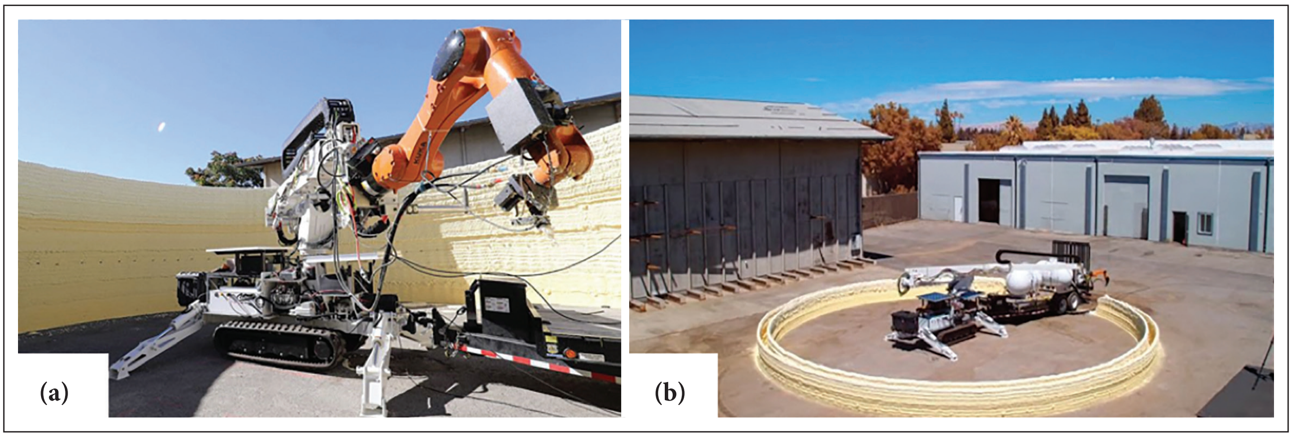

**Figure 8**. 3D concrete printing progress at Loughborough University [58].

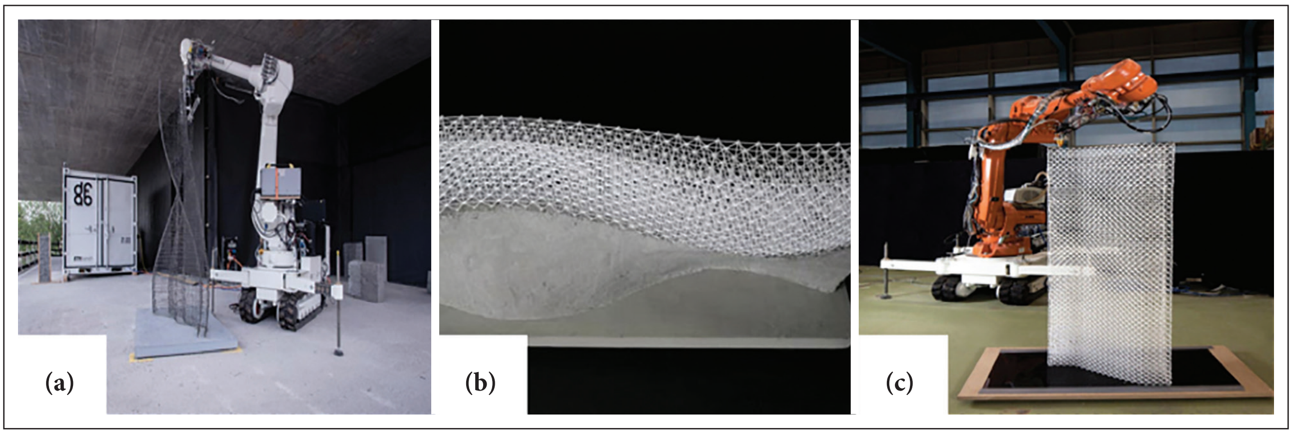

**Figure 9**. Mesh-mould technique-based formwork and reinforcement setup for concrete materials [60].

a printing material. A 12-foot-long wall will take five minutes the completion. To get a final surface finish, the end effector can be changed as a mill head for subtractive manufacturing and suitable for the desired surface finish [58].

### 3.7. Small Constructor

A coordinated system build consists of three small robots for the fabrication of in situ construction. They are lightweight, compact in size, and quickly available for mobility. During the printing process, each small robot has its unique feature to perform, described by Nan in detail [59]. Extrusion rate determines by the movement and speed of the robots, so a binary component resin material was prepared for these robots. Curing time must be compatible with flow rate and robot movement speed to avoid material clogging in the hose. To meet the required curing time property, an external heat source can be applied according to the environmental conditions, which will help adjust the material curing time by using the heat source's chemical effect.

### 3.8. Mesh-Mould Construction Technique

This technique is capable of printing in situ structures freely in three-dimensional space. For this purpose, a giant six-axis robot was used to extrude the thermoplastic polymer material to print structures. For a high level of control of the printing process, pressurized air has been used at the nozzle during printing, facilitating the weaving of structures freely in space. A relevant research application found that structures act as reinforcement for the concrete, as shown in Figure 9. Then concrete is poured over the formwork and later on troweled manually to get the smoothness of the surface [60]. This technique enables the fabrication of complex structures by reducing time consumption and making it feasible for large-scale applications. At the same time, the different densities of mesh can be printed. The most exciting thing is that the tensile force of concrete increases with the presence of mesh, ultimately a possible way to replace conventional steel reinforcement.

### 3.9. Building Information Modelling (BIM)

Building construction management covers the complete life cycle of a construction process, and the best way to deal with it is BIM [61]. For example, planning, scheduling, facility management, and estimation. BIM has the potential to provide the solution to problems that the construction industry has always faced, such as lack of innovation and

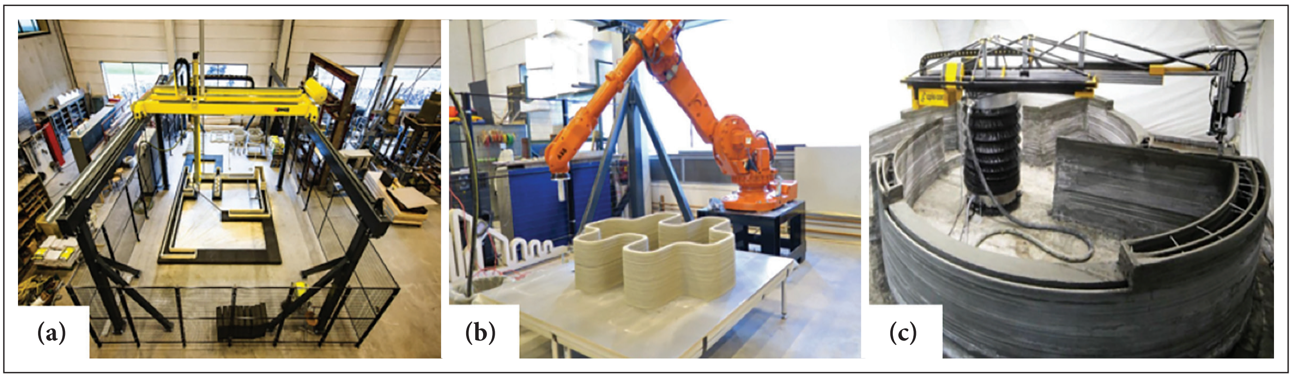

**Figure 10**. Currently used main 3D concrete printer **(a)** gantry printer [77] **(b)** robotic printer [82] **(c)** crane printer [83].

low productivity in its ongoing process [62, 63]. BIM also deals with equipment, material, available sources, and manufacturing data to deal with geometrical data [64]. This technique helps to overcome the lack of collaboration between the different teams during execution stages and provides an essential platform for automation applications such as mechanical construction and 3D printing.

A 3D printing construction based on BIM can quickly reduce the time required for the process completion in each step just by using a single software or interface. A common issue in the construction industry is that design is constantly changing, and BIM also deals with that issue effectively. As 3D printing needs no formwork, quickly abrupt changes can be done with little effect on the design compared to the conventional construction methods. It can effectively automate the printing process by storing and synthesizing the control data of the printer, delivery of material, and later on, process performance.

BIM is observed as a primary language in the construction industry and is a standardized method followed by the construction industries as 3D printing have a game changer effect in the construction industry, the same as BIM can bring many benefits in terms of labor and cost savings. Unfortunately, there is not enough research done in collaboration between 3D printing and BIM, while there is a potential opportunity for the researchers to fill the research gap between 3D printing and BIM.

## 4. CONCRETE 3D PRINTING IN B&C

A group of researchers at Loughborough University, England, built a system of concrete printing similar to a contour crafting system that extrudes concrete as a material layer by layer to build a physical object according to the CAD model [65, 66]. Concrete is used globally as one of the primary construction materials. It has several benefits as a construction material, such as high thermal resistance, low cost, good durability, high strength, good flow gaining ability, and molding into different shapes. There could be three reinforced concrete (RC) construction components: concrete, reinforcement, and formwork. Research shows that formwork waste a lot of cost and time of the total cost and time accounted for 35–54% and 50–75%, respectively [67]. However, as a new technique of Concrete 3D printing, construction companies can easily save a lot of time and cost compared to traditional construction methods. According to the UK's statistics, the UK construction industry produces about 54 Mt of construction and demolition (C&D) waste annually, from which only 9% goes for reuse after crushing [68]. It is welcomed that the adoption of 3D Concrete printing construction would be able to control the construction waste because the material's mixing and using will be in a systematic way as compared to the traditional ones. Ultimately, it will be economical, time-saving, good productivity, and help towards good environmental impact by reducing global warming because of this construction wastage.

### 4.1. 3D Printing Construction Systems

The most important advantage of 3D printing construction is that it rapidly manufactures complex structures and objects with non-standard geometries [69–71]. The 3D printing construction processes could be divided into three main categories by names given by their founder Contour Crafting, D-Shape, and concrete printing. These processes are discussed in detail and accessible in [72–74]. To utilize these processes for construction purposes, two kinds of approaches are extrusion and pumping approaches. In both approaches, the first step is slicing the 3D CAD model into 2D layers of the model. Then all the basic requirements to print an object are given to the printer in a readable language, such as printing speed, extrusion rate of the material, and other coordinate info of the object to get the final desired shape of the product [75, 76]. 3D concrete printers, nozzles, pumps and control systems, and feed mechanisms will be discussed in this section. These system parts must be in an excellent combination to achieve high-quality 3D printed products.

### 4.2. 3D Concrete Printers in B&C

Currently, according to the latest research review in universities and construction industries, three kinds of 3D concrete printers are successfully used: Robotic, Crane, and Gantry, as shown in Figure 10 [77–83]. Gantry belongs to

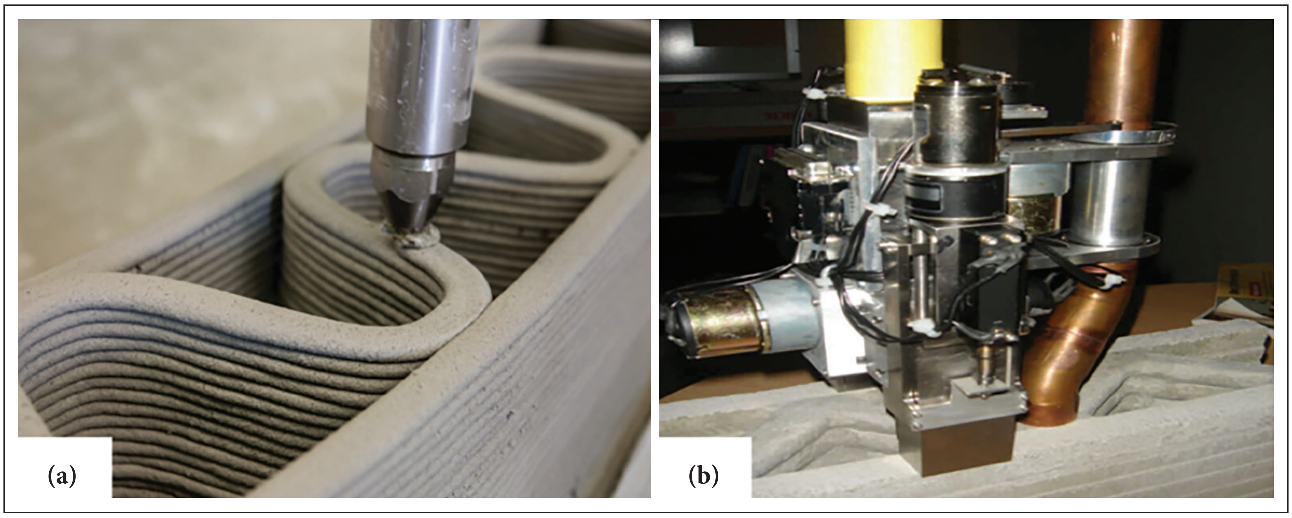

**Figure 11**. Concrete extruder nozzles main types **(a)** single orifice nozzle [86] **(b)** multiple orifice nozzle [91].

the crane type, but the main difference between these two is that gantry is a kind of fixed design regarding height, whereas Crane type printer's height can be adjustable in the vertical direction. The main benefit of these two printers is that they can get easily scalable concerning the size. While the robots are typically fixed in size, making it difficult to scale up according to the requirements. However, the degrees of freedom are more suitable in robotics six arms and enable them to perform many valuable operations compared to the 4-arms gantry printer.

Furthermore, using gantry printers is suitable where the printing object has little complexity instead of using the robotic printers. Robotics, like gantry printers, require high cost and less weight on the arms. The size of gantry printers varies from small-scale laboratory printers to large building construction scale printers, depending on the site and usage [77, 78]. Win sun Construction Company in china also used the same gantry printer technique to build multiple houses, including a five-story building apartment and a mansion. The material used for that construction consists of glass fiber, cement, hardening agents, sand, and some recycled waste of construction materials [77]. All the houses built were not wholly 3D printed. They prepared the parts at the company and then assembled them on the site [77].

Another Netherlands company, CyBe additives, used the CC technique to print a mortar capable of gaining bearable strength within 5 minutes. They used a print head with a six-axis robotic arm to perform the experiments with high speed and good strategy [82]. The additional rotational axis of a robotic over a gantry printer allows the designer to print more complex geometries easily. A Russian Company has built a crane-type printer that enables a printing area of 58 m$^2$ [83].

In 3D concrete, printing observed that print head speed affects the bead dimensions. For example, when the print head speed is higher, material layer deposition will not be enough, and the bead dimension will be short. On the other hand, if the print head speeds too slow, then the layer of deposition material will be higher than the nozzle orifice, increasing the bead dimensions and wasting the material too [76]. One of the previous research has noticed that the time gap between the two layers was a range of 11 to 60s, which enables the build of a 3D column at a rate of 1.1 to 6 m/h [84]. The extrusion rate generally varies in concrete construction processes ranging between 15 to 125 mm/s. It appears that the quality of the surface limits the extrusion speed to about 200 mm/s depending on the extrusion plate size, which was 15 x 70 mm [85]. Ultimately, it can vary from material to material for 3D construction printing.

### 4.3. Concrete Extrusion Nozzles

The shape and size of the material layer depend on the nozzle, which is the end part of the print head [86]. An appropriate nozzle at the end of the print head is essential to achieve the desired shape and quality of the material layers over the bedding layers. To obtain this nozzle, the printer should be tangent to the path [86] to avoid the collapse of the layers. Various kinds of orifice shapes of the nozzle are used, such as circular, rectangular, square, and elliptical. Furthermore, side trowels can be used for a better surface finish. Results of the research show that the circular shape orifice nozzle has more advantages than other orifice shapes, such as freedom in printing angle or vertices during the printing of an object [86]. Some studies show that a square orifice is far better than the elliptical one in terms of surface finishing and ease of manufacturing [87, 88]. Nozzle orifice sizes vary according to the shape and size of the object to be printed. Circular orifices vary in size from about 4–24 mm in use, while the other orifice shapes, such as rectangular, vary from 9x6 mm to 38x15 mm [76, 89].

Existing nozzles deliver material of about 0.05–0.1 L/s [90]. However, for 3D printing construction, the rate of ex-

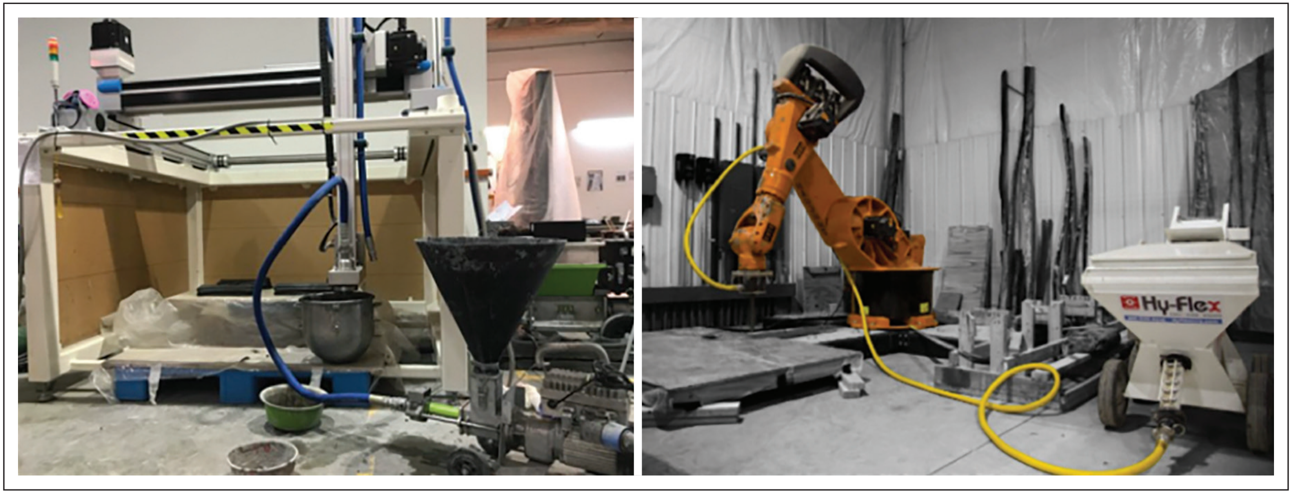

**Figure 12**. Concrete pumping and feeding systems for 3D concrete printing [76, 92].

trusion from the nozzle is about 1L/s, and a roughly estimated speed up to 2L/s is considered a realistic target rate, and multiple nozzle orifices can be used according to the shape and design of the object to be printed [91].

### 4.4. Pumping, Feeding, and Control System

One of the essential parts of the 3D printing construction system is pumping the material at a reasonable delivery speed without separating the particles. The pump feeds the material from the mixer through a pipe or hose to the nozzle from where the material is extruded to print the required object. The pump should be able to transport the material from the mixing unit to the nozzle by overcoming the challenge of large particle size aggregate and range of water to cement (w/c) ratio. Maintaining the high viscosity of the fresh material demands relatively higher pumping pressure ranging from about 1 to 5 MPa [92]. Blockage of material in the pipe may occur during pumping at high pressure, which can be caused to the loss of the smearing layer. The balance between the feeding system, Nozzle, and material properties is essential to obtain a smooth printing process and product. Pumping speed can be managed concerning the object size and shape, especially at the angles, to avoid the extra deposition of material.

It is essential to adjust the pumping speed to follow the shape discontinuities and movement of nozzle extrusion. Therefore, a complete single-unit control system is better for simultaneous control of nozzle movement, printer speed, and material pumping. One effective way to avoid collapse is to put chemical additives in the material at a stage when the material is in the nozzle instead of mixing additives in the mixer to boost the setting of the material [76].

### 4.5. 3D Printable Materials Properties

Viscosity, available time, shear stress, and strength are the essential properties of freshly prepared material and are directly related to pump ability, extrudability, and buildability. Flowability changes depending on available time, which enables the material to be printed without affecting the material properties like hardening etc. Generally, the Vicat apparatus is used to measure the initial and final setting time. The time between mixing and initial setting time is named open time. At the same time, pump ability and extrudability could be affected directly by shear stress and viscosity which Rheometers can measure.

Furthermore, the Slump test can indirectly measure fresh material's shear stress [93, 94]. The green strength of the material should be enough to bear the subsequent layers' load on the bed layers without any collapse or shape damaged [84]. Table 4 presents the mechanical performance of fiber-reinforced 3D-printable concrete materials.

#### *4.5.1. Pumpability*

Pumpability means the mobility of the material along with its initial properties under pressure conditions [95]. The material state needed at the nozzle and pump both are contrary, such as the material at the pump should be soft, which will be easy to move. On the other hand material at the nozzle should be stiff enough to maintain the shape. Concrete is a heterogeneous material consisting of different sizes and particles, so a pumpability system must be optimized and good enough to pump the material [96]. Acceptable paste content and consistency of grout of grains are necessary to improve pumpabaility [97]. Studies proposed that sliding pipe Rheometers are suitable for measuring permeability [95, 98].

#### *4.5.2. Extrudability*

The commonly concrete extrusion process for instance, the manufacturing of pre-cast hollow core slab elements, involves a plastic-like mixture forced through the nozzle, and for this kind of production, high shear force and compressive force are required [85, 99, 100]. In 3D printing construction, it depends on the type of printer (gantry,

**Table 4.** The mechanical performance and parameters used for fiber reinforced 3D-printed concrete [8–22]

| References | Fiber parameter | | | | Strength (MPa) | | |
|---|---|---|---|---|---|---|---|
| | Length | Shape | Content | Type | Compressive | Flexural | Tensile |
| [8] | 3 mm | Straight | – | Carbon | 83.7–87.4 | 20.3–119.6 | – |
| [9] | 3/6/8 mm | Straight | 0.25–1.00% | Glass | 20–27 | 2.6–7.0 | 0.9–1.5 |
| [10] | 18 mm | Straight | 0–0.7% | Basalt | 29.8–39.6 | 3.34–6.51 | 3.0–5.2 |
| [11] | 6/12 mm | Straight | 0–1.4% | PE | – | 2.13–15.09 | – |
| [12] | 6 mm | Straight | 0.25–1.00% | PP | 13.5–35.8 | 6.1–8.1 | – |
| [13, 14] | 12 mm | Straight | 2% | PVA | 23–30 | – | 3.4–5.0 |
| [15] | 8 mm | Straight | 2% | PVA | 24.2 | 10.8 | 4.7 |
| [16] | 12 mm | Straight | 2% | PVA | 16.45–19.23 | – | 1.6–3.5 |
| [17] | 8 mm | Straight | 2% | PVA | 34.98–44.09 | 1.64–2.41 | 4–8 |
| [18] | 6 mm | Straight | 0.3–1.5% | PE | – | 0.88–8.31 | 5.3–8.3 |
| [19] | 12 mm | Straight | 1–2% | PE | – | 3.2–19.4 | 4.6–5.8 |
| [20] | 12 mm | Straight | 1–2% | PE | 36.7–53.4 | 14.4–22.0 | 4.5–4.7 |
| [21] | 3/6/13 mm | Straight | 0.25–2% | Steel | 70–156 | 6–16 | – |
| [22] | 3/6/13 mm | Straight | 0.25–2% | Steel | 70–156 | 6–16 | – |

Fiber content in this table refers to volume fraction unless stated.

robotic, crane) size and the working volume, e.g., length, width, and height. These two parameters give information about fresh material pumping over the required distance. For the pumping, thixotropic concrete is desired, and fresh concrete material at the nozzle stage is less dense than the traditional ones. Stiffness is essential to maintain the object's shape and quick building of the object's layers. Segregation must be avoided at the nozzle because, at that point, the size of the nozzle becomes smaller compared to the delivery pipe, which may cause pressure at the nozzle end [78]. Material contents and proportions should be chosen carefully to achieve the properties of good thixotropic and permeability of the concrete material. On the other hand, failure at this stage may lead to the blockage of the material delivery pipe or nozzle.

#### *4.5.3. Buildability*

Properties of layers to maintain the shape of the object, being self-supportive, and enabling the bedding layers to bear the weight of subsequent layers without collapse and deformation of the shape; these all properties refer to the buildability of the material. Imperfection in layers may lead to an unbalanced shape during successive layers of material added [101]. Traditional work has formwork, so there was no worry about it, but 3D concrete printing is a formwork-free technique, so concrete must be self-supportive to achieve good results. There are several ways to achieve the buildability of the printed material instead of improving the properties of the material. The simplest way to change the structural buildability is the change of nozzle shape. For example, the contact area between the two beads is less in a circular orifice nozzle than in the rectangular one, and the contact area would help improve the structure's buildability [78, 101]. Another way to improve the buildability is by increasing the number of adjacent layers and cellular structure of layers by using a single nozzle or multiple nozzle head. However, a single nozzle's starting and ending point should be the same but not necessary for multiple nozzle heads [73].

#### *4.5.4. Flowability Control*

Flowability is a crucial parameter of 3D printable material, enabling the performance of fresh concrete material. Flowability control ensures that material is good enough to pump through the delivery system toward the nozzle without any blockage [102]. It depends on the grain size, and the wider particle size helps to gain a good flowability of a fresh state material mixer [102, 103]. Fine powder admixtures help the material to get a fluid shape which attains good flowability of cement mortar instead of getting bonds and getting higher in size [104, 105]. Incorporating an excess amount of fine powders may lead to an increase in viscosity and inter-particle friction forces. As a result, an adverse effect will be on the fluidity [106–109]. Studies proved that adding a superplasticizer can improve the flowability and the higher ratio of water to binding material also leads to improved flowability [110–113].

#### *4.5.5. Setting Time Control*

For a continuous flow and deposition of material layers, correctly printing material requires a long time to maintain. However, the material also needs a short setting time for early strength after extruding from the nozzle [114, 115]. Setting time property mostly depends on the retarder and accelerator admixtures, and studies show that by altering the amount of retarder or accelerator, every material can achieve the required initial and final setting time [116, 117]. The recommendation observed during the research shows the addition of accelerator should be in dry mixing instead of dilute with water mixing, and mixing speed and time should be 52 rpm in 20 seconds, respectively [118]. Studies proved the effect of retarder on the setting time; for instance, sodium tetra borate, and the mixing ratio varies from 0.1% to 0.3% could increase the jelling time about up to 29 minutes to 110 minutes and the final setting time slightly up to 50 to 148 minutes [119].

#### *4.5.6. Compressive Strength*

The stiffness and strength of concrete can be increased by using fine powder admixtures of small size compared to the Portland cement will be helpful to fill the voids and increase the packing density, resulting in good compressive strength. Silica fume and fly ash are usually rich in $SiO_2$ and affect the material's mechanical strength and help enhance the strength. These two ingredients affect the hydration process of the system and make the material denser and more compact by improving the mechanical strength of the concrete material or cement mortars [120]. It is reported that 10% use of silica fume by mass can increase the strength of concrete by up to 8–20% [120]. The effect of silica fume is not prominent at the starting stage of addition. It shows the effect after three days [121]. Concrete strength ration 1 day/28 day decreases as the silica fume addition amount increases and it ranges about 6% to 30% [122]. It does not work at the early stages to gain enough strength as needed [120]. Concrete 3days strength has been increased up to 81% by adding four wt.% of nano-$SiO_2$ [123, 124]. Studies showed that seven days and 28 days samples compared with the addition of silica fume and $SiO_2$, results revealed that the strength of samples containing $SiO_2$ is higher than all others [125]. Dispersing agents must disperse the particles effectively to get good strength [126]. It is noted that a large amount of fly ash into the material will lead to a decrease in the strength of concrete [127]. Fly ash works slowly to increase the strength but rises at the later stages [128]. One research also proposed that the high amount of limestone powder will decrease compressive strength at the early stages [129].

#### *4.5.7. Shrinkage Control*

Whenever disturbed, the dimensional accuracy and stability of the printed object are responsible for shrinkage, which usually affects the printing performance. To ensure good flowability and extrudability, high water content is necessary beyond the volume needed for the hydration process. The excess water evaporation leads the printed object toward shrinkage during the setting time and hardening stages [130]. As in 3D printed objects, most of the area is open and freely in contact with the environmental condition compared to the conventional methods, so it causes to evaporate the water easily from the object, and shrinkage occurs [131]. The possible solutions to control the shrinkage are increasing the mineral admixtures content and using the fine aggregates to avoid shrinking the composites [132]. The addition of fly ash to reduce shrinkage has been shown to have significant effects, as replacing cement with 80% fly ash can reduce shrinkage by approximately 67% [133, 134]. Shrinkage reduces up to 80% in dry conditions if combined use of fly ash and sulfoaluminate cement [135, 136]. Adding 10% to 15% of the silica fume can increase concrete's autogenous shrinkage, ranging from 33% to 50% [137–140].

### 4.6. Selection of Chemical Additives

#### *4.6.1. Superplasticizer*

To maintain the workability and strength of the concrete during preparation, using less water is possible by adding a chemical known as a superplasticizer. Negatively charged superplasticizer repels the cement particles to release the entrapped water, enabling the material to gain good flow ability [141, 142]. Research shows that superplasticizer addition did not change the hydration process but improved the process by improving the crystal structure [143]. Superplasticizer is divided into four primary groups and is readily available in the markets [144]. However, even from the same group, their effect on strength, setting time, and flow is different because of the different chemical structures of molecules [145–148].

#### *4.6.2. Accelerator*

3D concrete printing usually needs a quick setting of the material after coming out from the nozzle to bear the weight of the coming layer. Therefore accelerator is an additive that enables concrete to get enough early strength. Accelerator compositions work on a quick hydration process by reducing the setting time and quickly enhancing the material's setting. Accelerators can be an alkali or alkali-free group [149].

#### *4.6.3. Retarder*

Retarder is used to delay the hydration process of the cement by building an insoluble layer on the surface of the cement particles. Researchers recommend using Tartaric acid, citric acid, and sodium gluconate to achieve a favorable retarding effect [119, 150, 151].

#### *4.6.4. Viscosity Modifying Agents (VMA)*

Viscosity modifying agents are soluble in water and are frequently used to modify concrete flow and rheological properties. Even small dosages of viscosity modifying agents significantly affect the cement mortars and improve flowability and dimensional stability. The VMA decrease down the powder requirement still has the required dimension stability and flow properties [152]. The VMA connected the molecules through Van der Waals interaction and stopped the extra water movement, leading to increased plastic viscosity. The point to be noted is that if 3D printing material viscosity increases, higher pumping pressure is needed.

## 5. CURRENT LIMITATIONS, CHALLENGES, AND FUTURE WORK

Besides the benefits of 3D printing in the construction industry, such as the ability to build complex geometry and structures, freedom of design, and customization, there are a few limitations, challenges, and drawbacks observed from the previous research. These limitations and drawbacks required some further research and development of technology to overcome. In this section, limitations and future work will be discussed to provide a new direction for the reader and the researchers to explore so that the traditional construction industry can take full advantage of 3D Construction printing.

### 5.1. Limitations of 3D Construction Printing

Every production domain almost makes progress in automation and technology since the early decades of the 20th Century except the Construction industry, which is still facing a lack in automation and technology because of several factors [53–54, 153] most common ones:

- Automated fabrication technologies for large-scale production are not suitable.
- Automation technology is not according to the conventional design approaches.
- As compared to other production industries, its production ratio is significantly small.
- Expensive automated equipment reduces interest and attractiveness.
- Limitations of the materials.
- Management issues to deal with the process effectively.

Furthermore, the building industry's production rate cannot easily match other industries' production rates [154]. Because of different sites, materials, and client requirements, each building is different from others and reflects its prototype. Despite the differences, most designers believe that eventually, 3D printing will significantly contribute to the construction industry. They agreed that the 3D construction printing process is slow initially and becomes quicker in the later stages compared to the traditional methods [155]. The Figure 13 shows the time consumption by both the 3D construction process by a continuous line and the traditional process taking time by fluctuating dash lines.

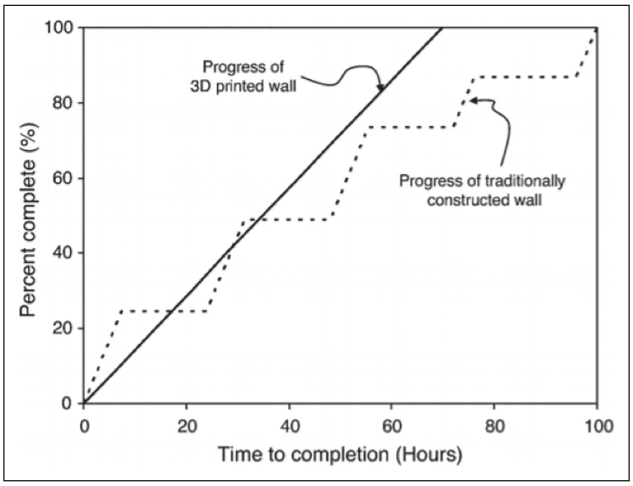

**Figure 13**. Time consumed by the 3D printing process and traditional construction method to complete a wall [64].

The components for 3D construction printing are significantly heavy and oversized, and avoid moving and lifting these parts of the system as much as possible. The other major problem is material sensitivity, which makes it challenging to perform at ambient conditions compared to UV or heated conventional systems; it is less controllable. Other limitations that need to be considered during the process are enlisted [156, 157].

- The concrete material will solidify and block the machinery if the idling time of the nozzle is too long.
- The time interval cannot be shorter than the minimum curing time, so the first layer must be able to bear a load of subsequent layers without any collapse or deformation.
- Subsequent layers of the material should be able to stick quickly because the time interval should not exceed a specific limit between the subsequent layers.
- The nozzles cannot be allowed to collide with deposited layers. If this happens, the nozzle cannot move in a straight line to avoid the hurdles.

The results come from these factors and the material limitations together recommends that at the moment, traditional construction methods should be continued for heavy construction and multi-story buildings, and small, lightweight construction should be done with the help of 3D Construction printing. There is a need to improve the technology to support 3D construction printing without any limitations and wait until success achieves, and 3D construction printing will enable building heavy construction [155, 156].

### 5.2. Challenges of 3D Construction Printing

#### *5.2.1. Balance of Stability & Flow*

There is a need for a material having two states for 3D concrete printing, and both states have opposite properties. Such as, before the extrusion of the material, it should be easy to pump and have a consistent flow. After extrusion from the nozzle, the material should be stable and robust enough to bear loads of the upcoming layers. This is a challenge faced many times during the experiments.

#### *5.2.2. Maintain Workability*

To achieve good printing results workability of the material is one of the critical factors. However, the material takes time to harden but loses its workability quickly as soon as it is mixed. Here is a need to add additives such as water reducing agents to maintain the material's workability and achieve good printing product results. Often, this challenge has been faced during working on the printing material.

#### *5.2.3. After Extrusion, no Deformation*

The 3D printing process proceeds by depositing material layers one by one. Each layer should be strong enough to bear the load of the next layer and each coming layer loaded by the previous layer. A material problem often occurs when the load of the layer is put onto the previous layer; it shows a slump problem. An effort for this challenge by using no slump material but no slump material has a problem while pumping the material, so it is a challenge faced during the experiments.

#### *5.2.4. Avoid Cracking Around the Corners*

Another common problem faced while working on 3D construction is cracking around the corners of the object to be printed. Cracking around the corner comes because of the fast nozzle speed around the corners. So this is a challenge to the product's strength that has been faced generally. These are some challenges observed during the review of previous studies. The following section will suggest future work and highlight the research gap for the researchers.

### 5.3. Future Work Recommendations

#### *5.3.1. Multi-Nozzle Combination*

A multi-nozzle combination could make possible high achievements and problem solutions in 3D construction printing. It can be done by using multiple nozzles at a single printer, and construction work can be done quicker than before by using a printer at different parts of the object simultaneously, which leads to fast production within a short period. Although, the system will become complex and need proper planning for handling the whole process. Moreover, one benefit is to use different materials from different nozzles simultaneously as per the hybrid construction requirement of the part to be printed.

#### *5.3.2. 3D Construction Printing Hybrid Systems*

Hybrid systems for 3D construction printing could be developed. Different materials and various components for structures can be used. For structural and non-structural applications, different grade types of material can be used for 3D printing in B&C in future work projects. For continuous monitoring of constructed buildings, using sensors and actuators in the material will be significantly worth full. These will provide real-time monitoring even during the phase of construction [158]. However, using sensors to get load-bearing properties and improved structural design reinforcement can be used with concrete.

#### *5.3.3. New Material Development*

Several friendly efforts were carried out to develop the material for 3D Construction printing using different combinations of cement, sand, flash, and fibers, which is still a challenging task for the researcher [13–14, 46, 159]. The success of 3D printing is majorly dependent on the development of new materials having properties according to each application. The material should contain functionality added values of light weight, thermal insulation, low cost, good setting time, enough mechanical strength, and good flow ability to be effective for future complex and large-scale construction [160–162]. However, the future of 3D printing is bright and has the potential to print complex and large-scale structures, as most researchers believe.

#### *5.3.4. Property of Reinforcement*

The low tensile strength and ductility of concrete is another major challenge for 3D printing in B&C. Adding steel reinforcement can solve this problem, but in the case of the 3D printing process, reinforcement of steel automatically is not straightforward compared to conventional one. Imbedding and post-tensioning reinforcements can be inserted manually instead of automatically [50, 56]. Vertical direction tensile strength could be increased using a steel extrusion gun similar to the staple gun at the back of the nozzle. Although to control the force of steel staple penetrating the filament would be a challenge. There could be two possibilities of force: fresh concrete will be destroyed if the force is too large, while there will be no penetration if there is a too small force. Using fibers in steel reinforcement will improve the ductility of concrete material.

#### *5.3.5. Optimization of Printing Parameters*

3D Concrete printing is significantly affected by printing parameters such as printing speed, the flow rate of the material, and the thickness of printing material layers because these properties play an essential role during the construction process [86]. Precautions are necessary to adjust these parameters. If something goes wrong, it will lead to severe failure and lousy printing quality. The major limitation in the printing process is void formation, which causes uneven material layers. Studies showed that this layering effect could be controlled by the proper selection of the layer thickness, but the time required would be more to complete the product if the layer thickness is too small. So printing time, layer thickness, and surface finish of the output product should be considered to print an object [163]. Finally, the overall surface quality can be improved by using post-processing such as grinding or plastering.

#### *5.3.6. Life Cycle Assessment (LCA) for 3D Concrete Printing*

In the construction industry, while the more significant impact of industries on the environment, Concrete 3D printing delivered a green and clean construction process without waste of material during construction compared to conventional methods. Researchers highlighted the environmental benefits of using material-efficient design in digitally fabricated architecture [164]. In these studies, the main focus was digital fabrication instead of 3D printing, which is related to some extent and necessary. There is a research gap in this study, and LCA must be used to assess the environmental impacts of all stages of the product life & process and the impact of 3D printing improvement on the environment.

#### *5.3.7. Life Cycle Cost Analysis (LCCA) for Concrete 3D Printing*

There is a lack of fundamental understanding of economics found in the past studies, and it should be included in future research as it can be helpful in 3D concrete printing. This way, an early analysis of the relationship between cost and design parameters could be proposed. The primary objective of LCCA is to achieve the lowest possible total cost of design, production rate, part disposal, product use, and product development [165]. Incorporating the LCCA system with a 3D concrete printing process will save all the process stages. The process will improve production rate, total cost, and product design.

#### *5.3.8. Requirement of Safety and Skills*

Safety on the construction site is one of the biggest challenges observed and proved by the studies. During designing preventive security systems, collisions, falling on the machine, and machines running over should be considered [166]. A physical barrier is necessary during the printing process to prevent the workers from a collision with the moving parts of the machinery. A safety video camera should be installed on the work site to avoid accidents and continuously monitor by safety management staff during construction [165, 166].

Another major challenge is the requirement for workers to have experience in both robotic and civil site work. Knowledge of printing parameters and material properties significantly impacts the design's quality and limitations. The 3D printing industry expects to grow significantly by 2022, as recent research shows the quickness in this field. Hence, existing workers need new skills for 3D concrete printing instead of conventional methods, and much research is needed to understand and overcome all challenges.

## 6. CONCLUSIONS

In conclusion, Concrete 3D printing in B&C is an emerging method that has the potential to revolutionize the traditional building and construction methods by providing the benefits in terms of low cost, high efficiency in automatic construction, freedom of design, and reduction of labor cost and risk of injury during the construction at working site. The main challenge is the development of appropriate material for continuous extrusion from the nozzle and stacking of depositing material layers over one another and should be able to bear a load of subsequent layers without destruction or deformation and collapse. For this purpose, some simulation work can be done to check the behavior of different materials under loaded conditions, which will be helpful for future work.

Concrete 3D printing use in large-scale buildings construction needs some requirements such as the development of building information modeling (BIM), degree of requirements at mass customization scale, and the essential requirement is the life cycle cost analysis of 3D printed projects/ products. The life cycle performance of the printed projects remains unclear as 3D printing construction is still growing. However, BIM can examine printed objects based on shape, performance, and assembly levels. Furthermore, the construction industry partially examined the degree of customization and categorization based on projects.

There is no need to abolish traditional construction methods altogether because the construction industry's future will most likely be a hybrid process that will simultaneously take advantage of both conventional and 3D printing technologies. By overcoming these obstacles, it is expected that 3D printing construction will reach its full potential in the building and construction industry.

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### DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

### CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

### FINANCIAL DISCLOSURE

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### PEER-REVIEW

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