Application and Development Prospect of 3D Printing Concrete Material in Construction Field

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Abstract. This paper reviews the research progress of 3D concrete printing in the whole construction field, summarizes the basic principles and related processes of this technology, deeply analyzes the necessary properties of concrete materials for 3D printing, and gives a detailed description of its research status. In addition, the article also collates the current challenges in the field of technology and the direction of future development, aiming to provide a constructive reference for the future research and exploration of concrete 3D printing technology.

Keywords: 3D printing concrete material; building; energy saving and high efficiency; Development prospects

1 INTRODUCTION

3D printing technology has flourished in the field of science and technology in the 21st century, and Economic Talent has commented that 3D printing technology will become a powerful propellant for the third global industrial revolution. It is an advanced manufacturing technology that transforms digital models into physical objects, also known as Additive Manufacturing (AM)[1].

For concrete materials, the core element of modern architecture, the application of 3D printing technology has become an important opportunity for the development of this field towards energy saving, material saving and high efficiency. As a new construction technology in the construction industry, concrete 3D printing technology has the characteristics of no mold, high efficiency and high precision, and has a large number of applications in military, flight navigation, power equipment and other industries, showing great potential and prospects. This paper focuses on the application of 3D printing concrete materials in the field of construction, and analyzes its development prospects, which provides new ideas for the application of 3D printing technology in the field of construction concrete materials.

Early experiments aimed to explore the feasibility of using 3D printing technology to fabricate concrete components in buildings, and a new production and construction mode of mechanical printing of cement-based materials was first proposed by Pegna[2]. These experiments are typically conducted by academia and research institutes with the

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aim of validating the potential and limitations of the technology. With the development of 3D printing technology, some companies have begun to try to apply it to the construction field. This phase has seen a number of initial commercial products and projects that, although relatively small in scale, have laid the groundwork for the development of the technology. Over the past few years, 3D printed concrete technology has undergone continuous improvement and expansion. Architectural 3D printing has gradually formed three construction methods, which are mainly contour process [3], D-Shape bonding settlement molding process [4], and "concrete printing" technology [5]. At the same time, some large-scale construction projects have begun to adopt this technology, such as building houses, bridges, and even building structures.

With the increasing concern about sustainable construction and environmental impact, people have begun to explore the use of 3D printed concrete technology to reduce carbon emissions and resource consumption in the construction process, including the use of materials such as recycled coarse aggregate[6] and waste glass [7] to reduce the environmental pollution caused by industrial waste materials. This has prompted more research and innovation to improve the sustainability and environmental friendliness of the technology.

2 FABRICATION AND PERFORMANCE OF 3D PRINTED CONCRETE

2.1 Concrete Production Method

2.1.1 Traditional Concrete Production Methods.

Traditional concrete is usually made by mixing water, cement, and aggregates, and in order to enhance the performance of the concrete, some admixtures are usually added to ensure sufficient performance [8], and it is cast in a mold, which requires time to wait for the concrete to harden and solidify.

2.1.2 3D Printing Concrete Production Method

The implementation process of 3D printing technology mainly includes three aspects: 3D printing design, imaging graphics slice processing and post-printing. Firstly, computer modeling software is used for three-dimensional modeling, so that the graphics are imaged as a whole, and then slicing processing is carried out. After manufacturing design and image slicing processing, printing materials can be filled for printing according to actual needs. The printing process is shown in Figure 1[9].

At present, the main body of the device used in 3D printing technology can be summarized into three components: mixing unit, transmission unit and extrusion unit. It is found that the performance evaluation of three-dimensional printing concrete mainly focuses on five core indicators, including material flow characteristics, extrusion performance, construction feasibility, setting time and material mechanical characteristics.

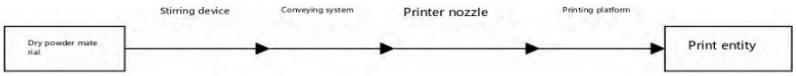


Fig. 1. Schematic diagram of 3D printing process [9]

2.2 specific Benefits:

2.2.1 Material Properties.

Affected by factors such as material ratio, pouring process, and curing time, while traditional concrete can achieve a certain strength and durability, there may be inconsistent quality problems in specific situations. 3D printed concrete uses specific printing equipment to build a structure by stacking concrete materials layer by layer. This method allows for precise control of the geometry and internal structure of the structure.

Because 3D printed concrete is built layer by layer, complex geometries and structural designs can be realized inside the structure, increasing design flexibility and performance customization. By optimizing print paths and material formulations, higher strength, durability, and other performance characteristics can be achieved. In addition, high-performance materials such as fiber-reinforced materials can be used to further enhance their performance.

2.2.2 Construction Efficiency

Traditional concrete construction usually requires the use of molds or carpentry frames to support the formation of concrete, which requires additional human resources and a certain amount of time to solidify and strengthen, thus extending the entire construction period. Construction can be affected by weather conditions and other environmental factors, such as temperature, humidity, etc., which can lead to construction delays or quality issues.

However, 3D printed concrete can complete the construction of a structure in a shorter time because it does not require traditional molds or support structures. This can significantly shorten the construction period, thus saving time and costs. In addition, 3D printed concrete is done through an automated printing process, so higher construction accuracy and consistency can be achieved, reducing the possibility of human error. It can also be applied without being subject to weather conditions, as it does not need to be affected by curing time and environmental influences like traditional concrete.

2.3 Performance Introduction

2.3.1 Liquidity

The actual printing effect of 3D printing concrete is determined by different parameters, among which the fluidity is one of the main factors. By adjusting the ratio of cement to water and mixing polymer powder to enhance its fluidity, Perrot's team produced concrete suitable for 3D printing technology and achieved a higher construction speed[9]. In the process of transporting the pipeline, if the concrete slurry is sticky,

sticky, caking and other agglomeration phenomena, there will be signs of blocking the pipeline, which can not meet the construction requirements. If the ratio is too small[10], the mixture will become dry and hard, and cannot be conveyed smoothly through the conveying pipeline; if the ratio is too large, the later strength will be affected[9]. Reasonable use of water reducing agent can save cement and other raw materials and properly enhance the strength of concrete products. The results of ZHANG Y and his team [11] showed that when the ratio of sand to cement was greater than 1.5, the fluidity would be significantly reduced, resulting in the inability to be extruded, while the ratio of sand to cement would be less than 0.8, resulting in easy deformation of the finished product. Wu tao [12] found that the fluidity of the material decreases with the increase of fiber content after adding fiber, and the effect of basalt fiber on fluidity is smaller than that of PVA fiber, and the effect of 3mm fiber on fluidity is smaller than that of 6mm. Longer fibers and large incorporation amounts tend to form intersecting nets in 3D printed concrete, creating a "sticky effect" that can significantly increase the consistency of the concrete.

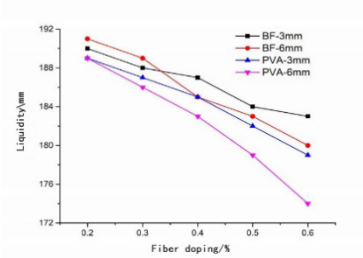
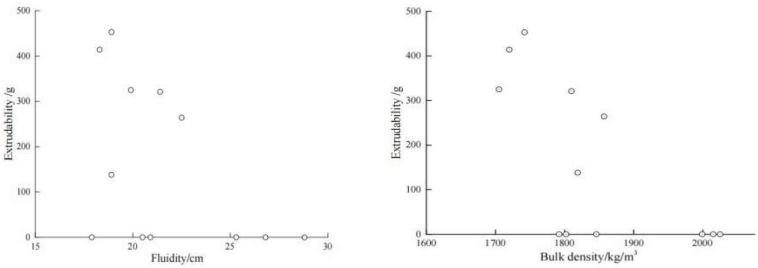


Fig. 2. Effect of different types and lengths of fibers on the properties of 3D printed concrete[12]

2.3.2 Extrudability.

Concrete materials used for 3D printing need to have good extrudability, that is, the ability to print materials smoothly from the storage bin continuously through the conveying pipeline and to accumulate concrete. In addition, the ratio of the diameter of the extrusion nozzle to the particle size of the aggregate is also one of the key factors to determine its performance. According to the research results of Zeina's team, if the maximum particle size of aggregate does not exceed one tenth of the diameter of the nozzle, the adhesive will be smoothly extruded through the nozzle[9]. However, Malaeb's research points out that reducing the amount of sand and increasing the proportion of cement will improve the extrusion of concrete[13]. Liu Qiaoling et al. studied the relationship between mortar extrudability and fluidity (a) and bulk density (B), and the experimental data are shown in Figure 2[12]. The study found that if there is no polymer addition in the mortar formula, its performance is difficult to meet the standard of printing mortar, resulting in the mortar can not be successfully extruded in Figure 3[14].

All structures were printed at a fixed print speed of 450 cm/min, and the time interval between adjacent layers was controlled at 30 seconds. At a rest time of 10 minutes, various mixtures containing different tailings content were squeezed layer by layer at a vertical speed of 1.3 cm/min until 20 layers of filament were printed, with good extrusion and good build ability in Figure 4[15].



(a)Extrudability–fluidity (b)Extrudability –bulk density

Fig. 3. Extrusion characteristics of 3D printing construction mortar and correlation analysis between its rheological property (a) and mass per unit volume (B)[14]

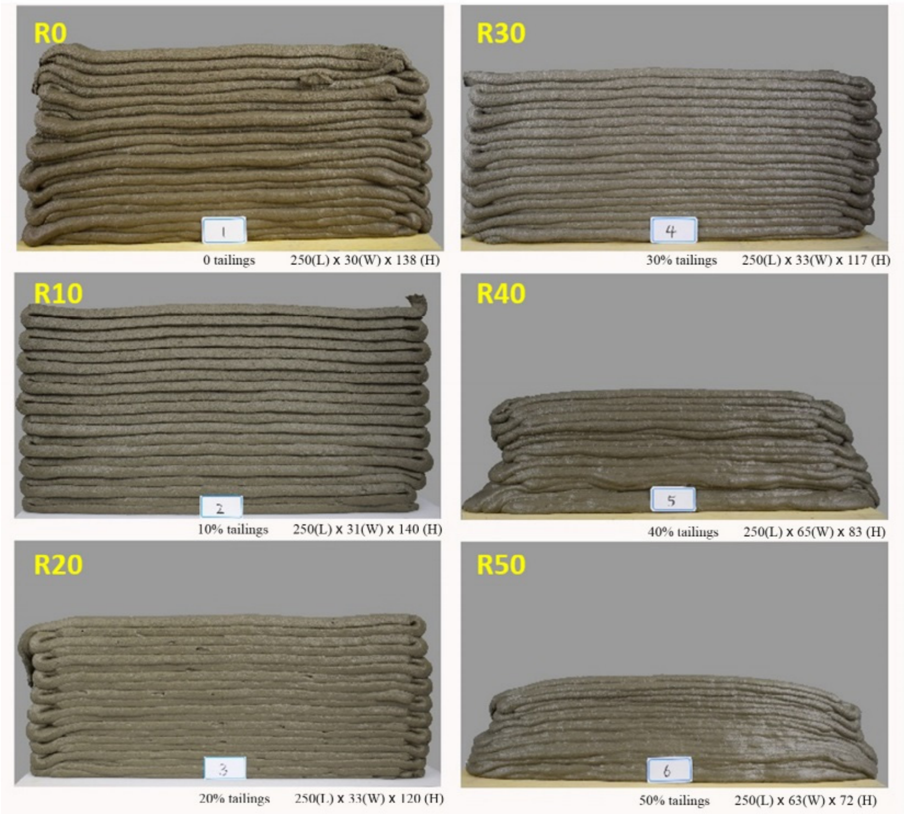


Fig. 4. Schematic diagram of experiments to explore the extrusibility effect of 3D printing[15]

2.3.3 Setting Time

Setting time will directly affect many characteristics of 3D concrete, too long time will affect the setting strength and printing effect, too short time will affect the fluidity and extrusion effect, so reasonable control of setting time is conducive to improving the quality of printing concrete, adding admixtures is still the main method to adjust the setting time of the mixture. At present, the common retarders used in ordinary concrete are mainly divided into organic retarders such as sucrose, tartaric acid, citric acid, etc., as well as inorganic retarders such as gypsum and borax. The results of chen et al. Showed that a certain amount of tartaric acid could extend the initial setting time of the concrete system to 20-30 min, and the final setting time to 92-123 min, improve its rheology, and control the deformation rate of the final system to less than 10%[16].Sun Jinqiao, Huo Liang and others found that the setting speed of 3D printing concrete materials is usually faster than that of ordinary concrete, but if the setting speed of materials is too fast, premature hardening may occur, affecting normal extrusion[17]. The relationship curve between strength and time of relevant concrete 3D printing materials is shown in Figure 5[6].

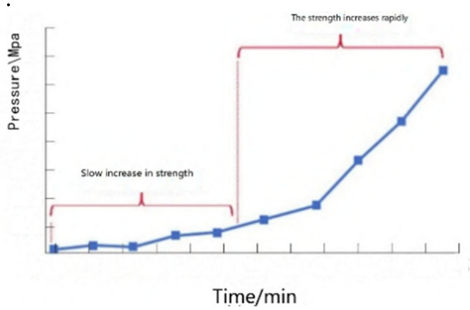


Fig. 5. Curve of material strength changing with time[6]

2.3.4 Constructability.

Constructability is one of the key parameters to determine the 3D printing ability of concrete materials, which involves the stability of the material after extrusion under the dual influence of its own gravity and upper load, as well as its resistance to deformation caused by external loading. The latest research shows that while increasing the proportion of sand used, the incorporation of mineral batch materials and additives also has positive benefits for the construction process. Using CFD numerical simulation method, Zhou Jiangang found that the printing speed and the diameter of the printing nozzle are the main factors to change the contour state of the printing body[18]. Academics such as T. T. Le of Loughborough University pointed out that the ease of extrusion and construction of freshly mixed 3D printed building materials is essentially the most critical attribute, and there is a close link between the workability of printed materials and the effective time of their operation[19].

2.3.5 Mechanical Properties

Due to the weight of the upper strip and the deformation of the printing layer caused by the extrusion force during the extrusion process, when the load exceeds the material yield stress, the base layer will flow and deform, thus affecting the stability of the printing structure[20]. Combined with the experiment of Zhang Tao et al., the equivalent compression curve of reinforced 3D printing concrete was obtained through the compression test of prism specimens (the experimental device is shown in Fig. 6)[21]. Figure 7 shows the average compressive strength of the printed concrete at different delay times and test directions. Anisotropy in the compressive strength of the printed concrete can be observed, depending on the orientation of the loading direction with respect to the layer[22].

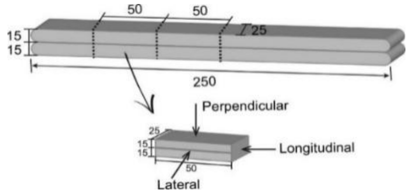


Fig. 6. (Left) Experimental cutting diagram [21]

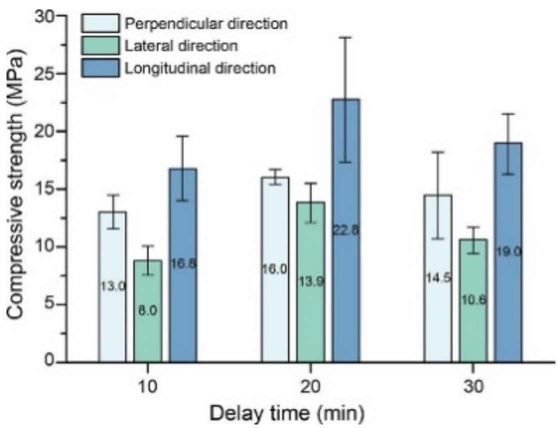


Fig. 7. (Right)compressive strength of 3D printed concrete[21]

In the study of 3D printing concrete flexural experiment, Liu Hua-wei found that most of the strip interfaces in the printing body are parallel to the direction of stress, and the strength is high; some of the strip interfaces in the printing body are parallel or approximately parallel to the splitting tensile plane, and the strength is low; The interface of the printing body strip is perpendicular to the splitting tensile plane, and the strength is high[22]. Wu Lei's team used the three-point bending method to apply pressure to the upper and lower surfaces of the 3D component during the printing process, as shown in Figure 8. Studies have shown that in 3D printed concrete materials, interfacial activators have very limited effect on improving the bending resistance of materials[23].

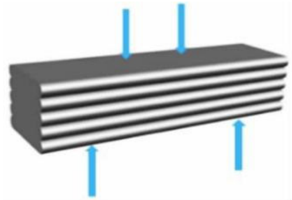


Fig. 8. Loading Direction of Bending Test[23]

Wu Tao [12] found in the bending and compressive test that the failure form of the test block was quite different with or without the addition of fibers. When the fiber content is low or zero, the test block tends to be brittle fracture, the cracks are many and wide, and when the fiber amount reaches a certain value, the failure cracks are narrow, and the failure load decreases slowly. It is reflected that the addition of fibers can effectively enhance the ductility of concrete and reduce the brittleness of concrete, which is beneficial to the practical application of 3D printed concrete in Figure 9[12].

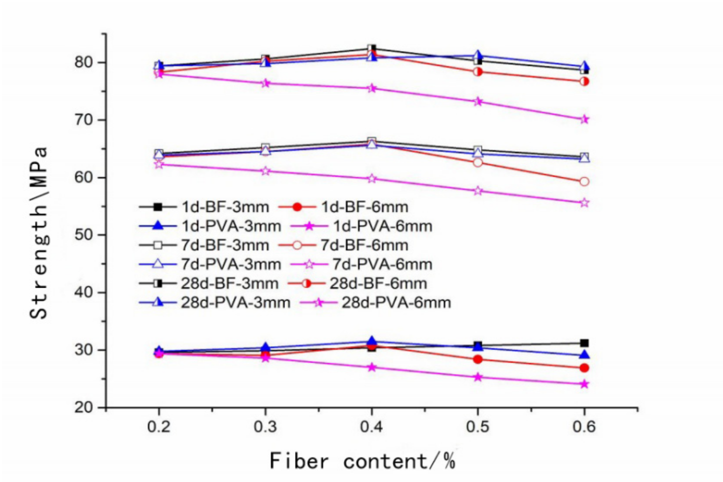
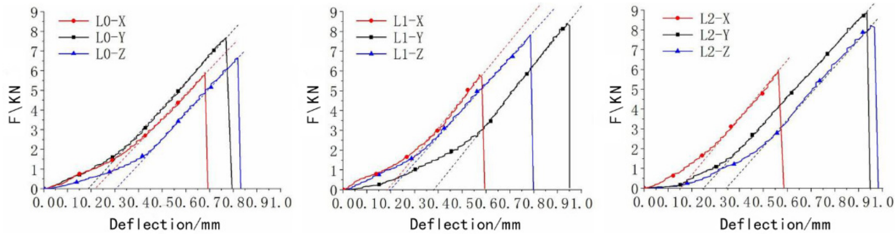


Fig. 9. Effect of fiber type and length on compressive strength[12]

The experimental research of Wei Wei and Yang Tao shows that the bending strength of 3D printing fiber concrete increases with the increase of fiber content, and the anisotropy of the material increases with the increase of fiber content, as shown in the force-deflection curve of three groups of concrete materials in Figure 10[24].



(a)W0 (b)W1 (c)W2

Fig. 10. Force-Deflection curve of W0, W1 and W2 in three loading directions[24]

3 ADVANTAGES AND CHALLENGES OF 3D PRINTING CONCRETE TECHNOLOGY

3.1 Advantages of 3D Printing Concrete Technology

3D printing concrete technology replaces the traditional template construction method, significantly improves the construction speed, reduces the construction cost, meets the requirements of green environmental protection, is suitable for the construction of personalized structures, breaks the restrictions of traditional concrete structure design, and gives architects more design freedom. In addition, it can also realize the cross-application of mechanics, acoustics, optics, thermal insulation and other aspects in the construction process[25].

3.2 Problems and Challenges of 3D Printing Concrete Technology

At present, three-dimensional concrete printing is not perfect enough in terms of manufacturing process, mechanical properties of equipment, allocation of raw materials and precise formation of solid structure. Therefore, it is urgent to formulate relevant technical specifications and implement engineering practices to guide technology development, aiming at promoting its wide application in the industrial field[25].

Unlike ordinary concrete structures, 3D printed concrete structures require specific design and construction standards and national specifications, and there is still a lack of relevant standards and acceptance specifications[26]. At the same time, it is still difficult for most 3D printing equipment to print directly on the construction site[18]. In order to meet the higher strength requirements, we must also deal with the bonding problem between the printing material and the steel bar or special fiber[27]. In-depth exploration of the material composition, printing process and technical barriers related to the use of equipment for 3D printed concrete can further develop 3D printed concrete.

3.2.1 Material Composition:

Existing concrete materials may not be suitable for direct use in 3D printing, and the material composition needs to be optimized and customized to improve its adaptability and printing performance. Researchers can explore combinations of different types of cement, aggregates, and additives to improve properties such as flow, hardening time, and strength of printing materials. At the same time, the sustainability and environmental friendliness of the material need to be considered to ensure its viability in practical applications.

3.2.2 Printing Process:
The printing process of 3D printed concrete requires meticulous parameter control and optimization, including printing speed, layer thickness, printing path, etc. Different printing process technologies, such as jet printing, extrusion printing, etc., need to be studied to determine the most suitable printing method for different scenarios. At the same time, it is also necessary to solve the problems that may arise during the printing process, such as clogging, uneven material flow, etc., to ensure print quality and stability.

3.2.3 Equipment Used:
The printing equipment used in 3D printing concrete needs to have a certain degree of accuracy and stability to ensure that complex structures can be accurately printed. More advanced printing equipment needs to be developed to improve printing speed, accuracy, and reliability, while reducing equipment and maintenance costs. For large-scale construction projects, the mobility and adaptability of printing equipment also need to be considered to meet the construction needs of different sites and environmental conditions.

4 DEVELOPMENT TREND AND PROSPECT OF 3D PRINTING CONCRETE TECHNOLOGY

4.1 Development Trend of 3D Printing Concrete Technology

In order to improve the printing efficiency and reduce the cost of building materials, it is urgent to design a printing equipment for coarse aggregate concrete. In addition, the shaping and flow properties of the coarse aggregate concrete need to be regulated in order to deliver the concrete smoothly to the printer head. It also shows better plasticity and constructability in the construction process[25].

In order to overcome these limitations and match different building requirements, further improvements and upgrades need to be made to large 3D printers and supporting transportation systems. The use of building information modeling (BIM) technology to integrate various reinforcement layout methods can effectively improve the efficiency of 3D printing concrete building structure construction[27].

4.2 Application Prospect of 3D Printing Concrete

In order to make full use of the benefits brought by 3D printing concrete technology, universities and research institutions should deepen cooperation, concentrate scientific research resources and share their achievements, so as to promote the further large-scale development of engineering practicability of 3D printing concrete technology.

Professor Wang Hong Kong of Southeast University led his research team [28] .Successfully used 3D printing concrete technology to quickly build a detection shelter for epidemic prevention and control in Nanjing, Xiongan and Puzhou. In the UK, Arup is promoting 3D printing technology to construct steel structures, an innovative approach that can reduce carbon dioxide emissions by 75% and material consumption by 40% during construction[26].

5 CONCLUSION

1) Concrete is one of the most commonly used materials in the construction industry. 3D printing concrete technology has great potential and incomparable advantages over traditional buildings, which are mainly reflected in the following aspects: 3D printing technology can build the entire building structure in a short time, greatly accelerate the construction speed, reduce labor costs, and greatly improve construction efficiency; 3D printing technology can achieve highly accurate construction and more innovative and personalized architectural design.

2) 3D printing concrete technology is regarded as a key technology for the transformation of the construction industry, which has a vital impact on the future development of the construction industry. However, the potential of this technology is huge, and it is urgent to develop it by clarifying development ideas, solving related problems and formulating development strategies.

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