

The Application of 3D Printed Concrete in the Construction Field

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Abstract. Concrete is a core material and construction method in the construction industry. 3D printed concrete can simplify the construction of complex concrete structures, shorten the construction period, and facilitate the construction process, with broad application prospects. Relevant practitioners need to master its principles and characteristics to promote the implementation of the technology. This article will conduct a comprehensive outlook on the application of this technology in the construction industry from the dimensions of material selection and mix proportion research, where six different mix proportions of concrete materials were studied and the differences in the states presented by concrete with different mix proportions were discovered; structural optimization design research, where the different mechanical properties presented by concrete after the addition of different amounts of basalt fiber were studied and the concrete suitable for 3D printing and research directions were found; and future prospects.

Keywords: 3D printed concrete, concrete materials, 3D printed concrete construction technology

1 Introduction

The selection of materials for traditional concrete and 3D printed concrete is roughly the same, including cement, coarse aggregate, fine aggregate and water. However, while traditional concrete can be combined with steel bars to form reinforced concrete to enhance its tensile strength, 3D printing relies on mechanical equipment and mathematical models to improve the tensile strength of components. The tensile strength of 3D printed concrete is difficult to enhance merely by using the five types of cementation materials: ordinary Portland cement, fast-hardening and early-strength special cement, composite ordinary cement, alkali-activated cementation materials, and gypsum-based cementation materials, which have been applied to some extent in 3D printing[1]. Nevertheless, there are still many problems. Currently, in China's 3D printing technology, there are still many issues with the application of 3D printing.

3D printed concrete has been applied to a certain extent in the field of architectural decoration, similar to setting up concrete frames or directly constructing or assembling concrete through 3D printing equipment for use in buildings or decoration. For instance, in 2014, an integrated 3D

printed project department building for both interior and exterior installation was carried out in Qingpu Garden, Shanghai, China. Also, the designer Aduatz from Vienna created a series of decorations using 3D printed concrete.

This article looks forward to the application of 3D printed concrete in the construction industry through material selection and mix proportion, structural optimization design, carbon emission comparison with traditional construction, and future prospects.

2 Material Selection and Mix Ratio

2.1 3D-printed Concrete under Different Aggregates

To enhance the strength of 3D-printed concrete, efforts should be made in the proportioning of the aggregates. According to the research by Zhang Yunsheng et al. [2], based on the current studies, fine aggregates use natural river sand with a fineness modulus of 2.19, and coarse aggregates use basalt stones with a particle size range of 4.75 - 20.00 mm. The admixtures include a polycarboxylic high-performance water reducer (PCE) with a water reduction rate of 34% and a solid content of 30%, as well as 200,000 units of viscosity of hydroxypropyl methyl cellulose ether (HPMC). Among them, there are 3 types of paste-aggregate ratios (0.9, 0.75, 0.5), 4 types of coarse aggregate gradations, and the water-cement mass ratio (W/C) of all groups is 0.3.

According to the four basic types of construable failure forms summarized by Zhang Yunsheng et al. [2], the first type is the overall instability and collapse form as shown in Figures 1(a) and 1(b). Both of these forms adopt a continuous gradation and a high content of aggregates. During the gradual stacking process, due to the excessive number of layers, local deformation is not easily occurred, and eventually instability occurs. Although the two forms have similar shapes, in (b), the content of coarse aggregates increases, and the thickness of the mortar layer wrapped around the coarse aggregates decreases relatively. Therefore, there are more cavities and defects on the surface of (c) than in (a), and it is more prone to fracture when extruded because the content of coarse aggregates increases. The second type is the failure form caused by local deformation as shown in Figure 1(c). (c) group uses 9.5 - 16mm aggregates. Due to the distribution state of coarse aggregates being insufficient to form a complete and tight spatial framework within the concrete, without lateral support, a sudden local deformation occurs eventually, leading to overall failure and also causing the deformation and flow of the lower layer mortar to be unable to be effectively restrained. The third type is the form of material extrusion interruption as shown in Figure 1(d). Most of the coarse aggregates used are large stones. Since most of the coarse aggregates are large stones, the 3D printer needs to constantly overcome large frictional forces to extrude the material during the printing process. This causes heat accumulation near the nozzle, resulting in the phenomenon of slurry dehydration. In the later printing process, the mortar and some of the coarse aggregates can only be extruded, while almost all other coarse aggregates near the nozzle are locked, ultimately causing the interruption of the printing process. The fourth type is the excessive expansion failure form as shown in Figure 1(e). The coarse aggregates are all small stones. Its form is exactly the opposite of the third group, which causes a layer structure failure with excessive lateral collapse.

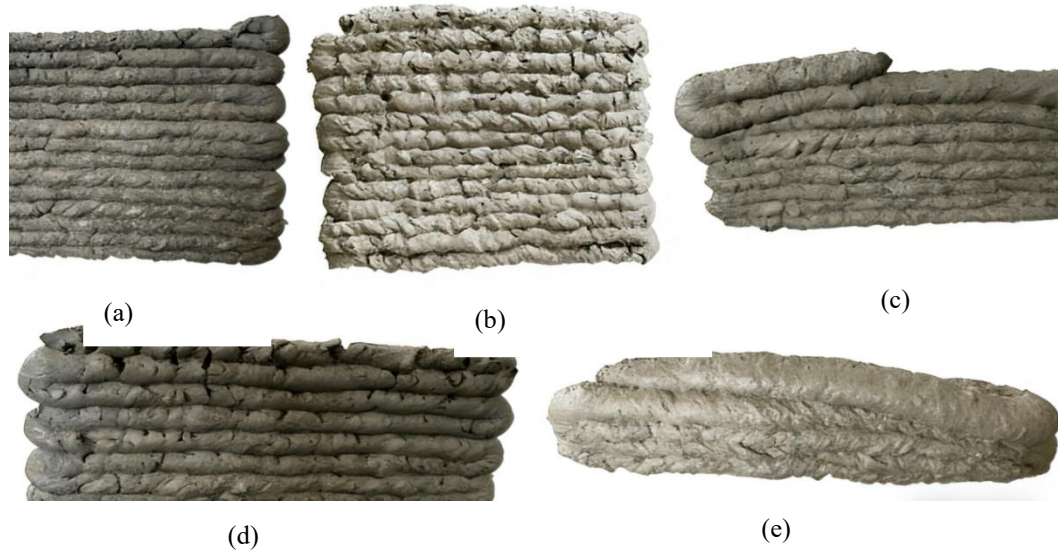


Fig.1. Forms of Constructive Failure[2]

2.2 Optimization Design

The research results of Zhang Yunsheng and others [2] indicate that groups (a) and (b) are the most suitable aggregate ratios. However, when choosing the appropriate aggregate ratio, one also needs to consider its mechanical properties and drying shrinkage conditions. Based on the above experimental results, in terms of mechanical properties, due to the lower P/A value, the absolute proportion of coarse aggregate components with higher elastic modulus and strength in the concrete will increase in both compressive strength and flexural strength. Further enhancing the overall strength of the concrete, and this strength improvement will not be affected by changes in the loading direction. Therefore, when designing 3D concrete containing coarse aggregates, one should, under the premise of ensuring print ability, try to increase the absolute proportion of the aggregates as much as possible.

3 Structural Optimization Design

3.1 Research on the Mechanical Properties of 3D Printed Concrete

3D printed concrete differs from traditional methods of pouring and vibrating concrete. During the process of 3D printing where the printing nozzle continuously extrudes freshly mixed cement composite materials and builds up the structure, gaps are inevitable between layers, and it also causes weak bonding interfaces between printing layers. [3] The microscopic heterogeneity directly affects the macroscopic mechanical properties of engineering materials. Therefore, 3D printing will study the influence of the extrusion and stacking process of freshly mixed cement composite materials on the mechanical properties of the material. However, there are few research reports on the various isotropic of fiber-reinforced 3D printed concrete materials' mechanical properties.

3.2 Structural Optimization Experiment

Based on the research by Wang Li ET al. on the mechanical properties of 3D-printed concrete [3], five different amounts of basalt fiber concrete materials were prepared. The printing effect was verified using an extrusion-type 3D printer. Finally, the appropriate mix ratio was selected, and test specimens were prepared for uni-axial compressive and flexural tests. The tests were conducted in three orthogonal directions and the mechanical anisotropy was evaluated [3]. After the raw material ratio was tested, according to the research by Wang Li et al. on the mechanical properties of 3D-printed concrete [3], the extrusion speed of the nozzle concrete material was set at 8.4 L/min, the horizontal printing speed was 12 m/min, and the height of each layer was set at 10 mm. A rectangular model with dimensions of 480mm * 360mm * 170mm was printed. After curing, it was cut into 100mm * 100mm * 400mm prisms for flexural performance tests and 100mm * 100mm * 100mm cubes for compressive performance tests.

Based on the results of the above experiments, it can be concluded that the working performance of concrete is significantly affected when the amount of fibers is relatively large. On one hand, the working performance of concrete deteriorates as the amount of fibers increases, resulting in a less smooth concrete extrusion process without any interruptions. The more fibers are used, the lower the flow-ability of the cement composite material becomes, and the less likely it is to cause blockage. On the other hand, when excess fibers are mixed together, it will destroy the best internal structure of the already formed concrete. The fibers cannot be fully encapsulated by the cementitious materials, causing the gaps to become larger.

Based on the above mechanical test results of the compressive and flexural properties, 3D printed concrete, under the condition of a fixed mix ratio, exhibits significantly different mechanical characteristics depending on the direction of force application. This is due to the anisotropy in mechanics. The anisotropic property is greatly influenced by various factors such as printing material parameters and printing process parameters. However, in the mortar specimens formed by template pouring, it can be regarded as an isotropic material. For specimens of the same size, if the number of printing layers is small and closer to the pouring sample, the mechanical difference will be smaller; conversely, the anisotropy will be more obvious.

4 Concrete 3D Printing Equipment and Construction Techniques

4.1 Printing Equipment

With the continuous advancement of intelligent construction technology in the construction field, currently, 3D printing construction equipment for buildings can be mainly classified into three types: gantry type, robotic arm type, and mobile robot type [4]

The gantry-type printing system positions the printing nozzle within the XYZ Cartesian coordinate system. It achieves printing by moving back and forth between corresponding coordinate points in the building. It has 3 or 4 degrees of freedom and the printing size is restricted by the gantry-type framework structure.

The robotic arm-based printing system, like the concrete printing system relying on robotic arms, is also limited by the range of the robotic arm's length. However, the robotic arm printing

system can maintain a continuous curvature change rate during the printing process, and can achieve a smoother transition between printing layers, resulting in a more aesthetically pleasing appearance.

The mobile robot system can be divided into independent robots and multi-position combined robot systems. After reasonably planning the robot's walking path and printing path, more flexible and efficient printing can be achieved. This system also has 6 complete degrees of freedom.

4.2 Construction Process

With the gradual development of intelligent construction technology in the field of architecture, currently, the 3D printing construction method in building construction mainly includes two types: on-site printing and prefabricated printing [4].

On-site Printing. The building structure is directly printed on the foundation in a continuous printing and layer-by-layer stacking manner. Predetermined positions for equipment holes and structural columns need to be reserved. Subsequently, node connections and secondary concrete pouring are carried out to form an integrated structural form. The surface of the 3D-printed building walls without decoration will present horizontal or vertical patterns along the printing path. The configuration of reinforcing bars for on-site printing can be selected according to different printing requirements. The 3D printing concrete technology can print building components in the form of squares, circles, and various irregular shapes, even entire houses, based on the building information model on-site. Compared with traditional construction methods, the more complex the architectural geometric structure is, the more obvious the advantages of 3D printing technology will be. However, the on-site printing process has some disadvantages: The printing equipment used is usually large in size, for example, the printer used in the Qingpu building complex has a size of 32m×10m×6.6m [4]. On-site installation and debugging will consume a lot of time; at the same time, the size of the equipment support frame increases, which not only raises the construction cost of the building but also makes it difficult to control the construction accuracy, thereby affecting the construction quality of the building.

Prefabricated. Similar to the concept of traditional prefabricated buildings, 3D-printed prefabricated buildings also print out components and accessories such as floor slabs, wall panels, stairs, balconies, etc. in the factory, and then transport them to the construction site. The assembly and installation are completed through binding, welding, etc. on-site. Before printing, the positions and sizes of open spaces such as pipes and windows need to be determined in the computer information model, and the positions of tie bars and embedded parts should also be reserved. After the components are transported to the site, secondary concrete pouring is required to achieve the connection of the walls. To improve the strength and tensile performance of the printed components, steel bars are usually added inside the components, forming a steel-concrete system; the node connections of walls, columns, and beam-columns can be achieved by using common prefabricated grouting sleeves or bolt connections, and the steel bars arranged in the prefabricated components are connected to the top and bottom steel bars through welding, and the straight steel bars between regions can be connected using steel connectors, and the bent steel bars between regions can be connected by means of lapping. In addition, the internal structure of 3D-printed prefabricated walls can be optimized according to environmental requirements, based on principles such as acoustics and mechanics. For

example, 3D-printed walls can be customized into free-form cavity structures, which not only can reduce the weight of the wall itself, but also can fill with different functional materials such as insulation and soundproofing materials [4].

5 The Current Situation of Application in the Field of Architecture

5.1 Residential Buildings

3D printed concrete has great potential in the construction industry, significantly reducing labor costs and time consumption. In 2014, 10 project departments' office buildings in Qingpu Park, Shanghai, China, underwent integrated interior and exterior installation using 3D printing technology. This 3D-printed building complex adopted on-site printing construction methods, and its various mechanical properties were comparable to those of traditional concrete. By using 3D printed concrete technology, this project saved a considerable amount of time and approximately 50% of the construction cost compared to traditional construction methods.

In the same year in Suzhou, a 1,100-square-meter two-story building was constructed using a production line construction method. The construction process was simple, and the building walls maintained the original texture of 3D printing while ensuring a beautiful shape. No unnecessary decorations or treatments were applied, saving construction costs. However, the drawbacks were also quite obvious. The on-site assembly work consumed a lot of manpower and time. If significant breakthroughs were made in this aspect, it would become the mainstream in the future.

5.2 Industrial Buildings

A $12.1\text{m} \times 4.6\text{m} \times 4.6\text{m}$ distribution substation was constructed on-site using the gantry type 3D printing concrete technology. The particle size of the concrete aggregate was $\leq 15\text{mm}$, and the slump was approximately 110mm. The initial setting time was controlled by an early setting agent to be within 5-10 minutes, and a layer-by-layer steel mesh was set up vertically. At a 28-day age, under the design strengths of 20MPa and 25MPa, the strength of the printed specimens was 19.7% and 16.3% lower than that of the poured specimens, and the strength performance was significantly inferior to that of the poured concrete[5].

5.3 Decoration

Although 3D-printed concrete is generally used in various fields of house construction, it has the potential to be a solution to the global housing crisis. However, in the design field, few people use the concrete 3D printing technology to manufacture furniture or sculptures.

The designer Aduatz [6] based in Vienna has created a series of decorations using 3D-printed concrete, such as lounge chairs and vases. They have developed limited-edition functional objects with a high degree of sculptural nature, and have also utilized 3D printing technology to innovate materials and manufacturing techniques. Incremental3d was the first to develop a unique concrete 3D printing method, whose working principle is similar to FFF 3D printing. This technology enables very fine free shapes to be printed quickly without any support structures. In the decorative field, complex artistic forms can be directly formed without additional molds, achieving personalized decorative textures; it can complete both the structure

and the finish in one step, eliminating the need for subsequent decoration processes, significantly shortening the decoration construction period[6].

5.4 Bridge

The entire Zhaozhou Bridge, with a total length of 28.1 meters, a single arch span of 18.04 meters, and a bridge width of 4.20 meters, is a prefabricated concrete 3D-printed Zhaozhou Bridge [7]. It was printed at a scale of 1:2 based on the original prototype and then assembled on-site. It is currently the largest concrete 3D-printed pedestrian bridge in the world and has become the largest concrete 3D-printed walking bridge in the world. The printing material selected is a special cement-based composite material with rapid setting and hardening, low heat of hydration, high early strength, and no use of form-work and reinforcing bars in the main body printing construction, which greatly saves the project cost. It has long-term working performance such as low shrinkage, micro-expansion, high crack resistance, and self-repair [8-10].

6 Conclusion

How to address the compatibility of concrete materials and the mechanical properties obtained through 3D printing, as well as the research and development of 3D-printed high-performance materials, remains a relatively important research topic for promoting its application in construction. This is the most significant and direct issue regarding 3D-printed concrete. To meet the requirements of 3D printing, concrete must have better rheological properties and be able to solidify quickly in the environment. To ensure that all materials can effectively bond together, the maximum particle size requirements of different aggregates also need to be considered. Therefore, different chemical additives are required.

One aspect is about the research and development of printing equipment and their standardization. As mentioned in the text, the mainstream 3D printing concrete equipment includes gantry type and single mechanical arm type. Free-moving robots have not been widely adopted yet. These types of equipment each have their own advantages and disadvantages. How to balance the relationships among them to make 3D printed concrete more efficient and convenient, so that 3D printed concrete can be widely used in the construction industry, is the key issue.

In the field of architecture, the development of 3D printing concrete technology in China is still in its infancy. Some high-tech enterprises have ranked at the forefront of the industry in terms of engineering applications. Enterprises, universities, and research institutions need to strengthen industry cooperation, based on research results, to jointly promote the large-scale application of 3D printing in engineering. Oriented towards engineering applications, they should guide the research and development of 3D printing concrete to further leverage the advantages of 3D printing concrete technology, improve application levels, and achieve efficient, green, and industrialized development in the construction industry.

References

- [1] Dong, L.: Application of 3D Printing Technology in the Construction Field. *Inf. Rec. Mater.* 22(5), pp. 111–113 (2021)
- [2] Zhang, Y., Chen, Y., Liu, C.: Analysis of Printability, Mechanical Properties, Shrinkage Performance and Carbon Emissions of 3D Printed Concrete Containing Coarse Aggregate. *J. Silicate.* 51(9), p. 2153 (2023)
- [3] Wang, L., Wang, B., Bai, G., Ma, G.: Research on the An isotropic Mechanical Properties of 3D Printed Concrete. *Exp. Mech.* 35(2), pp. 243–250 (2020)
- [4] Xiao, J., Bai, M., Tang, Y., Ma, Y., Chen, H., Liu, H.: The Development History and Trends of 3D Printing Concrete Technology. *J. Archit. Eng. Sci.* 38(5), pp. 1–14 (2021)
- [5] Zhang, D., Wang, D.: Advances in 3D Printed Concrete Materials and Concrete Construction Technology. *Cem. Concr. Res. Appl.* 34(6), pp. 1583–1588 (2015)
- [6] Anonymous: Concrete and cement product mesh 3D printing concrete technology can be used to manufacture furniture or sculptures. [Online]. (2018) https://www.sohu.com/a/227823293_199344 2018-04-10
- [7] Sheng, L., Wu, L.: Review of 3D Printing Concrete Technology. *Cem. Concr. Prod.* (010), pp. 7–11 (2021)
- [8] Wen, J., Jiang, Y., Hu, J., et al.: Research on 3D Printing Construction Materials, Typical Applications and Future Prospects. *Cem. Concr. Prod.* (6), pp. 26–29 (2020)
- [9] Ma, W., Jiang, Z., Su, Y.: The Development and Prospects of 3D Printing Concrete Technology. *Concr. World.* (7), pp. 41–46 (2014)
- [10] Li, F., Deng, C., Wan, J.: 3D Printing Construction Technology and the Future of the Commercial Concrete Industry. *Concr. World.* (3), pp. 28–29 (2013)