

## A brief review of 3D printed concrete

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**Abstract.** From the outline molding process invented by Professor Khosnevis of the University of Southern California in 2004, which is recognized as the earliest architectural 3D printing technology in the industry, to the concrete printer of COBOD, a 3D printing and construction company in Denmark, which adopts the one-time printing technology, the whole structure is not assembled or printed in pieces. It took three weeks to print the wind turbine, which has a base height of 10 meters and a support height of 200 meters, all at once. Many countries, construction companies and research institutions around the world are committed to the development and promotion of 3D printing construction technology. 3D printing is the most important reason of concrete construction technology with quick construction speed, low labor costs, no template construction, resource waste and design degrees of freedom less advanced advantage, through increased significantly at the same time the construction process of mechanization, better able to introduce intelligent design and control, to improve and optimize the construction process provides a great opportunity, Provide technical innovation and institutional reform for the construction industry. With the rapid development of urbanization and industrialization, modern difficulties such as talent shortage, resource exhaustion and security problems have seriously restricted the development of the construction industry. 3D printing these advantages can relieve some of the problems in the traditional buildings, such as the lack of industrialization, serious environmental pollution, labor shortages, and raw resources waste, etc. This paper takes the development of 3D printing concrete progress as a starting point, introduced the concrete of the 3D printing, general 3D printing concrete, high strength concrete, the 3D printing and on the basis of them, further conclusions are drawn.

**Keywords:** 3D printed concrete; review; compressive property; mix ratio; 3D printed high strength concrete.

### 1. Introduction

Concrete refers to a mixture of cemented materials, coarse aggregates, water and chemical additives, and mineral admixtures added when necessary. It is a composite material with a stacked structure with plasticity and a certain strength after hardening, also known as artificial stone. Although concrete has defects such as low tensile strength, easy cracking, it has incomparable advantages of other building materials: it can be combined with various properties of concrete; it can be poured into concrete buildings of various shapes and sizes; it has good bonding force with steel bars; high compressive strength, water resistance, and fire resistance. And good durability; the composition materials come from a wide range of sources and low prices, and can be taken from the

spot. Because concrete has the above advantages, it is the most widely used building material in civil engineering today.

At the same time, it has made incalculable contributions to the development and construction of human society. With the development of social science and technology, the high energy consumption and high pollution of concrete in the process of production and application have gradually become prominent, which has become a significant resistance to the development of concrete materials. 3D printing technology, as the iconic technology of the Third Industrial Revolution, leads the trend of the times, and its emergence also provides a new direction for the sustainable development of concrete.

3D printing concrete technology is a new technology developed based on 3D printing concrete technology for concrete construction. Its main working principle is to use the configured concrete for concrete pulp through an extrusion device. Under the control of three-dimensional software, according to the preset printing procedure, the nozzle is squeezed out for printing and finally obtain to the design of concrete components. 3D printing concrete construction technology has the advantages of fast construction speed, low labor cost, less waste of resources, and high design freedom. At the same time, by greatly improving the mechanization of the construction process, intelligent design and control can be better introduced, which provides a huge opportunity to improve and optimize the construction process, and provides technological innovation and institutional reform for the construction industry. To meet people's growing needs, the strength and performance of concrete have developed greatly. So far, concrete can be divided into three types: ordinary concrete, high-strength concrete, and high-performance concrete. Ordinary concrete and high-strength concrete play an important role in building structures.

This article summarizes the development process and existing achievements of 3D printed concrete from the combination ratio of ordinary concrete, the mixing ratio of high-strength concrete, and the mechanical properties of ordinary concrete.

## 2. Concrete Proportion

Designing a suitable printing medium is one of the most challenging parts of 3D concrete printing. The primary goal is to optimize the mix for compatibility with the printer on the one hand and mechanical behaviour minimum criteria on the other. Extrudability, buildability, adhesion, and open time are all requirements for printed concrete [1]. The influence of various materials on improving the performance of concrete is being examined widely. The impact of superplasticizers, retarders, and accelerators on workability, strength, and open time was investigated by Le et al. [2]. Khoshnevis et al., on the other hand, used plaster and clay-like material to improve the surface quality and geometric resolution of printed concrete. Similarly, several studies have focused on other characteristics related to printing materials, and further investigation is required in this area [3].

Researchers attempted to provide 3D printed concrete with self-reinforcement by adding fibres in order to decrease or eliminate the usage of steel in 3D printed buildings. Hambach et al. [4] investigated the mechanical characteristics of 3D-printed cement paste using a variety of fibres (including carbon, glass, and basalt fibres). They discovered that adding 1 vol percent carbon fibres to cement paste increases flexural strength by 18.5 MPa/174.5 percent but affects compressive strength. Soltan et al. [5] investigated the characteristics of fibre-reinforced cementitious composites in both their fresh and hardened states. They discovered that adding hydroxypropyl methylcellulose to cementitious composites can change the beginning flowability but not the hardening rate. It was also shown that adding a tiny quantity of nano clay to cementitious composites reinforced with fibres can reduce flowability and shorten hardening time. However, the difference in hardening rate was not noticeable. By replacing some silica sand with micro silica and powdered silica, fibre reinforced cementitious composites can harden faster while preserving their initial flowability. Additionally, the use of calcium aluminate cement improved initial flowability and hardening rate. As a result, the water concentration in cementitious composites has to be adjusted to provide adequate mixing and fibre dispersion, improving mechanical characteristics. Le et al. [6] examined the mix design of a

high-performance printing concrete using rheological theory. They discovered that a combination of 0.26 water-binder ratio, 3:2 sand-binder ratio, 1% superplasticizer, and 0.5 percent retarder could maximize the fresh characteristics of concrete when the nozzle diameter is 9 mm.

The use of admixtures can affect the characteristics of 3D printed concrete to some amount (including flowability, buildability, and viscosity). Meanwhile, adding an accelerator or retarder to cementitious composites might improve their characteristics. Mineral additives (such as micro silica, quartz flour, fly ash, and shell rock flour) and polycarboxylate plasticizers can regulate the rheology of cementitious composites and enhance workability, according to Inozemtcev et al. [7] (including increase the flowability and moderate the viscosity). Scholars have also done a lot of work on the impact of aggregate on the performance of 3D printed concrete. Lin et al. [8] discovered that sand of various sizes, grain morphologies, and fineness modulus had no discernible influence on extrusion under identical pumping circumstances. The fine aggregate of sand enhances the flowability, mechanical characteristics, and a number of stable printed layers with a given mixing percentage but reduces the viscosity and printing width of single-layer printing.

Before the optimal mixture was found, many trial mixes had to be developed and tested on the printer. The best mix was determined to be the one that needed the least amount of water to cement ratio while satisfying all of the requisite flowability, Extrudability, buildability, adhesion, and open time requirements [9]. Generating an ideal mixture of components requires the production of a control mix. Extrudability of mixes created by changing the quantities of dry ingredients (cement, aggregates, and sand) and water was the first step in the testing method. To determine the best nozzle diameter, a series of syringes with diameters ranging from 1 to 3 cm were employed to test the flowability of each combination. However, concrete behaviour differs from one nozzle to the next, depending on various parameters such as the nozzle's diameter, length, material type, and surface roughness, among others.

After a series of tests, it was discovered that increasing the amount of cement while decreasing the amount of sand resulted in greater extrudability. After several trials, a suitable mix of fine aggregate to cement ratio of 1.28 and fine aggregate to the sand ratio of 2 was discovered. Afterwards, when the dry component proportions were set. After that, the minimum water-cement ratio required for optimum extrudability was discovered to be 0.48. Finally, it was discovered that a nozzle diameter of 2 cm was optimum, while lower nozzle diameters resulted in obstruction and segregation. Additional tests were required to determine the amounts of additions after the correct proportions of essential elements were established. This step aimed to enhance strength by lowering the water-to-cement ratio while maintaining the concrete's flowability. Superplasticizers were used to achieve this. The superplasticizer helps to reduce the amount of water in building concrete while keeping its flowability. If the superplasticizer was applied in excess, the mixture can become too flexible and lose its capacity to sustain itself, reducing buildability.

The lowest water/cement ratio corresponds to the maximum compressive strength. All of the samples outperformed the specified compressive strength of 40 MPa. As a result, strength is not a critical factor. Rather, the flowability and buildability of the concrete mixture were the most important factors. The number of concrete layers that could be piled on top of each other before a severe deformation or failure occurred was counted in the buildability test. It intended to see if the layers corresponding to each combination could stand stiff without support while bearing the load produced by the upper layers. The experiment data determined the number of buildable levels, and the number of layers decreases as the quantity of superplasticizer is increased.

### **3. 3D printed normal concrete**

This section discusses the compressive strength, tensile strength, shear strength, and flexural strength of 3D printed normal concrete under the optimal mix proportion and summarized the above basic mechanical properties.

As the basic parameter of structural design, the compressive strength of concrete is very important for the application of 3D printing concrete. According to the research, the compressive strength of 3D printing concrete is basically consistent, and there is little difference in each direction. The pressure of the printer nozzle improves the compactness of concrete, the uniform and dense short column improve the bearing capacity of concrete, and the compressive strength is greatly affected by interlayer porosity [10]. Due to the different mix proportions, curing method, and sampling method. For example, in WOLFS [11], the printed specimens of normal concrete cured in a water bath did not show obvious anisotropy. However, the strength in three directions is lower than that of the cast-in-place specimen, which may be related to the matrix composition. This inconsistent conclusion indicates that the mechanical properties of 3D printing components are affected by many factors, such as printing equipment parameters, mix proportion, printing path, additives, sampling methods, etc. A good printing process can make the material subject to greater extrusion during printing, and the density of the material is higher than that of the cast-in-place specimen [12]. Compared with the round nozzle, the rectangular nozzle has less interlayer gap and higher strength.

The tensile strength of concrete refers to the axial tensile strength of concrete, the stress value obtained by dividing the maximum load of the concrete specimen after fracture by the sectional area. At present, the tensile strength test methods of 3D printing normal concrete mainly include a direct tensile method, splitting tensile method, and cross tensile way. The lamination process determines the Interlaminar weakness of 3D printing specimens, which greatly impacts the tensile properties. The tensile failure often occurs in the middle of the layer in the bonding layer. It is brittle failure. Interlaminar tensile strength is one of the important indexes of mechanical properties of 3D printing concrete. The root cause of Interlaminar weakness is the increase of porosity at the junction of new and old printing layers and the insufficient Interlaminar bonding strength. For 3D printing normal concrete, there is little difference in tensile strength in three directions [13].

The shear strength test methods of 3D printing concrete materials mainly include a cross method, direct shear test, and double shear test. Liu Zhiyuan et al. [14] found that the Interlaminar shear strength of 3D printing normal concrete is closely related to the printing interval. When the printing interval is less than the final setting time, the Interlaminar shear strength decreases with the printing interval and increases with the further increase of printing interval. This may be due to the mechanical occlusal effect of the interface between the old and the new. With the rise of printing interval, the occlusal effect increases with the hardening of the cement.

Flexural strength is also one of the important performance indexes to evaluate the quality of concrete. The Interlaminar weakness makes the concrete perform worse in the flexural test in the parallel direction. In contrast, the concrete is denser in the vertical direction, which is not affected by the weak interface due to the greater pressure during the printing process. The flexural strength may be higher than that of the whole cast specimen. Therefore, the flexural strength has more obvious anisotropy than the compressive strength. The results show that the flexural strength is generally affected by the change of loading direction, and the strength of each direction is Y direction, z direction > x direction. For 3D printing normal concrete, the flexural strength in X direction is 14% lower than that in Z direction, and it decreases with the increase of printing interval time [11]. In the test of Paul et al. [13], the flexural strength in Z and Y directions is about 7% and 14% higher than that of the cast-in-place specimens, respectively. The flexural strength is still affected by the interlaminar bonding strength, and the factors affecting the interlaminar bonding effect can indirectly affect the flexural strength. Therefore, it is particularly important to study the methods to enhance the interlaminar bond strength to improve the mechanical properties of 3D printing normal concrete.

#### 4. 3D printed high strength concrete

After considering the history of 3D printed concrete, mix ratio, and ordinary 3D printed concrete, we can find that 3D printed reinforcement technology is not mature, so the current 3D printed concrete is all used without reinforcement, ordinary concrete is difficult to meet the requirements of bending

resistance, bending resistance, crack resistance and bearing capacity. And the tensile strength of 3D-printed concrete is similar to that of ordinary poured concrete, with the tensile strength being about one-tenth of the compressive strength. It is very difficult to use plain concrete directly in engineering practice. After comprehensive consideration, we found that 3D printed high-performance concrete has high compressive strength, high tensile strength, and good durability. 3D printed high-performance concrete can better adapt to the structure's bearing capacity. Moreover, steel fiber is one of the earliest, most mature, and most widely used fiber forms in fiber reinforced concrete.

The brittleness of steel fiber reinforced concrete (SFRC) has obviously improved and has a broad application prospect in architecture. By adding steel fiber to 3D print high-performance concrete, the influence law of steel fiber content on concrete's compressive, bending, and bending properties can be found. We have learned that steel fiber has good strength and toughness, and it can be used to improve the performance of concrete by mixing it into ultra-high performance concrete. Therefore, how much steel fiber to add has become a vital issue in the UHPC field. When the amount of steel fiber is small, the performance improvement effect of UHPC is not significant. More mixing will have the opposite effect, and one or more performance indicators may be improved, while others severely weaken the response.

Xu et al. [15] found that when steel fiber was added, the compressive strength and flexural strength of UHPC would be significantly improved with the increase of steel fiber content. However, the flow performance of UHPC will be affected when steel fiber is added too much. In the design and preparation process of UHPC, Kong et al. [16] found that the critical value of the influence of steel fiber content on the compressive strength and bending strength of UHPC was 2.0%. Even a 0.5% increase in steel fiber, that is, 2.5%, decreases the compressive strength by 3.1% and the bending strength by 5.3%. Zhang et al. [17] found that when the content of micro-steel fiber was lower than 1%, it could significantly improve the 28-day compressive strength of UHPC and effectively improve the toughness of concrete. However, when the content was higher than this value, its working performance would significantly decrease. UHPC with 1% steel fiber content cannot meet the requirement of a self-compaction index. Xu et al. [18] conducted uniaxial compression tests to study the effect of 0%, 1%, and 2% volume steel fiber content on the performance of UHPC. They also found that the compressive strength of UHPC increased significantly with the increase of steel fiber content within this range, and the compressive strength of the sample with 2.0% volume steel fiber content was about 1.5 times that of 1.5%. Zhong et al. [19] selected steel fiber with the same material and different content to test with UHPC compressive strength and bending strength tester. The test results show that the compressive strength of the specimen increases with the increase of the content, and the UHPC specimen with the content of 2.5% has the highest compressive strength ( $\geq 130$  MPa). Compared with the matrix concrete, the flexural strength is also increased by 82.55%. Zhai et al. [20] studied the influence of different steel fiber content on ultra-high performance concrete (UHPC) strength performance with strength greater than 150MPa as assembly wall material. They found that when the steel fiber content increased from 0.5% to 2%, the strength increased by 37.5%. The flexural strength and compressive strength of UHPC are improved remarkably. Du et al. [21] studied 16 groups of different sizes of ultra-high performance concrete specimens under the condition of the different steel fiber content of compressive strength, found that the effect of steel fiber content on specimen strength has nothing to do with the size of the specimen. When the steel fiber content is 2%, the compressive strength of the specimen value is maximum, but if further increase content, the compressive strength value of the specimen is reduced. The results show that the incorporation of steel fiber can effectively improve the failure mode under compression.

## 5. Conclusions

This article summarized the development process and existing achievements of 3D printed concrete from the combination ratio of ordinary concrete, the mixing ratio of high strength concrete, and the mechanical properties of ordinary concrete. The following conclusions can be drawn:

(1) The high workability and mechanical properties of 3D printed concrete are highly dependent on materials selection (such as various types of fibers, admixtures, and high-quality sand) and printing parameters, both of which can be optimized. The optimal mix proportion have been obtained and considered to be implemented on large-scale 3D printing

(2) 3D printed normal concrete's compressive strength, splitting tensile strength, and bias properties are similar to the normal concrete.

(3) Comprehensive analysis of the research results shows that steel fiber can improve the compressive strength and flexural strength of UHPC within a certain range of content, but when the content exceeds a certain value, these two performance indexes will decay. Therefore, the optimal content of steel fiber is about 2%.

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